IAG (Geodesy)

G01a - G01 Reference Frames

IUGG-0554

Creation of a terrestrial reference frame via Kalman filtering of Very Long Baseline Interferometry data

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Terrestrial reference frames (TRF), such as the upcoming ITRF2014, are primary products of geodesy. In the past, the TRF station positions and velocities have been modeled linearly, with discontinuities where necessary due to, e.g., Earthquakes or equipment changes. Nowadays, however, more sophisticated models are being discussed. The parameters are usually estimated in a least-squares adjustment.

In this paper, we have followed a different approach to TRF creation. By applying a Kalman filter on the observational data of VLBI, we have determined continuous station positions of VLBI telescopes for the past 30 years. Contrary to the conventionally adopted assumption of linear behavior, we utilize a random walk process to describe the station motions. The stability is gained by enforcing a restrictive stochastic model, which can be softened dynamically to take into account episodic events like Earthquakes and the following post-seismic activity. The station coordinates are delivered epoch-by-epoch, allowing for a high temporal resolution. In contrast to so-called “epoch TRF”, for which the solutions of each epoch are computed individually, the Kalman filter estimates are determined by all observations collected in 30 years. The results have been compared to solutions based on the standard approach, e.g., the latest official VLBI TRF (VTRF) and ITRF solutions.

In addition to the possibility of easily dealing with non-linear motions, the Kalman filter approach also has the advantage of making updates to the TRF highly efficient and even possible in real-time, which is needed when new observational data becomes available. In the future, it is planned to expand the Kalman filter to include data from other space geodetic techniques.

IAG (Geodesy)

G01a - G01 Reference Frames

IUGG-1544

Twin Telescopes at Onsala and Wettzell and their contribution to the Very Long Baseline Interferometry Global Observing System

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During the last years the International VLBI Service for Geodesy and Astrometry (IVS) spent efforts to improve the accuracy of the geodetic Very Long Baseline Interferometry (VLBI) system to 1 mm for station positions and 0.1 mm/yr for station velocity. To achieve these ambitious goals the VLBI2010 concept was developed, which includes broadband observations with fast-slewing antennas and suggests twin telescopes to reduce the source switching interval and increase the number of observations. Wettzell in Germany has already installed a Twin Telescope and more Twin Telescopes will be installed in the coming years at Onsala (Sweden), Ny-Ålesund (Spitsbergen, Norway) and probably Kazan (Russia).

In this study, the Vienna VLBI Software (VieVS) was used to schedule and simulate a global VLBI network using the sites that participated in the CONT11 campaign, with and without the Twin Telescopes in Onsala and Wettzell. Different scheduling approaches (Onsala60 telescope or Twin Telescope, continuous or multidirectional mode, etc.) were compared by evaluating the numbers of observations and scans as well as baseline length repeatability, station positions, Earth orientation parameters, atmospheric parameters and clock estimates.

In general an improvement in the estimated parameters is visible with the Twin Telescopes especially with the Onsala Twin Telescope operated in a continuous observing mode and the scheduling strategy with four sources observed in the network simultaneously.

IAG (Geodesy)

G01a - G01 Reference Frames

IUGG-2595

Highlights of the German Research Group on Space-time Reference Systems

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Reference systems are an indispensable component for the description of the geometry and the kinematics of the Earth and other objects in space. Since 2012, a group of scientists in Germany, Austria and Switzerland is cooperating under the umbrella of a Research Unit (RU) of the German Science Foundation (DFG) to develop integrative methods and procedures for a consistent definition and realization of reference systems on Earth and in space. The RU covers multiple aspects of reference systems including the inertial system, the Lunar reference system, dynamic reference systems of satellites, and the terrestrial reference system. At the same time a consistent framework is realized by addressing modern data analysis challenges, planetary ephemerides, inter-system observations, datum definition issues, and ties of observing systems on Earth and in space. In late 2014, the RU has secured funding for the second three-year phase allowing a continuation and extension of the successful work of the first phase. Here, we will present an overview of the key achievements of the first phase and of the challenges addressed in the second phase. The talk will be an introduction to several presentations submitted to session “G01 Reference Frames”.

IAG (Geodesy)

G01a - G01 Reference Frames

IUGG-2803

Combination of session-wise VLBI solutions for generating individual celestial reference frames

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The combination of solutions of the International VLBI Service for Geodesy and Astrometry (IVS) are performed rigorously using datum-free normal equation systems (NEQs). At present, seven analysis centers regularly contribute their solutions on a session-by-session basis in the form of these NEQs. The mechanism permits the propagation of the full variance-covariance information and is used to compute the two major products of the IVS, i.e., time series of Earth orientation parameters (EOPs) and station coordinates. Nowadays these freely available solutions also contain the NEQ elements of the radio source position parameters. These can now be used for computing improved combined celestial reference frame (CRF) solutions for, e.g., the next realization of the International Celestial Reference System.

There are two options for the combination process: (1) combining solutions of identical sessions of several analysis centers first and then compile a complete CRF solution from the resulting session series. Here the intermediate output of the first step is again a series of NEQs. The new approach of option (2) is to generate, for each analysis center separately, a full CRF solution in the form of a complete NEQ system from the individual NEQs and then combine these to the final solution. The first step in itself is again a combination process of its own. Option (2) also offers the opportunity to solve the complete NEQs resulting in individual CRFs with full variance-covariance information. Here, we present results of this new type of computations of individual CRFs and discuss their characteristics. Intercomparisons help to identify blunders and to distinguish systematic from stochastic deviations.

IAG (Geodesy)

G01a - G01 Reference Frames

IUGG-3471

Analysis strategies for the densification of the International Celestial Reference Frame with VLBA Calibrator Survey sources

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Six campaigns with a total of twenty-four VLBA Calibrator Survey (VCS) observing sessions were carried out with ten radio telescopes in North America from 1994 to 2007. The aim of those sessions was to estimate and improve source positions. Coordinates of about two thirds of the sources in the ICRF-2 catalogue are estimated from VCS sessions, but their precision is up to five times worse than from non-VCS sources, which is mostly due the limited number of observations. Moreover, there are systematic errors due to the deficiencies of a continent-wide network for the estimation of Earth orientation parameters (EOP) and the linking between the celestial and terrestrial frame. We investigate the impact of EOP estimation on source positions for those sessions and we use polar motion estimates from the analysis of GNSS observations to strengthen the solution. Furthermore, we discuss future scheduling and analysis strategies for these sessions, including the proper use of datum or 'transfer sources'.

IAG (Geodesy)

G01a - G01 Reference Frames

IUGG-3648

The ICRF-3: Status, plans, and progress on the next generation celestial reference frame

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ICRF-3 seeks to improve upon the highly successful ICRF-2. Our goals are to improve the precision, spatial and frequency coverage relative to the ICRF-2 by 2018. This date is driven by the desire to create radio frames that are ready for comparison with the Gaia optical frame. Several specific actions are underway. A collaboration to improve at S/X-band precision of the VLBA Calibrator Survey's ~2200 sources which were 5 times less precise than the rest of the ICRF-2 is close to completing data acquisition expected to correct most of this deficiency. S/X-band southern precision improvements are underway with observations using southern antennas such as the AuScope and HartRAO, S. Africa. We also seek to improve radio frequency coverage with X/Ka and K-band work. An X/Ka frame of 660 sources now has full sky coverage from the addition of a 2nd southern station in Argentina which strengthens the southern hemisphere in general. Median X/Ka precision is now comparable to the ICRF-2 for common sources. A K-band collaboration has formed with similar coverage and southern precision goals. Initial data have been acquired and are being processed. On the analysis front, special attention is being given to combination techniques both of VLBI frames and of multiple data types. Consistency of the CRF with the terrestrial reference frame and Earth orientation parameters is another area of concern. Comparison of celestial frame solutions from various groups is underway in order to identify and correct systematic errors. Finally, work is underway to identify and pinpoint sources bright enough in both radio and optical to allow for a robust frame tie between VLBI and Gaia optical frames.

IAG (Geodesy)

G01b - G01 Reference Frames

IUGG-1403

The IGS contribution to ITRF2014

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Eight IGS Analysis Centers (ACs) have completed a second reanalysis campaign (repro2) of the GNSS data collected by the IGS global tracking network back to 1994, using the latest available models and methodology. The AC repro2 contributions comprise in particular daily terrestrial frame solutions including station coordinates and Earth orientation parameters. The AC daily terrestrial frame solutions are currently being combined by the IGS Reference Frame Working Group. The IGS daily combined solutions will form the IGS contribution to the next release of the International Terrestrial Reference Frame (ITRF2014).

We will first present the methodology used for the IGS repro2 terrestrial frame combinations, as well as results from inter-AC comparisons of global frame parameters (scale, origin), individual station position time series and Earth orientation parameters.

We will then present the stacking of the repro2 daily combined solutions into the long-term GNSS terrestrial frame that will enter the ITRF2014 computation. Our focus will be on the methodological advances made since the ITRF2008 computation (detection of jumps in station position time series; modelling of non-linear station motions).

IAG (Geodesy)

G01b - G01 Reference Frames

IUGG-2188

DTRF2014: The 2014 ITRS Realization of DGFI

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A new realization of the International Terrestrial Reference System is in preparation and will be finished in 2015. The input data series - including observations from VLBI, SLR, GNSS and DORIS until end of 2014 - will be available by the end of February 2015 and the final solution is assumed to be finished before mid of the year. Like the previous solution, ITRF2008, the new realization ITRF2014 will contain station positions and velocities as well as consistently estimated Earth Orientation Parameters (EOP). Additionally, sine-cosine fits of the station positions' annual signals will be provided. The ITRF2014 will be more accurate and stable than ITRF2008 because of two reasons: (1) six more years of observation data of the four space geodetic techniques, new observing stations and improved models are available (2) for ITRF2014, for the first time, non-tidal loading effects caused by atmosphere will be considered.

Three ITRS Combination Centres of the IERS (DGFI, IGN and JPL) are each in charge of the computation of this new realization. While the combination strategies of IGN and JPL are based on the combination of parameters, DGFI's strategy uses the combination of normal equation systems. This paper presents the latest results of the DGFI realization DTRF2014. It demonstrates shortly the combination strategy applied by DGFI and its characteristics. It discusses the results of the individual technique analyses, in particular the datum parameters and the station position time series. Finally, it presents the latest results of the combination of the four space geodetic techniques and the outcome of reference frame and EOP validation procedures.

IAG (Geodesy)

G01b - G01 Reference Frames

IUGG-2690

Impact of station-dependent, satellite-dependent SLR observations on global geodetic parameters

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Global SLR (satellite laser ranging) stations yield mm-precision ranging data that is valuable for the determination of global geodetic parameters such as terrestrial reference frames, the gravity constant (GM) and the low-order coefficients of the Earth. The size of the retroreflector array has become one of the key error factors as it broadens the scatter of laser pulses. This effect has been numerically simulated for most of the current spherical SLR targets in our previous studies (Otsubo and Appleby, JGR, 2003) (Otsubo et al, J Geod, 2015), where the system-dependent offset amounts to 4-5 cm for large targets, 1 cm for LAGEOS, and 7 mm for small targets. In addition to the underlying system-dependent constant offset, the range measurements are also sensitive to the often variable energy of return signals.

Using our geodetic analysis software “c5++”, the impacts of such systematic errors are investigated for the last 15 years. It is revealed that the constant offset directly affects the GM parameter by more than 0.5 ppb, and the scale of a terrestrial reference frame by a similar amount. The intensity-dependent offsets cause more complicated impacts on the realization of the origin of a terrestrial reference frame at a sub ppb level.

IAG (Geodesy)

G01b - G01 Reference Frames

IUGG-4433

Evaluation of ITRF2014 with ILRS data and products

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The development and release of the new realization of the International Terrestrial Reference Frame—ITRF2014 requires elaborate testing to ensure the quality of the final product. The evaluation effort ensures that the ITRF is of the indicated quality by its error estimates and the combination has not compromised the contributing techniques' input. The International Laser Ranging Service (ILRS) contributes unique information that only Satellite Laser Ranging—SLR is sensitive to: the definition of the origin, and in equal parts with VLBI, the scale of the model. The ILRS analysts adopted a revision of the internal standards and procedures in developing our contribution to ITRF2014 from our eight Analysis Centers. Since the release of ITRF2014 we worked on designing and executing tests using data and products unique to ILRS. In addition to the data contributed to ITRF2014, ILRS has several other targets, in lower and higher orbits, the SLR tracking data of which are used as independent data for the evaluation process. Since SLR data are primarily sensitive to the origin and scale definition of the TRF model, these model attributes are the best to be validated using SLR data. LAGEOS and ETALON data collected outside the span of data used in ITRF2014 can also evaluate the quality of the estimated velocity vectors. The use of independent SLR data evaluates the model throughout the period that such data are available. SLR data from low altitude missions can validate the performance of the model from the late '70s all the way to present (using e.g. STARLETTE and LARES data). This presentation will give an overview of the new model's evaluation using exclusively ILRS tracking data and other ILRS products.

IAG (Geodesy)

G01b - G01 Reference Frames

IUGG-4605

Geocenter motion from space geodetic observations

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The Terrestrial Reference System (TRS) is a fundamental concept for all studies in the geosciences. Determination of the Earth's center of mass (CM) is an important component for the realization of the Terrestrial Reference System and geo-information applications. The CM or geocenter as the center of mass of the entire Earth system is defined in the satellite orbit dynamics and referred to the position of CM with respect to origin of ITRF reference system, which can be determined from observation of Earth-orbiting satellite. Satellite Laser Ranging (SLR) provides accurate and unambiguous range measurements to direct estimate the variations of the vector from the origin of the ITRF to the CM as geocenter motion. The geocenter variations have also been determined from the GRACE GPS tracking data and the global inversion based on the displacement of the global GPS network. A combination solution of geocenter motion from those techniques will be presented. Theoretically, the difference between the results from SLR and Global GPS based inversion could be an indication of the mass center of the solid Earth in ITRF based on a unified theory of geocenter motion.

IAG (Geodesy)

G01b - G01 Reference Frames

IUGG-4687

The ILRS contribution to the development of the ITRF2014

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The latest International Terrestrial Reference Frame (ITRF2014) was initially to include data up to the end of 2013. In late 2013 it was decided to extend it to the end of 2014 under a tight delivery schedule. The ILRS Analysis Working Group (AWG) planned carefully to meet this deadline. Although Satellite Laser Ranging (SLR) data contributed to the definition of the ITRF over several decades, delivering products under such a tight schedule was never before required. Planning the availability of data and use of validated procedures demonstrated that it is possible to do so even routinely. The ILRS contribution spans 1983 to end of 2014. Primary focus of the last two ITRF re-analyses is monitoring systematic errors at individual stations, accounting for undocumented discontinuities, and improving the target signature models. The latter was addressed with the adoption of mm-accurate models for all our targets. On the station systematics, the AWG had since long embarked on a major effort to improve the handling of such errors prior to the development of ITRF2008. During this re-analysis station engineers and analysts have worked together again to determine the magnitude and cause of systematic errors, rationalize them based on events at the stations, and develop appropriate corrections whenever possible. With the completion of ITRF2014 the ILRS has turned its attention to pilot projects for the development of new products that can soon be delivered on a routine basis. Amongst others, they include precise orbits, low-degree gravity model harmonics, and quality control of ground system systematics. This presentation will give an overview of the development and evaluation of the extended ILRS contribution to ITRF2014.

IAG (Geodesy)

G01c - G01 Reference Frames

IUGG-0227

Initial realization of epoch Terrestrial reference frame

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Epoch Reference Frame is useful to improve the accuracy of Terrestrial Reference Frame (TRF). It could provide the present-time position and velocity of every site in time and also can reflect some changes due to earthquakes, instrument update and so on. Chinese Earth Rotation and Reference System Service (CERS) set up at SHAO (Shanghai Astronomical Observatory) could provide monthly or weekly Terrestrial Reference Frame (TRF) named STRF series and EOP products based on VLBI/SLR/GNSS/DORIS SINEX solutions. The accuracy of EOPs is similar with that of DGFI's EOPs with respect to IERS 08 C04. The accuracy is about 0.11 mas for PMX, 0.08 mas for PMY, 0.010ms for UT1-UTC and 0.02ms for LOD. The position and velocity for our TRF are close to that of ITRF2008 for regular space geodetic sites. The accuracy is better than 5mm for positions and 1mm/yr for velocities. We analyze one-year weekly and monthly epoch TRF solutions and hope to obtain some conclusions such as this epoch TRF is better than 5-year update TRF.

IAG (Geodesy)

G01c - G01 Reference Frames

IUGG-2421

1985-2015: Thirty years of R&D on the International Terrestrial Reference Frame

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The BIH (Bureau International de l'Heure) Terrestrial System of 1984 (BTS84) was the first global terrestrial reference frame published in 1985 and based on combination of space geodesy products (station coordinates and Earth Orientation Parameters) available at that time from VLBI, LLR, SLR, and Doppler Transit system (the predecessor of GPS). Since then, over the past 30 years, a significant progress has been made in technology, modeling and data processing, leading to improve the accuracy and precision of the International Terrestrial Reference Frame (ITRF) from a few decimeters to a few millimeters. The ITRF requirements for Earth science applications become nowadays more and more demanding, imposing a sub-millimeter accuracy. At this level of accuracy, not only linear, but also non linear deformations cannot be ignored. Periodic signals, as well as post-seismic deformations (for sites subject to major Earthquakes) should be accurately modeled in the ITRF implementation. After a brief review of the ITRF history, we focus on the progress made to improve the ITRF modeling and accuracy. Using the expected ITRF2014 results we show the current level of the ITRF performance: the accuracy of its defining parameters and in particular the origin and the scale given their importance for Earth science applications; the impact and benefit of modeling non-linear station motions; the level of agreement between space geodesy techniques and local ties at co-location sites and finally the associated Earth Orientation Parameters. Conclusions will be made regarding the limiting factors to be taken into account for future enhancement of the ITRF performance.

IAG (Geodesy)

G01c - G01 Reference Frames

IUGG-3441

"Global cooperation on Geodesy – Challenges in terms of organization and infrastructure "

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The work on global geodetic reference frames has since ancient time formed the necessary basis for evolution of a modern and well-functioning society. Today geolocation is about to become a megatrend and in such a context precise position determination turns to play a key role.

Trends point in the direction of a global geodetic reference frame that covers all purposes for the entire globe. A global reference frame with an accuracy of 1 mm and a stability of 0.1 mm/year is a necessary tool for satellite provided precise positioning, studies of the changing world and an efficient development of the developing countries. A key goal of the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) is to fulfill these requirements.

Global cooperation on Geodesy in science and administration has successfully been going on for decades. Nevertheless, the situation today is still not secure since the success has always been dependent on voluntary contributions from agencies in committed countries. As the coordinating body to link the IAG services GGOS can serve as a key to ensure a sustainable infrastructure and thus to advance the global reference frame. After more than 10 years of GGOS and looking at the intergovernmental efforts in the frame of the United Nations initiative GGIM it is time to evaluate the situation from a strategic perspective.

IAG (Geodesy)

G01c - G01 Reference Frames

IUGG-4730

100th anniversary of Einstein's theory of general relativity - its impact on reference frames and geodetic tests of relativity

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In 1915, Einstein has finalized the mathematical framework of General Relativity. It has completely changed the description of space and time. In geodesy, all measurement processes are affected by General Relativity. Thus, modelling of the space geodetic techniques (VLBI, GNSS, SLR/LLR) has to be done based on Einstein’s theory, i.e. all reference and time systems involved, signal propagation, motion and rotation of satellites and solar system bodies, measurement of distances, frequencies and time intervals, etc. Exemplarily for Lunar Laser Ranging (LLR), we will show where relativity enters the analysis and how the whole measurement process is modeled. But we will also give examples for VLBI.

By analysing the 45-year record of range data, LLR is one of the best tools to test General Relativity in the solar system. It allows for constraining gravitational physics parameters related to the strong equivalence principle, geodetic precession, preferred-frame effects, or the time variability of the gravitational constant. We will present recent results for the various relativistic parameters, again added by examples from VLBI and SLR.

IAG (Geodesy)

G01c - G01 Reference Frames

IUGG-5415

The ITRF kinematic datum: rigid plates vs. global deformation model

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The orientation of the ITRF station velocities, i.e. the ITRF kinematic datum, is aligned to the geologic-geophysical plate model NNR-NUVEL-1A (DeMets et al. 1994). It is assumed that this model, derived from geophysical observations over the last 3 million years, is valid for the present plate motions, and that the condition of no-net-rotation (NNR) with regards to the entire Earth surface is fulfilled. Recent studies (e.g. Altamimi et al. 2012, Drewes 2009) show significant deviations of the plate rotation vectors derived from the ITRF and from the NNR-NUVEL-1A model, respectively, i.e. the resulting station velocities differ noticeably. Furthermore it is evident that the NNR condition is not fulfilled at present. The principal shortcoming of the NNR-NUVEL-1A model is that not any of the extended plate deformations, in particular in the orogeny zones along the plate boundaries (e.g. the Mediterranean from the Alps to the Himalaya and the Andean from Alaska to Tierra del Fuego, are incorporated, and that these deformations are considerable and time-dependent according to seismic activities.

The consideration of these datum discrepancies is important for the scientific use of the terrestrial reference frame, in particular for pre-seismic and post-seismic investigations. As a consequence it is proposed to introduce a global deformation model derived from geodetic observations as the kinematic datum and to realize the NNR condition by global integration of its velocities over the entire Earth surface. An example computed from recent geodetic observations by least squares collocation is presented.

IAG (Geodesy)

G01d - G01 Reference Frames

IUGG-0699

GPS observations of seismo-ionospheric TEC disturbances: Cases study and characteristics

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Understanding and prediction of Earthquake are still challenging issues based on traditional seismometer and space geodetic deformation measurements. Ionospheric disturbances following the earthquake may provide new insights. In this paper, GPS seismo-ionospheric disturbances and characteristics are presented following recent bigger earthquakes, e.g., 2008 Mw 8.0 Wenchuan (China) earthquake, 2011 Mw 9.1 Tohoku (Japan) Earthquake and 2011 Mw 7.2 Van (Turkey) earthquake. Significant pre-seismic and co-seismic ionospheric disturbances are observed with about 0.2~0.5TECU from continuous GPS measurements. Furthermore, different seismo-ionospheric behaviors and patterns are presented and discussed. The significant seismic ionospheric disturbances are mainly driven by the ground-coupled air waves from ground vertical motion of seismic waves propagating with acoustic coupling effect of the atmosphere and solid-Earth.

IAG (Geodesy)

G01d - G01 Reference Frames

IUGG-1879

Annual horizontal surface displacements observed by GPS and GRACE: a comparison and explanation

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Agreements between GPS vertical coordinate observations and Gravity Recovery and Climate Experiment (GRACE) model prediction of the vertical surface displacements have been widely discussed in previous studies. Here we focus on discrepancy of the annual variations of horizontal displacements observed by GPS and GRACE, which is much larger than in the verticals. We compare ITRF2008-GPS horizontal residuals (232 IGb08 core stations) with horizontal surface displacements derived from the GRACE gravity fields (CSR RL05 version). Results indicate that the difference of the annual phase are smaller than 60 days for about half of the stations and the annual amplitude of GPS are about 2~3 times larger than GRACE. Comparison between different GPS time series (ITRF2008-GPS vs JPL) shows that some of the discrepancy between GPS and GRACE is due to technique uncertainties and errors in the GPS data processing. However further analyses show GPS-related uncertainties are not the major error source for the discrepancy. Firstly about 50% of the discrepancy in the N-S direction between GPS and GRACE can be explained by GPS displacements induced by temperature variations. Thermoelasitc displacements observed by GPS (not captured by GRACE) should be removed when we study surface loading using GPS data. Secondly we find that the annual horizontal variations observed by GPS are not as coherent as GRACE, especially over Europe, although the uncertainty of GPS annual horizontal variations over Europe is better than other regions. Analyses demonstrate that the variability from station to station within Europe may be induced by small-scale loading variations.

IAG (Geodesy)

G01d - G01 Reference Frames

IUGG-2468

Impact of in-situ meteorological data on station coordinates and terrestrial reference frame determined by very long baseline interferometry

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The International Terrestrial Reference Frame (ITRF) is one of the most important products of geodesy. For the current realization, the ITRF scale is defined as the mean value of the scales of the Very Long Baseline Interferometry (VLBI) and the Satellite Laser Ranging solutions.

We assess the impact of using meteorological data from different sources on VLBI analysis: original in-situ measurements, empirical models like GPT2w, Numerical Weather Models, and the homogenized and calibrated version of the in-situ measurements. The latter data set was produced using ERA-Interim Reanalysis for the homogenization and data from selected World Meteorological Organization stations located in the vicinity of each VLBI station for the calibration. For the mitigation of inconsistencies an approach was adopted based on the segmentation least absolute shrinkage and selection operator (LASSO). The in-situ meteorological data span the period from 1979 to 2015.

Here we consider the impact of meteorological data on the atmosphere delay and antenna thermal deformation models. The differences are most obvious in the radial component of station coordinates and thus contaminate the scale parameter. We conclude that a homogenized and calibrated meteorological data set is necessary for precise operational VLBI data reduction as well as for reanalysis efforts aiming for TRF determination.

IAG (Geodesy)

G01d - G01 Reference Frames

IUGG-2590

Water vapor radiometer data in very long baseline interferometry data analysis

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The propagation delay in the troposphere needs to be corrected in the analysis of very long baseline interferometry (VLBI) observations; otherwise there will be large errors in the estimated station positions and other parameters. Normally this is done by parameterizing the tropospheric delays as functions of zenith wet delays and gradients, and estimate also these parameters in the data analysis. However, the estimated tropospheric parameters and station coordinates are typically highly correlated. Thus, if we instead could apply accurate external information on the tropospheric delays, this would improve the precision of the station coordinates.

In this work we investigate a possible source of external information on the tropospheric delay, namely water vapor radiometers (WVR). These instruments infer the wet tropospheric delay from measurements of the thermal radiation from the sky at frequencies close to the 22 GHz water vapor line. For our investigation we use data from the continuous VLBI campaigns CONT02, CONT05, CONT08, CONT11, and CONT14. From these campaigns, there exist WVR data at a few VLBI stations, in particular at Onsala where WVR data are available for all campaigns. We test different ways of including the WVR data in the VLBI analysis – i.e. fixing the tropospheric delays to the WVR values or including the WVR data as additional observations in the analysis while still estimating the tropospheric parameters – and study the impact on the estimated station positions. We also investigate the effect of possible calibration errors in the WVR data and how these can be dealt with. Finally, we discuss the potential benefits of using WVR data in the upcoming VGOS (VLBI Global Observing System) network.

IAG (Geodesy)

G01d - G01 Reference Frames

IUGG-2733

Atmospheric, non-tidal oceanic and hydrological loading effects observed with GPS measurements

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Surface displacements due to loading processes can be modeled using atmospheric, non-tidal oceanic and hydrological general circulation model (GCM) outputs convolved with the appropriate Green's functions, describing the Earth's elastic response to surface loads.

We compute atmospheric loading effects using surface pressure provided by the latest reanalysis and the operational models of the ECMWF. A model describing the ocean response to the pressure forcing is required. The inverted barometer (IB) hypothesis is usually chosen and is considered valid for periods exceeding typically a week. At higher frequencies, the dynamics of the ocean response cannot be neglected, and we use a global barotropic ocean model forced by ECMWF air pressure and winds, the Toulouse Unstructured Grid Ocean model (TUGO-m).

The combination ECMWF+TUGO-m is incompatible with non-tidal ocean loading estimated using bottom pressure variations of classical baroclinic ocean GCMs, as both the latter and TUGO-m are forced by surface winds. However we can compare ECMWF+TUGO-m with ECMWF/IB + ocean GCM loading models. Hydrological loading inducing long period displacements, we add to our atmospheric and non-tidal oceanic loading computations the contribution of the continental water storage using different global models.

We compare our loading models to two global sets of positioning time series, and investigate how they can be reduced looking at different frequency bands: periods > 2 months, > 2 months without seasonal, > 7 days and the whole spectrum (> 1day). We find that ECMWF+TUGO-m better agrees with vertical surface motion than the ECMWF/IB model. Besides, continental hydrology significantly helps

improve the agreement between observation and loading models at seasonal timescales.

IAG (Geodesy)

G01d - G01 Reference Frames

IUGG-5381

Consistency of parameters derived from global SLR, VLBI and GNSS solutions when using non-tidal loading deformation on the observation level

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The complex Earth's system undergoes everlasting changes covering a wide band of different periods and scales. Drawing conclusions about such processes, reliable measurements and a consistent, global and precise reference frame are necessary. Space-geodetic techniques used for this purpose are affected by different geophysical phenomena. Unmodeled effects cause e.g. variations in the station position and also propagate to other estimated parameters like the Earth Orientation Parameters (EOP) and the geocenter. These variations are often caused by tidal and non-tidal mass redistributions in the atmosphere, the ocean and the continental hydrology. Besides their impact on the Earth’s shape, the gravity field and the Earth’s rotation are affected, too. Special data sets to model the non-tidal effects are available at the Global Geophysical Fluids Centre (GGFC) of the IERS.

We introduced loading-induced deformations at the observation level in VLBI, SLR and GNSS analysis. Several global solutions with different model combinations were processed. The consistency between common parameters like the EOPs and the stations coordinates derived from the three techniques is studied. The impact of non-tidal loading models on technique-specific parameters like the range biases for SLR is also studied.

IAG (Geodesy)

G01e - G01 Reference Frames

IUGG-0435

Geophysical interpretation of GPS surface displacements: a preliminary study over Europe

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We analyze more than 10 years of GPS height residuals and vertical displacements derived from surface mass loads observed by the Gravity Recovery and Climate Experiment (GRACE) for 37 IGS stations in Europe. Seasonal surface displacements, mostly due to atmospheric and hydrologic loading, are significant in both GPS and GRACE measurements. Our new analysis shows considerably improved agreements between GPS and GRACE observations than those from previous studies. Most of stations have a significantly reduced weighted RMS of the GPS height residuals after GRACE predicted vertical displacements have been removed. Through further analysis, we attribute the better agreements to improvements of GPS time series and also improved accuracy of GRACE data. The amplitudes and phases of GPS observed annual displacements become spatially more coherent.

IAG (Geodesy)

G01e - G01 Reference Frames

IUGG-1918

A comparison of existing and new method for the analysis of nonlinear variations in coordinate time series

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Two existing methods for the analysis of nonlinear variations in coordinate time series, after or simultaneously with linear trend removal, namely the Fourier analysis with annual, semiannual and other periodic components and the Singular Spectrum Analysis (SSA) are compared with two new methods, both producing an analytical representation of the nonlinear variation.

The first method is the use of an annual carrier frequency modulated in both amplitude and phase by piecewise linear functions. The second method refers to the interpolation of the coordinate time series residuals after linear trend removal with cubic splines over a partition of the time domain into intervals of the same length.

The role of the choice of parameters related to the above two representations on the obtained results is thoroughly investigated. In addition the stochastic characteristics of the remaining "error" terms after the removal of both linear and nonlinear terms are also investigated.

IAG (Geodesy)

G01e - G01 Reference Frames

IUGG-3658

Analysis of the European velocity and deformation fields by a new approach

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Networks of permanent GPS stations provide data which are very dense in time but discrete in space, while the analysis of a velocity and deformation field requires a spatially continuous modelling: therefore, to investigate deformations from permanent network data a time modelling and a spatial interpolation are needed. As time is concerned, the linear model is typically adopted by international agencies to estimate the individual velocities of the stations. Horizontal estimates are more accurate than height estimates: in spatial modelling, the adoption of a two dimensional approach seems justified to investigate geodynamics deformations. The proposed approach models the regional deformation as a stochastic process in space. The displacements and deformations spatial field is predicted by the stations velocities through a collocation approach. Prior trend removal is based on the transformation to a new reference system satisfying a discrete Tisserand principle. In the spatial interpolation, new approaches to model the covariance structure of the displacements and the rigorous estimation of the accuracies of the predicted deformation parameters have been studied. The algorithms and their implementation are presented. As a case study, they have been applied to Europe: official European Permanent Network velocities and covariances of about 260 stations provide input data. The results are discussed.

IAG (Geodesy)

G01e - G01 Reference Frames

IUGG-4337

The IAG Working Group "Integration of Dense Velocity Fields in the ITRF": Final Results and Conclusions

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The objective of the IAG Working Group “Integration of Dense Velocity Fields in the ITRF” is to provide a GNSS-based dense, unified and reliable velocity field globally referenced in the ITRF (International Terrestrial Reference Frame) and useful for geodynamical and geophysical interpretations. The WG is embedded in IAG Sub-Commission 1.3 “Regional Reference Frames” where it coexists with the Regional Reference Frame Sub-Commissions AFREF (Africa), APREF (Asia & Pacific), EUREF (Europe), NAREF (North America), SCAR (Antarctica), SIRGAS (Latin America & Caribbean). These IAG Regional Reference Frame sub-commissions are responsible for providing GNSS-based densified weekly solutions for their region. To obtain such a densified velocity field, the WG combined the individual weekly solutions from 7 individual contributors (AFREF, APREF, EUREF, NAREF (NGS, GSB), SIRGAS, IGS) and then stacked these weekly combined solutions in order to derive an ITRF2008 densification as well as the associated residual position time series for more than 2800 sites. As this WG is reaching the end of its term, final results will be shown and conclusions will be drawn.

IAG (Geodesy)

G01e - G01 Reference Frames

IUGG-5556

Assessment of weighted and un-weighted inner constraints on multi- session solutions for estimating station velocities in regional GNSS networks

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The estimation of station velocities is one of the most important products from a GNSS multi-session network adjustment with significant value for Earth science applications. The datum definition is typically based on a subset of reference stations with well-known positions in a global reference frame (e.g. ITRF) while its proper implementation is a crucial factor affecting the accuracy of the estimated velocities in the underlying frame. The usual strategy relies on the so-called inner constraints over the selected reference stations which nullify the Helmert transformation parameters, and their rates, of the adjusted network with respect to the prior positions of the reference stations. The advantage of the inner constraints is the minimization of the propagated data noise on the adjusted positions of the reference stations without distorting the network geometry as defined by the GNSS observations. Recently a generalized type of inner constraints was introduced by the authors which is able to minimize simultaneously the data noise and datum noise effects (the latter caused by the random errors in the known positions of the reference stations) over all network stations, thus overcoming the limitations of the classic inner constraints. The key aspect is the use of a prior weight matrix for the reference stations within the inner constraints which is computed by closed formulae based on a zero-order network optimization process for the estimated station positions. Our aim is to assess the accuracy improvement of the weighted inner constrained solution relative to the un-weighted inner constrained solution for station velocities in regional GNSS networks through case studies for multi-session solutions using the two types of inner constraints for their alignment to ITRF.

IAG (Geodesy)

G01e - G01 Reference Frames

IUGG-5563

Comparison of frame alignment strategies in GNSS coordinate time series

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Coordinate time series constitute an important tool for investigating the dynamic behavior of the Earth's crust and the study of unmodelled loading signals on time-dependent station positions with respect to a long-term global reference frame. A key factor that can significantly affect the geophysical interpretation of non-linear variations in a coordinate time series is the frame alignment strategy used to map daily or weekly solutions of a GNSS monitoring network to a time series of station coordinates in a well-defined frame (e.g. ITRF). The aim of this paper is to compare the impact of four different frame alignment techniques on the behavior of multiyear coordinate time series generated in regional monitoring networks of permanent GNSS stations. The first two techniques correspond to well-known strategies which are commonly used in geodetic practice, namely the implementation of inner constraints over a subset of reference stations during the daily or weekly network adjustment or, alternatively, the application of a Helmert transformation to free-network solutions on the basis of known reference stations in the preferred target frame. Two additional techniques are also considered which include the use of a weighted type of inner constraints on the reference stations or, alternatively, the application of a modified Helmert transformation that takes into account the co-variances between the reference and non-reference station coordinates in the initial frame during the transformation procedure. The comparison among the aforementioned frame alignment strategies reveals important aspects regarding the assessment of real geophysical signals in GNSS coordinate time series and the elimination of artifacts due to suboptimal definition of the coordinate reference frame.

IAG (Geodesy)

G01f - G01 Reference Frames

IUGG-1246

Aligning a Regional Reference Frame to ITRF2008 using minimum constraints approach

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CGCS2000 (China Geodetic Coordinate System 2000) was aligned to ITRF97. Update of CGCS2000 is planned in the near future. An experiment was made for aligning Chinese regional reference frame to ITRF2008 using minimum constraints approach. A set of 64 globally distributed IGS stations with ITRF2008 coordinates and velocities are selected to serve as control in the reference frame alignment. Data were collected from 27 CMONC (Crustal Movement Observation Network of China) stations and 64 IGS stations for the periods of 16-31 December 2011 and 24 April to 5 May 2014. Loose constraints with 1m uncertainty are applied in the loosely constrained solutions. After removing the constraints, the minimum constraints constructed by the 64 IGS stations are added to the solutions and the coordinates and velocities of the 27 CMONC stations referred to ITRF2008 are obtained.

IAG (Geodesy)

G01f - G01 Reference Frames

IUGG-2919

SIRGAS: The core geodetic infrastructure in Latin America and the Caribbean

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Understanding geophysical phenomena, such as global change and geodynamics, require geodetic reference frames with 1) an order of accuracy higher than the magnitude of the effects we want to study, 2) consistency worldwide (the same accuracy everywhere), and (3) a long-term stability (the same accuracy at any time). The realisation of the ITRS is oriented to guarantee a globally unified geometric reference frame (ITRF) with reliability at the cm-level. The densification of the global ITRF in Latin America and The Caribbean is SIRGAS (Sistema de Referencia Geocéntrico para Las Américas), primary objective of which is to provide the most precise coordinates in the region. At present, SIRGAS is the backbone for all scientific and practical applications based on the generation, use, and analysis of geo-referenced data. However, the reliability of SIRGAS as reference frame is being affected by the occurrence of seismic events deforming the geometry of the network and by the omission of non-lineal station movements. In this context, this presentation summarises the main challenges faced currently by SIRGAS: 1) A high-resolution monitoring of the reference frame deformation by

means of continuously operating GNSS stations and improved analysis standards; 2) Co-seismic deformation models (derived from GNSS) for the transformation of station positions between pre- and post-seismic realisations; (3) Modelling of non-lineal station movements in the reference frame computation to improve the estimation of epoch coordinates.

IAG (Geodesy)

G01f - G01 Reference Frames

IUGG-2928

Development of a geodetic deformation model for Papua New Guinea (PNG)

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PNG is located within the plate boundary zone between the Australian and Pacific Plates. The tectonic setting in PNG is complex with many smaller microplates and deforming zones. The complexity of the deformation field makes it difficult to maintain integrity of the PNG geodetic datum (PNG94) and derived spatial data infrastructure. Furthermore, increased use of GNSS Precise Point Positioning (PPP) is resulting in inconsistencies between the PPP reference frame (currently ITRF2008) and PNG94 unless differences between the two frames are modelled within required tolerances. Time-dependent transformation strategies such as a 14 parameter model are not suitable where deformation is non-uniform. In areas of complex deformation, crustal block rotation and gridded deformation models can be used to enable transformation from a global geodetic reference frame such as ITRF to an epoch fixed local reference frame such as PNG94 in order to support localised positioning and spatial data integration.

This paper describes the development of a PNG deformation model to support positioning and datum modernisation in PNG. Recent geodynamic studies and campaign GPS data have been used to develop a kinematic representation of the velocity and deformation field in PNG to support positioning activities. The territorial extent of PNG is divided into microplates and crustal blocks for which Euler poles of rotation have been defined by inversion of observed GPS site velocities, fault locking models and other geophysical data. A deformation model grid is then developed that includes both intraplate and plate boundary interseismic deformation. A site velocity model grid is also developed by plate rotation and residual deformation models. These models can be implemented in GNSS software and GIS.

IAG (Geodesy)

G01f - G01 Reference Frames

IUGG-5420

Practical and technical considerations for the replacement of U.S. national datum NAD 83

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The official U.S. horizontal mapping datum, the North American Datum of 1983 (NAD 83)—in both its definition, as well as the services NGS provides for its access—is in need of improvement. As defined, it is non-geocentric by over two meters and has non-zero, residual plate velocities. Since 1983, increasingly accurate International Terrestrial Reference Frames (ITRF) have become available and have been adopted by many groups, including Mexico's INEGI and the U.S. National Geospatial-Intelligence Agency.

The U.S. National Geodetic Survey is planning a replacement of NAD 83 with a new ITRF-aligned geometric datum, to be released with a new GNSS-accessible geopotential datum replacing the North American Vertical Datum of 1988. We will discuss the importance of a modern national datum, how its definition will be aided by and differ from international frames, the tools (Real-Time GNSS, Online Processing User Service, passive monuments) expected to provide datum access, and the anticipated benefits and challenges recognized by our Federal, state, private sector partners.

IAG (Geodesy)

G01g - G01 Reference Frames

IUGG-1082

Combination of GPS and VLBI on the observation level

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Co-located instruments at space geodetic observatories allow us to take benefit from sharing infrastructure at the site and make it possible to combine solutions from different techniques. Local ties relate between the reference points of the individual space geodetic techniques, but one can also take advantage from the close proximity of instruments and estimate nuisance parameters, in particular troposphere and clocks, in site-wise models rather than parametrizing these unknowns for each technique separately. In order to realize such an approach, a suitable model for the nuisance parameters as well as proper weighting of the observations from the individual techniques are necessary. These aspects and the application of such an analysis strategy to VLBI and GPS data are being studied with the multi-technique space geodetic analysis software c5++. This software allows us to combine several space geodetic techniques on the observation level and provides also a variance component estimation (VCE) feature, which aims to give proper weight to the observations from the individual techniques. We are going to evaluate the concept of combination on the observation level based on campaigns of continuous VLBI sessions (CONT) from the last years and we are going to discuss which steps are necessary in order to realize such an approach for larger networks which include other space geodetic techniques as well.

IAG (Geodesy)

G01g - G01 Reference Frames

IUGG-1313

Combined processing of LEO and Ground-based GPS Observations: Impact on the Terrestrial Reference Frame

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The GPS observations provided by the global IGS (International GNSS Service) tracking network play an important role for the realization of a unique terrestrial reference frame that is accurate enough to allow the monitoring of the Earth's system. Combining these ground-based data with GPS observations tracked by high-quality dual-frequency receivers on-board Low Earth Orbiters (LEO) might help to further improve the realization of the terrestrial reference frame and the estimation of the geocenter coordinates, GPS satellite orbits and Earth rotation parameters (ERP).
To assess the scope of improvement, we processed a network of 50 globally distributed and stable IGS-stations together with four LEOs (GRACE-A, GRACE-B, OSTM/Jason-2 and GOCE) over a time interval of three years (2010-2012). As high-quality LEO orbits are a pre-requirement, individual parametrizations and force models were considered and the derived orbits were compared against external solutions and SLR observations. To ensure fully consistent solutions the zero-difference phase observations of the ground stations and LEOs were processed in a common least-square adjustment, estimating GPS orbits, LEO orbits, station coordinates, ERPs, site-specific tropospheric delays, satellite and receiver clocks and ambiguities.
We present the significant impact of the individual LEO and a combination of all four LEOs on the geocenter coordinates which also depends on the orbit parametrization. We compare the derived geocenter coordinate time series w.r.t. solutions based on ground-based GPS only, on SLR and on geophysical data and discuss the influence on the orbits and ERPs.

IAG (Geodesy)

G01g - G01 Reference Frames

IUGG-1917

A combined TRF of GNSS single differences and VLBI at the observation level during CONT11

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To test the GNSS-VLBI hybrid observation concept, where GNSS signals are received by GNSS antennas and correlated with VLBI correlators, GNSS delays during CONT11 are analyzed together with standard VLBI observations. The GNSS delays between the ranges from two stations to a satellite were generated by using post-processed range measurements from a precise point positioning (PPP) GPS solution with the c5++ software. At seven sites of the CONT11 network, VLBI and GNSS antennas are connected to the same clocks, which means that clock parameters can be regarded as site common parameters. We estimate station coordinates as well as Earth orientation parameters and site common parameters, i.e. zenith wet delays and clock parameters, with the Vienna VLBI Software (VieVS). Local tie vectors, which contribute to the combination of frames between VLBI and GNSS, are introduced as fictitious observations and then reassessed according to stations coordinate results. We will also compare our results to the combination results from c5++.

IAG (Geodesy)

G01g - G01 Reference Frames

IUGG-2715

Positioning Accuracy Using a Combination of GNSS and Inter-Satellite Observations

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Today's GNSS Systems are equipped with or considering implementing inter-satellite ranging and communication capability. The inter-satellite links are primarily used for autonomous navigation, shorter update intervals for the ephemerids in the navigation message and for reducing operational costs. Moreover inter-satellite links have a high potential to improve precise orbits. Especially the relative position of the orbits in a constellation can be determined with high accuracy using inter-satellite range observations. Therefore the resulting satellite orbits can be considered a realization of a dynamic reference system. This reference frame can be connected with the terrestrial reference frame (TRF) introducing additional observations from GNSS ground stations. Then the TRF is accessible to the user by using these obits for positioning with a GNSS receiver.

The positioning accuracy in the TRF shall be assessed using orbits based on inter-satellite observations. Therefore a network of inter-satellite observations as well as observations from ground stations are simulated. Orbit determination is performed using a combination of these observations. Several scenarios will be assessed, which differ in the number of ground stations used to interlink the orbits with the TRF.

IAG (Geodesy)

G01g - G01 Reference Frames

IUGG-4145

GRASP 2015 – revised design and data analysis for a mission to improve the terrestrial reference frame

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The Geodetic Reference Antenna in Space (GRASP) mission concept will be proposed once more to NASA in response to the expected Earth Venture Mission (EV-M) call in 2015. While the mission remains dedicated to the collocation in space of the four geodetic techniques used to the determine the terrestrial reference frame, namely GNSS, SLR, VLBI, and DORIS, the updated mission architecture contains several important improvements relative to the well-received concept that was proposed in 2011. These include changes to the orbital configuration, the onboard space geodetic sensors, and to the spacecraft. We will describe the new mission architecture and present new data analysis using both simulations and actual data to demonstrate the transformative contributions of this mission to the production of terrestrial reference frames meeting the exacting GGOS requirements.

IAG (Geodesy)

G01g - G01 Reference Frames

IUGG-4899

Double-Difference SLR Approach with GNSS, GEO, LAGEOS and LLR

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Differencing of common-view SLR measurements to GNSS satellites offers an alternative approach for reference frame realization. The main advantage is in the reduction of common-view systematic effects, leading to differential SLR ranging with mm-accuracy. This offers an interesting application of SLR measurements in the global GNSS solutions. SLR double-differencing can also be applied between LAGEOS and GNSS satellites in a combined GNSS+LAGEOS global reference frame solution. A similar common-view differencing technique could in principle be applied between the GNSS constellation and Lunar Laser Ranging (LLR), or between Lunar laser retroreflectors, potentially offering an interesting new combination strategy with LLR. On the other hand, a geometrical double-difference SLR approach with GNSS is still limited by the orbit accuracy of GNSS satellites, on continental scales: however, we show that it offers a purely geometrical definition of the terrestrial reference frame (similar to GPS) and a bias-free estimation of relative local ties. We present new results with the double-difference SLR approach for GNSS and LAGEOS, including SLR stations in Europe and the first intercontinental SLR baselines. In the sequel, we focus on the concept of SLR double-differencing between GNSS constellations and laser reflectors on the Moon and present the potential of this approach.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-228

Effects of different loading models on station positions and Earth rotation from Very Long Baseline Interferometry data analysis

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In this study, the impact of applying different loading-induced displacement models on station position and Earth orientation parameter time series from VLBI data processing is investigated. The network geometry of VLBI observatories taking part in geodetic sessions allows un/mis-modelled loading displacements at specific sites to contaminate the rest of the participating stations. Hence, it is imperative that a rigorous and consistent approach employing accurate loading models is adopted for treating such accuracy-limiting effects.

Every loading model available from the Global Geophysical Fluid Center accounting for atmosphere, ocean and hydrological loading was examined. The performance of all loading-induced deformation corrections due to Earth's fluid envelope was tested by applying them in reasonable combinations at the observation equation level in the least squares adjustment, while processing more than 30 years of VLBI data using the VieVS@GFZ software.

In addition, we calculated deformations induced from atmospheric pressure loading directly at the VLBI stations by convolving Farrell Green's functions with topographically adjusted surface pressure values from ERA-Interim reanalysis spanning the period from 1979 to 2015. Additional meteorological fields of the former as well as GTOPO30 and EGM2008 were combined for the hypsometric adjustment. The new model was tested through the analysis of the entirety of VLBI observations. This new model outperforms the existing models, in terms of admittance factors and baseline length repeatability.

We suggest a certain combination of models to be used for loading correction. Future research includes non-tidal ocean loading and hydrological loading reduction model development, in terms of maximum consistency.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-229

Modern Russian reference frame

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Reference frame is one of the key elements of a united system of Position Navigation and Timing, which largely determines its main characteristics. Improving accuracy of Position Navigation and Timing also depends on improving the accuracy of the reference frame.

The paper discusses the coordinate systems SK-95 and PZ-90.02, developed in Russia, as well as the principles of construction of the reference frame, implementing these systems. The shortcomings of these coordinate systems and constructed reference frame are considered.

At present, Russia has developed two new coordinate systems - one for geodetic and cartographic activities - a highly accurate state geodetic coordinate system (GCS-2011), and the other - for space navigation - PZ-90.11.

A new reference frame structure is being established to implement effectively these coordinate systems. The paper presents the principles and hierarchy of the new state reference frame, algorithms and transformation parameters of the above coordinate systems.

The newly created reference frame is focused on the most efficient and effective use of GNSS. This system will also provide broader applications of GLONASS, not only to geodesy, but also to other areas of scientific and industrial activities. The accuracy of the relative position of points in the reference frame of the new generation is estimated to be a few centimeters.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-230

Warkworth - Improving New Zealand's connection to the ITRF

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New Zealand has one facility that contains more than one space geodesy technique. The Warkworth Radio Observatory has a Continuously Operating GNSS Reference Station, which became an International GNSS Service (IGS) station in 2013 and two Very Long Baseline Interferometry (VLBI) capable radio telescopes, one of which is an International VLBI Service (IVS) telescope. A newly established absolute gravity station adds to the geodetic significance of the observatory for New Zealand.

The first Warkworth local tie survey was undertaken in late 2012 and was repeated in early 2015. This survey included the second telescope which was enabled for VLBI observations in mid-2014. The local tie survey derives a relationship between the antenna reference point (ARP) and the invariant reference point on the telescope, neither point can be directly observed.

The International Terrestrial Reference Frame (ITRF) will rely on the local tie surveys for future realisations.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-231

The Effect of Planetary Torques on the Lunar Reference Frame

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The five laser retroreflectors from the Apollo and Luna missions represent the realization of the lunar reference system. At the moment, these are the only geodetic ground marks on the Moon which have been regularly observed over a long time span by Lunar Laser Ranging (LLR). Future missions will be able to deploy new reflectors or radio transmitters on the lunar surface. To better determine the orientation of the Moon in space, the best positions for these devices are near the limb of the visible lunar disk. The analysis of the current and future LLR measurements, e.g. to determine the coordinates of the reflectors or radio transmitter, requires a good theoretical model of lunar ephemeris (position and orientation). Here we investigate the effect of external torques from the planets on the Moon, treated as an extended, non-spherical body. We compute the effect of planetary torques on the translational motion of the Moon as well as on its rotation. For example, torques from Venus affect the estimated reflector coordinates in the order of 2 cm.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-232

Refined and site-augmented tropospheric delay models in the analysis of VLBI observations

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Modeling tropospheric delays is one of the major error sources in the analysis of Global Navigation Satellite Systems (GNSS) and Very Long Baseline Interferometry (VLBI) observations. In this presentation, two standard approaches in the modeling of tropospheric delays are improved: the estimation of linear horizontal gradients by Chen and Herring (1997) is extended to higher orders so that the azimuthal-dependent variations are modeled more precisely. Moreover, the standard approaches of using the Vienna Mapping Functions (VMF; Böhm et al., 2006) or the empirical Global Mapping Functions (GMF; Böhm et al., 2006) are enhanced by temperature measurements at the site. Thus, the temporal resolution of the temperature values, which are usually available every 6 hours from numerical weather models, is increased. The different approaches are finally compared to each other by investigating baseline length repeatabilities for the continuous VLBI campaign in 2011 (CONT11).

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-233

Stochastic optimization of parameters for an asteroidal mass ring model in ephemeris computation

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Theoretically, a barycentric ephemeris represents the dynamical realization of the Barycentric Celestial Reference System (BCRS). The BCRS through its intimate relation to the Geocentric Celestial Reference System (GCRS) is thus fundamental for any high precision geocentric reference system. Modern Solar-System ephemerides simultaneously integrate the (relativistic) equations of motions of a large number of major bodies. Even though sophisticated numerical integrators are being employed, it is not feasible to take all significant (point) masses into account individually. Therefore, the gravitational effect of the very large number of minor bodies, e.g. in the main asteroid belt between Mars and Jupiter, can be modelled, for instance, by a (circular) mass ring. All groups creating ephemerides have to deal with the problem of asteroid selection for the list of individual bodies to be integrated, and the corresponding estimation of ring parameters, especially its mass, which are then suitable to account for the combined effect of the remaining minor bodies. Here, we present a unique approach for this task, based on a stochastic optimization technique, namely an evolutionary algorithm. We check this new approach with results of established ephemerides like the French INPOP versions.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-234

The Validation of the Transformation between a Classical Datum and a Modern Reference Frame, by using External Space Techniques

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The rapid development of GNSS techniques during the last 30 years has changed dramatically the geodetic, surveying and mapping activities in the daily practice. A crucial issue concerning the use of GNSS measurements is the fact that the majority of the geodetic and cartographic infrastructure is - as usually - referred to local (national) classical datums. These datums mainly suffer from systematic effects, blunders and discrepancies due to observation errors and the computation methods, as well. In order to tackle this problem, many state agencies implement the classical 3-D Helmert-type transformation for the connection of the GNSS-based Reference Frame (ITRF or any regional) and the classical datum, respectively. The magnitude of the estimated transformation errors gives a sense of the discrepancies between the two frames. In the present study, a new technique is suggested for the validation of the transformation, by using external space techniques from sites (e.g GNSS/SLR/VLBI/DORIS) which belong to a global or/and a regional Terrestrial Reference Frame (TRF). The main characteristic of the suggested methodology is the use of the estimated velocities, which allow the coordinates determination back to the time of the classical datum realization. This methodology is tested in the Hellenic area, resulting into some interesting results on the external validation of the transformation between, the classical geodetic datum (HGRS87) and the local densification of European Terrestrial Reference System of 1989 (ETRS89).

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-235

On the time-changeable signals in GPS time series

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The GPS time series are commonly described as the sum of trend, seasonal signals and underlying noise that directly influences the errors of above parameters. Not only do the mismodelled satellite orbits, large-scale atmospheric effects or monument instability result in lower spectral indices of noises shifting them to flicker or random-walk ones, but also seasonal signals when being improperly modelled and removed. In this research we focused firstly on synthetic data simulated with fixed length, value of trend and noise amplitudes and added a hydrological/atmospheric loading signal (http://loading.u-strasbg.fr/ITRF/) that varies a bit from year to year in amplitude. Then, the real GPS data from IGS network was analyzed. These series were processed by the Jet Propulsion Laboratory using GIPSY-OASIS software in a Precise Point Positioning mode. The seasonal changes in synthetic and real series were modelled with least-squares estimation and wavelet decomposition. The Chandlerian, tropical and draconitic curves were modelled with least-squares estimation up to 9th harmonic which still is significant in stacked spectra at the level of 0.05. The same periods were modelled with wavelet decomposition using Meyer mother wavelet and 9 levels of it. This presentation shows that wavelet decomposition performs better than least-squares estimation when seasonal curves are changing in amplitudes.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-236

The Assessment of the Temporal Evolution of Space Geodetic Terrestrial Reference Frames

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The temporal evolution of the Terrestrial Reference Frames (TRFs) is a certain measure of their stability through time. TRF stability is directly reflected in its velocity field: optimally the magnitude of the velocities becomes as minimum as possible and the distribution of the velocity directions becomes conveniently homogeneous. Each of the space geodetic techniques DORIS, GNSS, SLR and VLBI realizes its own TRF, eventually the techniquewise TRFs form the global TRF (GTRF) as the recent International TRF (ITRF) and the DGFI TRF (DTRF) available to the public. The assessment of the techniquewise TRFs is mainly implemented by comparisons to the GTRF one. The validation relies on the well-known Helmert type transformation which connects the techniquewise frame to the GTRF. It should be noted that none of the space geodetic techniques sense the orientation and its rate respectively, thus there is no way of validating the orientation. So the main characteristic of these assessment techniques is the fact that the TRFs are compared to each other. We shall present a new approach which relies also on the Helmert transformation formulas, but is applied to the full velocity field and, it provides a new conceptual manner for TRF temporal evolution assessment. It allows the simultaneous estimation of all the transformation rates from all points. The new methodology is applied to all the four space geodetic techniquewise TRFs of the GTRFs. The results are discussed indicating some interesting findings about the stability of the techniquewise TRFs and of their parent GTRFs.

IAG (Geodesy)

G01p - G01 Reference Frames

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The MICROSTAR Electrostatic Accelerometer to improve the GRASP Mission

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The Geodetic Reference Antenna in Space (GRASP) is a micro satellite mission concept dedicated to the enhancement of all the space geodetic techniques, and promising revolutionary improvements to the definition of the Terrestrial Reference Frame (TRF). GRASP collocates GPS, SLR, VLBI, and DORIS sensors on a dedicated spacecraft in order to establish precise and stable ties between the key geodetic techniques used to define and disseminate the TRF.

Taking advantage of the new testing possibilities offer by the catapult facility at the ZARM drop tower, ONERA's team can propose an up-dated version of its electrostatic accelerometers developed for the Earth gravity missions CHAMP, GRACE, GOCE and GRACE-FO with a cubic proof-mass. Called MICROSTAR, and slightly miniaturized, it provides the 3 linear accelerations with a resolution better than 10^{-11} $ms^{-2}/Hz^{1/2}$ into a measurement bandwidth between 10^{-3} Hz and 0.1 Hz. In addition, the instrument provides also the 3 angular accelerations about its 3 orthogonal axes with $5x10^{-10}$ $rad.s^{-2}/Hz^{1/2}$ resolution.

The integration of such an ultra sensitive accelerometer at the center of mass of the satellite can provide not only improvement of the Precise Orbit Determination (POD) by accurate measurement of the non-gravitational force acting on the surface of the satellite but provide also the possibility to calibrate with an accuracy better than 100 µm the change in the position of the satellite center of mass as it is performed in the GRACE mission. In the same way, the precise motion of the antennas can be determined, assuming some rigid structure between them and the accelerometer as it is done between the star sensors, the optical cube assembly of satellite laser ranging system and the accelerometer in the GRACE-Follow On mission.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-238

Preliminary Satellite Orbit Determinations Using a New System for Geo-Referencing

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The orbit of an artificial satellite carrying a radio signal transponder is determined using a new geo-referencing system. It utilizes four ground-based reference stations, synchronized in time, installed at well known geodetic coordinates, and a repeater in space. It is based in coded time signal propagation times from one base to the others bounced back by the transponder. The process corrects added up time delays due to signal transit times in the transponder, and for delays due to propagation paths and electronics at distinct ends. We examine the process application for an artificial satellite carrying transponder, the orbit of which we want to determine. The influence of harmonics of high order and degree due to the non-uniform distribution of the Earth's mass are considered in orbit determination. The paper describes aspects of the new geo-referencing system and the dynamic modeling used in the orbit determination system. The specific uncertainties of measurements arising from this system are properly taken into account. A simulation performed with four ground bases located in Brazil and low altitude transponder proved the system concept. Results show that transponder position accuracies of less than 1 meter are attainable using standard good quality synchronized clocks. We extend this simulation to orbit determination of satellites. The major advantages and drawbacks of such system are discussed. Actual tests on orbiting satellites may be accomplished using available transponders in existing satellites, as well as in future cubesat satellites being developed by Brazilian universities.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-239

GEOSAT: Combining VLBI, SLR, GPS, and DORIS at the observation level

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GEOSAT is a multi-technique geodetic software that has been under development for about 30 years [P. H. Andersen, 'Multilevel arc combination with stochastic parameters'. Journal of Geodesy 01/2000; 74(7): 531 - 551]. The last couple of years the development efforts have been headed by a team at the Norwegian Mapping Authority.

The GEOSAT software can be used in the analysis of space geodetic data by combining data from VLBI, SLR, GPS and DORIS at the observation level epoch by epoch. As a result technique dependent systematic errors will be visible as anomalous a posteriori residuals, and can be compensated for by introducing technique dependent empirical models. GEOSAT is based on factorized Kalman filters which allow the estimation of stochastic parameters common for several techniques.

GEOSAT contributed to the IVS solution used in the upcoming ITRF. In addition to VLBI analysis the software can process SLR and GPS data, while DORIS based analysis is under development. Experiments in combining data from different techniques according to the GEOSAT philosophy are currently being done. This presentation will be a description of how GEOSAT combines data from the different techniques, while at the same time reporting the current state of the project and our plans going forward.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-240

Collinearity assessment and estimation of geocentre coordinates from SLR data

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Geocentre motion is induced by mass redistribution occurring in the Earth system. At present, the International Terrestrial Reference Frame (ITRF) origin is defined only by SLR observations to the LAGEOS-1 and 2 satellites. The accuracy and stability of the origin are approximately a factor of two lower for the Z component compared to the equatorial components. Despite their long observational history and high data yields, the low Earth orbit (LEO) geodetic satellites (Starlette, Stella and Ajisai) are ignored mostly due to the more complicated modelling of non-gravitational forces, particularly atmospheric drag, acting on their surfaces. By means of collinearity diagnosis, we assess the current capability of SLR to sense geocentre motion via the network shift approach using real ground networks and LAGEOS-1 and 2 observations. We show that the combined processing of LAGEOS and LEO satellite data reduces the collinearity issues of the Z geocentre coordinate under certain solution parameterisations. The frequent estimation of drag coefficients can, however, severely amplify the collinearity problems for all components. The study will present and compare geocentre motion determined from LAGEOS and LEO's by the network shift approach and by estimation directly within the multi-satellite precise orbit determinations.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-241

A new crustal velocity field of Greece based on seven years (2008-2014) continuously operating GPS station data.

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Greece is characterized by complex and intense geodynamics, because is located between the collision boundaries of two tectonic plates (Africa-Nubia and Eurasia), with major active tectonic features such as the Hellenic Arc, the Anatolian fault in North Aegean Trough and the Kefalonia fault in the Ionian Sea. GPS is a well established tool for geophysical research purposes, because it is able to provide time dense measurements for monitoring displacements of the earth's crust.
The aim of the present study is to create a modern and improved geodetic velocity field for Greece using GPS observations from continuously permanent reference stations. The new set of geodetic velocities is derived from the process of seven years (2008-2014) daily GPS data, using 150 stations distributed in the broader Greek territory and 24 IGS GPS sites. The GAMIT/GLOBK software packages were used to process GPS measurements in ITRF2008 reference frame.
The analysis showed that the northern region in Greece is the most stable and identical to the movement of the Eurasian plate in contrast with the region of the southern part and the Aegean Sea. According to the results, the estimated horizontal geodetic velocities are heterogeneous between northern and southern Greece with significant differences both in magnitude and direction. The derived site values were used for a velocity grid creation in order to predict velocities within the Greek area and to enforce proper realization of GNSS reference systems in Greece.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-242

VLBI technique: Impact of the change of ICRS realizations

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In this work we investigate on the change in the International Celestial Reference System (ICRS) from the first ICRF (International Celestial Reference Frame) second extension ICRF-Ext.2 (ICRF1), to the last ICRF realization (ICRF2) .At this aim we have processed a set of VLBI experiments during 27 years to estimate session-wise station coordinates, their velocities, baseline lengths and Celestial Pole Offsets (CPO) components, using as radio source reference catalog once ICRF1 and once ICRF2.

We have analyzed time series of estimated geodetic parameters and their formal errors, and the time series of the differences of the parameters estimated in the two reference source catalogs. For the analysis of the time series we have used ADEV (Allan Deviation) and its modifications.

Our findings confirm that the switchover from ICRF1 to ICRF2 yields improvements for example in the baseline lengths repeatability and in the scatter of CPO series of about 2 μas. However our results highlight also some discrepancies: the series of station coordinate differences (ICRF1-ICRF2) show significant noise at mm level and the series of baseline length differences has a bias of about 2 mm, then a time variable residual signal is present in the CPO difference time series.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-243

The national reference frame MONREF97 in Mongolia and its development

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As of January 2009 the old Mongolian geodetic datum which is based on Pulkovo 1942 Soviet system (Krassovsky ellipsoid) has been legally (The Degree 25 of the Mongolian Government) replaced by a new national reference frame MONREF97 as local realization of WGS84/ITRF2000 at the epoch of 1997.8 with a reference ellipsoid of GRS80. The old Mongolian geodetic datum had the internal distortions due to accumulation of crustal deformations in North East Asia region and the survey errors which limited by the traditional methods.

The reference frame MONREF97 was defined already in 2000 based on a field campaign carried out in 1997 on passive geodetic points of 2nd and 3rd order of the existing old triangulation network. Meanwhile 27 CORS has been built up and used for geodetic works. Two national field campaigns (2010 and 2014) have been carried out for determination of MONREF97 coordinates on the existing national CORS and for getting information on the consistency and deformations of MONREF97.

Newly adjusted coordinates of MONREF97 stations (35) by field campaigns of 2011/2014 and existing CORS network (11) are presented. We briefly describe the comparison of the combined solutions in different epochs (1997, 2010 and 2014), assess its accuracy and consistency of the terrestrial reference frames.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-244

Effect of combining GNSS and SLR measurements via their space-ties on the definition of the terrestrial reference frame parameters

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The accurate and precise definition of the origin and of the scale of the International Terrestrial Reference Frame (ITRF) is a fundamental requirement for the development of Earth System Sciences. The studies affected by the selected reference frame realization span, in fact, from precise satellite orbit determination to altimeter calibration, satellite antenna offset assessment for Global Navigation Satellite System (GNSS) vehicles and validation of the center of mass corrections for spacecrafts carrying on board retroreflectors for Satellite Laser Ranging (SLR) tracking. As a consequence, all the studies relying on the knowledge of crustal motion severely depend on the availability of an accurate and stable realization of the ITRF physical parameters.

In this work, we present the results of a combination study involving GNSS data and SLR observations to the two LAGEOS and to the GNSS satellites equipped with retroreflector arrays. The last type of measurements is currently not included in the computation of the official ITRF solutions. The assessment of the benefit that they could provide to the definition of the origin and scale of the ITRF is however worth investigating, as such data provide the potential for linking the GNSS and SLR techniques via the so-called space ties, instead of relying on the local ties evaluated with ground measurement campaigns at co-located ITRF sites. In order to ensure the highest possible consistency, the raw data of both techniques are treated with the same analysis Software (Bernese GNSS Software 5.2) following IERS2010 conventions. The combination is carried out at the normal equation level either within the Bernese and the Combination and Analysis of Terrestrial Reference Frames (CATREF) Software.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-245

PPP carrier phase residual stacking for turbulence investigations

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Space-geodetic observations such as Global Navigation Satellite Systems (GNSS) or Very Long Baseline Interferometry (VLBI) are delayed in the neutral atmosphere. In order to improve the quality of these techniques for precise applications like reference frame realisation, we need to get more knowledge about the temporal and spatial refractivity variations in the neutrosphere. In addition to the annually to hourly long periodic variations, which can be considered within the adjustment process, micro-scale meteorological phenomena in the range of minutes to sub-second affect space-geodetic observations as well. Thus induced phase fluctuations of wavefronts passing through the turbulent medium form a significant error source for electromagnetic GNSS and VLBI wave propagation on the one hand side. On the other side they reveal information about the turbulent media through which the signal has travelled and thus can be used to enhance the modelling of neutrospheric refraction.

In order to identify high-frequency atmospheric effects, we analysed 1Hz high-rate GPS observations from the continuous operating GNSS station at the Geodetic Observatory Wettzell and derived post-fit carrier phase residuals for several days with a Kalman-Filter based Precise Point Positioning (PPP) approach. Since undifferenced carrier phase observations contain superposition of several effects, the computed power-law behaviour of the residuals did not follow the theoretically predicted stochastical behaviour for refractivity fluctuations. Hence, first the influence of multipath was identified. A residual stacking was performed, and the reduced residuals were analysed with regard to turbulenct characteristics.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-246

Multi-technique combination of space geodesy observations

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Over the last few years studying combination at the observation level of the different space geodesy techniques yielded that some common parameters can be taken advantage of. Some of these parameters, such as Zenithal Tropospheric Delays, are available on co-location sites, where more than one technique is present.
Local ties are provided for these sites, and act as intra-technique links and allow resulting terrestrial reference frames to be homogeneous, but their use can be problematic. Similar co-locations can be found on multi-technique satellites, where more than one technique receiver is featured, but the challenge of using these space ties relies in the accurate knowledge or estimation of their values.
In this study, results from a multi-technique combination including the Jason-2 satellite and its effect on the GNSS orbit determination are presented, as well as results on station positions' determination. Comparing resulting orbits with official solutions provides an assessment of the effect on the orbit calculation by introducing orbiting stations' observations.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-247

International timescales with optical clocks

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A prerequisite for a redefinition of the SI second based on optical atomic clocks is their integration into the international timescales TAI and UTC. This requires a coordinated programme of clock comparisons to be performed, to validate the uncertainty budgets of the optical clocks, to anchor their frequencies to the present definition of the second, and to establish the leading contenders for a new definition. Such a programme is underway within the EMRP-funded project "International Timescales with Optical Clocks" (ITOC), involving optical clocks in five different laboratories. Several new measurements have already been completed and the current status will be reported at the conference. New methods developed to analyze the self-consistency of the clock comparison data and to derive optimized values for the frequency of each optical clock transition will also be described.

To support this programme, an evaluation is being made of all relativistic effects influencing time and frequency comparisons at the 10^{-18} level of accuracy, including the gravitational redshifts of the clock transition frequencies. Significant progress has been made towards improved determination of the gravity potential at the sites participating in the clock comparisons; gravity surveys have been carried out at all locations and will feed into the computation of a revised European geoid model.

An experiment is also being prepared to demonstrate the impact that optical clocks could have on the field of geodesy. This aims to measure with high temporal resolution the gravity potential difference between two well-defined locations separated by a 90 km baseline and a height difference of 1000 m.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-248

Progress in determining ties between kinematic and dynamic reference frames through differential very long baseline interferometry

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Our goal is to assess the potential of differential-VLBI (D-VLBI, or phase referencing) for the establishment of frame ties for geodesy and astrometry. Determining the frame ties will show the level of consistency among the involved reference frames. We use differential-VLBI measurements to tie the dynamic reference frames of spacecraft and Solar system bodies to the international terrestrial reference frame (ITRF) and the international celestial reference frame (ICRF). Earlier work in this project has focused on, 1, extending the VLBI analysis and scheduling software VieVS to generate delay models for moving targets at finite distances within the Solar system and to simulate VLBI observations of various spacecraft constellations to estimate the potential accuracy in deriving station ITRF parameters, and 2, analyzing in-beam D-VLBI observations of the SELENE Lunar orbiters and scheduling and analyzing VLBI tracking observations of a GLONASS satellite. Our future research will be focused on, 1, scheduling, observing, and analyzing new proof-of-concept D-VLBI experiments to demonstrate and measure our ability to tie dynamic objects to the ICRF and ITRF, 2, collecting and (re-)analyzing D-VLBI observations of deep space probes, including the Chinese Chang'e missions, performed by other groups to enable us to improve the tie between the ICRF and Solar system ephemerides, and 3, to realize ICRF and dynamical system frame ties based on the available D-VLBI observations in collaboration with other members of the 'Space-time reference systems for monitoring global change and for precise navigation in space' Research Unit 1503 of the German Research Foundation.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-249

Contribution of multi-technique combinations at the "observation level" to the realization of EOP and reference frames

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Time series of station positions and Earth orientation parameters are nowadays derived simultaneously and in a consistent way by the different Technique Centers for each specific technique, i.e. VLBI, GPS, SLR and DORIS. These intra-technique solutions are the basis of the realization of the ITRF. An alternative approach is the global combination “at the observation level.” of the different astro-geodetic techniques. Observations are separately processed at the different analysis centres of GRGS (Groupe de Recherches de Géodésie Spatiale) using unique software package GINS. Normal equations which are obtained are then collected and stacked at Paris Observatory.The strength of the method is the use of a set of identical up-to-date models and standards in unique software. In addition the solution is supposed to benefit from the mutual constraints brought by the various techniques. The datum-free normal equation matrices weekly derived from the analyses of the different techniques are stacked to derive weekly solutions of station coordinates, daily Earth Orientation Parameters (EOP) and weekly quasar positions over several years. The purpose of the presentation is to show the strategy that has been applied and the preliminary solution such as EOP, station coordinates and quasars coordinates.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-250

Simulating very long baseline interferometry observations to determine a global terrestrial reference frame for the global geodetic observing system

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A global terrestrial reference frame (TRF) with highest accuracy, consistency and stability is necessary for the correct interpretation of geodetic products associated with the Earth. Typically, space geodetic observations from Doppler Orbitography and Radiopositioning Integrated by Satellite, Global Navigation Satellite System, Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) are combined to determine a TRF. In the framework of the Global Geodetic Observing System (GGOS) the parameters defining a TRF should have an accuracy and stability of 1 mm and 0.1 mm/yr, respectively. This goal has not been met yet. Therefore technique-specific and combination related issues have to be re-investigated.

Simulated observations from all space geodetic techniques along with rigorous combination strategies allow to understand the error sources limiting TRF accuracy. This is due to the fact that contrary to actual observations, the constituents of the simulated ones are completely known since they are artificially generated by a sophisticated software. Within the project GGOS-SIM, the current ground network of VLBI in the time span of 2008-2014 is simulated using the VieVS@GFZ software, applying state of the art models to achieve the highest consistency with the other techniques. We compare the simulated with real observations to ensure reliable solutions.

Further research includes the combination with the other techniques to simulate a global TRF w.r.t. the PLATO Working Group. For this, we initially simulate an SLR TRF as well and then apply different combination strategies. The results are assessed w.r.t. the latest TRFs particularly regarding origin and scale, the strengths of these two techniques.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-251

"The 2014 JPL Realization of the ITRS: JTRF2014"

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A Kalman filter and smoother, KALREF, will be used to determine the JTRF2014, a combined terrestrial reference frame (TRF) obtained by analyzing the input SINEX files submitted by the IDS, IGS, ILRS, and IVS for the computation of ITRF2014. JTRF2014 is determined by combining on a weekly basis time series of station positions and Earth Orientation Parameters (EOPs) along with local ties at co-located sites.

In the JTRF2014 the temporal evolution of the station positions is formulated by accounting for linear and seasonal terms (annual and semi-annual periodic modes). The station position noise processes are characterized by non-zero variances whose values are derived by analyzing station displacements induced by temporal changes of planetary fluid masses (atmosphere, oceans and continental surface water).

The JTRF2014 frame will be delivered as a time series of weekly SINEX files containing the filtered and smoothed station positions and EOPs observed from the early 80s through the end of 2014 and predictions of station positions afterwards. Datum specification (origin, scale and orientation) of the resulting frame will be discussed.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-252

A standard file format for gridded geodetic data

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The use of gridded data in geodetic applications is increasing. For some geodetic datum transformations the Natural Resources Canada NTv2 format is widely used although other national and ad hoc formats are also in use. There is no global standard for these and other geodetic data sets such as geoid grids, position displacement grids and numerous others. Producers often define a proprietary or some other convenient format. The adoption of a standard file format will facilitate the creation and use of gridded data sets. It would relieve grid producers of the necessity for producing file readers and it will assist software developers to incorporate new grids with minimal effort. Users will benefit from quicker access to the data. This paper describes the business case for and technical requirements of an international standard for a geodetic data grid format (GDGF). It outlines a proposal for producing an international standard.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-253

Towards Russian national integrated terrestrial reference frame

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The new reference frame GSK-2011 has been officially introduced in the Russian Federation for geodesy and mapping. This reference frame is physically represented by the Russian state geodetic reference network, which comprises more than 350 000 reference points. Apart from it more than 450 continuously operating reference stations are currently in use in the country. These stations belong to separate networks developed and operated by different organizations. Also the Federal Satellite Differential Network is supposed to be established under the governmental program for development of geodesy and cartography until 2020. These networks should be integrated to be used efficiently. A new structure of the integrated geodetic reference frame and principles of its adjustment are discussed in the paper. The study is funded by the Russian Scientific Fund (project 14-27-00068) and carried out by the Siberian State University of Geosystems and Technology.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-254

Assessment of empirical tropospheric delay model - Global Pressure & Temperature 2 and its implications for atmospheric loading

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Troposphere modeling plays a significant role in radio space geodetic techniques. The slant delay model(VZHD/VMF1), which combines Vienna Zenith Hydrostatic Delay and Vienna Mapping Functions 1, has been regarded as the best tropospheric delay model, where the empirical Global Pressure & Temperature and Global Mapping Functions (GPT/GMF) model is also employed as backup. Recently, GPT/GMF is reported to be superseded by the newly updated combined model GPT2. This paper evaluates the improvements with GPT2 and investigates its implications for atmospheric loading by comparing with GPT/GMF and VZHD/VMF1. Data set of 73 global distributed stations over 6 years were adopted and GAMIT/GLOBK software was utilized. We find that GPT2-derived ZHDs have a better agreement with VZHDs than GPT-derived ZHDs. The differences between GPT2-derived ZHDs and VZHDs show a latitude dependence with a maximum at the poles. Moreover, the station height differences caused by different troposphere models above are in general below 2 mm. Both annual and semi-annual amplitudes of station height time series based on GPT2 have a better agreement with those based on VZHD/VMF1 than those based on GPT/GMF. Additionally, repeatability of station height is utilized for assessing the implications for atmospheric loading due to different troposphere models. The results show that, without applying atmospheric loading corrections, GPT/GMF performs slightly better than GPT2 and much better than VZHD/VMF1. However, with atmospheric loading corrections applied, VZHD/VMF1 has the best performances while GPT/GMF performs the worst. This demonstrates that GPT2, similar to GPT/GMF, is likely to partly compensate for the atmospheric loading signal due to mismodeling of tropospheric delay but to a lesser extent.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-255

Removing discrepancies between local ties and GPS-based coordinates

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Using different GPS observables can result in apparent coordinate changes of GPS reference stations, i.e. offsets in the coordinate series although the GPS antenna remains in the same geometrical place. These variations can be classified as mathematical and physical effects. In addition, local network solutions from L1 observations correspond very well to the coordinate differences from terrestrial geodetic measurements, whereas in global networks the ionosphere-free linear combination with an estimated tropospheric zenith path delay (L3T) has to be used. Based on experiments on short baselines at the Institut für Erdmessung (IfE) a proposal how to deal with these effects in different network scenarios has been developed.
In this paper, the gained insights are transferred to coordinate discrepancies in local ties of global networks, e.g. the EUREF Permanent Network (EPN). Based on the (known) relation between tropospheric delay and height component, this procedure yields improved results for the height component agreeing well with terrestrial local tie measurements. Analyses of EPN twin stations show that the relation between height coordinate and tropospheric delay stays constant over time. The value of this relation is site dependent due to site-specific effects, e.g. signal interruptions at low elevations.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-256

Relativistic effects measured with geodetic VLBI

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The Sun's gravitational field deflects the positions of close objects in accordance with the formulae of general relativity. Geodetic VLBI is capable of measuring the deflection of the light from distant radio sources across the whole sky due to the high-precision estimating of the astrometric positions. We estimated the radio source positions and showed that all reference radio sources display an annual circular motion with the magnitude proportional to their ecliptic latitude. The largest light deflection was observed in 1997 and has a magnitude about 0".3 for radio source 0229+131 elongated from the Sun at 100 arcminutes. We show that post-Newtonian parameter gamma could be effectively estimated from a single, specially organised VLBI session, instead of the traditional analysis of all available VLBI data.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-257

Which Orbit for the GRASP Mission?

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The Geodetic Reference Antenna in Space (GRASP) is a mission specifically designed for an enduring and stable Terrestrial Reference Frame (TRF), needed in accurately measuring and understanding of changes in the sea level, ice sheets and other elements of the dynamic Earth's system. This mission was first proposed in 2011 by JPL in response to the NASA NNH11ZDA012O call for Earth Venture Missions. Recently, considering the recommendation of the Prospective Scientific Seminar, CNES expressed its interest and investigates the possibility to participate in the next new JPL proposal.

To reach the goals for the TRF realization of 1 mm accuracy and 0.1 mm/year stability (GGOS, Meeting the Requirements of a Global Society on a Changing Planet in 2020, Plag and Pearlman, 2009), GRASP will carry very precise sensor systems for all the key geodetic techniques used to define and monitor the TRF (DORIS, GNSS, SLR and VLBI). The orbit of the GRASP mission must also support the achievement of these accuracy and stability objectives. The choice of the orbit implies to fulfill conflicting constraints. Indeed, on one hand, obtaining the best visibility of GRASP from GNSS satellites favors low orbits; on the other hand, having more common visibilities from stations requires high orbits; finally, limiting the total radiation dose can imply low or high orbits.

In this study, we present an original approach for determining optimal GRASP orbit configurations. Our method uses an evolutionary algorithm and an analytical theory of the satellite motion. It permits to search for possible orbits optimizing some specific criteria, such as the visibility of the satellite from ground and space, the total radiation dose received by the spacecraft, etc.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-258

Evolution of DORIS data processing at analyses center GOP

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Geodetic Observatory Pecny (GOP) is officially associated in International DORIS Service since 2008. DORIS data are processed using a modified version of the Bernese GPS Software. Data are analyzed in a stepwise process, based on single-satellite daily solutions and their combination. As a standard output, SINEX files corresponding to weekly multi-satellite solutions are delivered to IDS data centers. In addition, long time series of estimated parameters are analyzed, i.e., station coordinates and transformation parameters, ERP parameters, satellite orbits, troposphere parameters and frequency offset. Initially, the reduced-dynamical orbit modeling was used for GOP DORIS solutions as the only possibility of the Bernese GPS Software. Recently, the dynamical orbit model is applied, including precise modeling of the satellite macro-models and the non-conservative perturbation forces. Paper presents the differences between current processing standards and the solution strategies applied in the past, including the comparison of the solution accuracy. GOP analyses center participated on the DORIS combination created for the ITRF2008 and oncoming ITRF 2013(14). Comparisons of the analysis strategies are interesting also from this point of view.
Following part of the paper belongs to the testing of the chosen applied models and their impact on the DORIS solutions. Gravity field application study is presented, analyzing the improvement of the solution using the time-variable gravity field model instead the static model. Another complex set of the tests focuses on the application of the data corrective model for satellite SPOT-5, developed to compensate the frequency bias originated in South Atlantic magnetic anomaly.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-259

Dependency of geodynamic parameters from GNSS constellation

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Significant differences between daily geocenter coordinate and Earth Rotation Parameter (ERP) time series in GPS-only, GLONASS-only, and combined GPS/GLONASS solutions exist and need to be explained. Meindl et al (2013) explained in particular the geocenter differences to some extent by deficiencies in the empirical solar radiation pressure model. Based on combined solutions Arnold et al (2015) showed that the spurious effects can be substantially mitigated in the ERPs, as well.

From inspecting the a posteriori errors in the Meindl et al (2013) analysis it is clear that GLONASS is much weaker for estimating the mentioned parameters. This may be due to the number of satellites, the number of orbital planes, and/or the inclinations of the orbital planes. In our analysis we focus on the number of orbital planes. This aspect can be studied by splitting up the GPS constellation into two groups of three planes each, where the orbital planes within each group are separated by 120 degrees in the equator.

Three series of solutions may then be generated and analysed: two GPS-based series and a GLONASS-only series, by design based on three orbital planes. In these solution series the Earth rotation parameters, the geocenter parameters and the station coordinates will be analyzed for systematic differences and their spectral behavior will be inspected.

The understanding of the relation between the satellite constellation and the resulting geophysical/geodetic parameters is important, because the systems under development will all consist of only three orbital planes (Galileo and the MEO-constellation of BeiDou). If the number of planes turns out to be a disadvantage with respect to the GPS with its six orbital planes this may impact the method of combining different GNSS.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-260

Impact of non-tidal loading effects on regional GPS solutions

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We examine the impact of non-tidal deformation signals on the results of a regional GPS permanent network. Non-tidal corrections are currently not recommended to include them in routine data processing of space geodetic techniques, however validation of existing models and developing strategies to include them in analysis should be performed.
We homogenously procesed 10 years of GPS data collected at 51 permanent stations evenly distributed in Europe. We carefully chose well behaving GPS stations, with more than 90% of observations during analyzed period and with small number of discontinuities in coordinate time series. Apart from standard solution, we generated solutions with atmospheric loading, non-tidal ocean loading and hydrological loading models taken from services recommended by Global Geophysical Fluid Center. We applied these models at the observation level and a posteriori. We examined the impact of each model separatly and different combinations of them on coordinates, velocities and on transformation parameters between weekly solutions and the long-term solution. We observed reduction in variance of height time series for more than 90% of stations; the average decrease in weighted root mean scatter with respect to the standard solution was 13% when applying all models. We also observed a decrease in scatter of transformation parameters between weekly solutions and the long-term solution; we found that applying hydrological model removed the annual signal from scale variations. We found marginal effect of applying loading models on estimated velocities. Comparison between results when applying models at the observation level and a posteriori will be also presented.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-261

Development of web tools to disseminate space geodesy data-related products

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In order to promote the products of the DORIS system, the French Space Agency CNES has developed and implemented on the web site of the International DORIS Service (IDS) a set of plot tools to interactively build and display time series of site positions, orbit residuals and terrestrial parameters (scale, geocenter). An interactive global map is also available to select sites, and to get access to their information. Besides the products provided by the CNES Orbitography Team and the IDS components, these tools allow comparing time evolutions of coordinates for collocated DORIS and GNSS stations, thanks to the collaboration with the Terrestrial Frame CombinationCenter of the International GNSS Service (IGS). A database was created to improve robustness and efficiency of the tools, with the objective to propose a complete web service to foster data exchange with the other geodetic services of the International Association of Geodesy (IAG).
The possibility to visualize and compare position time series of the four main space geodetic techniques DORIS, GNSS, SLR and VLBI is already under way at the French level. A dedicated version of these web tools has been developed for the French Space Geodesy Research Group (GRGS). It will give access to position time series provided by the GRGS Analysis Centers involved in DORIS, GNSS, SLR and VLBI data processing for the realization of the International Terrestrial Reference Frame.
In this presentation, we will describe the functionalities of these tools, and we will address some aspects of the time series (content, format).

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-262

Error mechanisms in precise GNSS analysis

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GNSS analysis techniques are typically based on minimization of measurement residuals along the lines of sight of all available observations. Global network solutions, such as performed by the International GNSS Service, adjust the station geometry and receiver clocks simultaneously with the satellite orbits and clocks (and further parameters) over a data batch of typically one day or more. Along any line of sight, the sum of projected orbit errors and satellite clock errors is minimized to exactly the same observation residual as the sum of projected station position errors and receiver clock error. However, the explicit separation of satellite clocks from orbit geometry is always less accurate than the explicit separation of receiver clocks from the station geometry, due to the fact that the geometric dilution of precision at the satellite end of the observation is much higher than at the station end. As a result, the absolute accuracy of station coordinates and receiver clocks determined from a global network solution is always superior to the absolute accuracy of orbits and satellite clocks that are computed in the same process. If these orbits and clocks are subsequently used as fixed inputs to a precise point positioning solution for some other receiver, the sums of projected orbit errors and satellite clock errors along the lines of sight can never be minimized to the same low level as in a global solution. This paper briefly revisits the fundamental error mechanisms in GNSS analysis, and illustrates the error mechanism summarized above using precise analysis results from the IGS. It will be shown that GNSS stations coordinates reach the highest possible accuracy if they are all included in a single global network solution.

IAG (Geodesy)

G01p - G01 Reference Frames

G01p-263

The application of A-optimal uniform Tykhonov-Phillips regularization in establishment of global geodetic terrestrial reference frame

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With the development of the space geodesy the modern geodetic reference frames are substantially established by different national and international organizations. The realization and maintaining of the global geodetic terrestrial reference frame (TRF) infrastructure is remaining one of the main tasks of geodesy. In the TRF datum definition and TRF combination with intra-technology und inter-technology we meet not only singular problem (rank deficiency or strict multicollinearity) corresponding to the number of TRF parameters but also near-singular problem (ill-posed problem or weak multicollinearity). For the first case there are several minimum constraint methods developed and successfully applied to overcome the first problem. For the second problem the application of regularization method in the datum definition of TRF has also discussed and analyzed and invested in different TRF analysis Centres, such as one study of loose constraint regularization from DGFI (2003). In this talk the uniform Tykhonov-Phillips regularization (a-weighted S-homBLE) by A-optimal design is introduced and its application to overcome the near-singular problem in TRF datum definition and TRF combination with intra-technology is also proposed. The difference and connection between both regularization approaches are analysed. The TRF combination results with GPS intra-technology input data (SINEX files) derived by these two regularization approaches shows the coordinate differences between these two approaches are in 3cm.

IAG (Geodesy)

G02a - G02 Static Gravity Field Models and Observations

IUGG-1260

Second geodetic boundary-value problem with the geocentric reference ellipsoidal surface as the boundary: A spherical approximation solution

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This presentation deals with the second geodetic boundary-value problem with the geocentric reference ellipsoidal surface as the boundary and the gravity disturbance as the boundary value. First of all the reason why we pose this problem is addressed, and then it is formulated and solved by a spherical approximation. The problem is treated in such a way that (1) it is transformed from real space into Helmert space, and (2) solved in Helmert space and (3) solutions are transformed from Helmert space back to real space. The remove-restore method is also used with a Helmertlized disturbing potential model as a reference field. Finally, results for an experiment with data on an 4°x 6° area are presented.

IAG (Geodesy)

G02a - G02 Static Gravity Field Models and Observations

IUGG-2484

A numerical study of up- and downward continuation effects in the solution of the Geodetic Boundary Value Problem

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According to the theory of Marych-Moritz the solution of the Geodetic Boundary Value Problem (GBVP) is interpreted as analytical downward continuation of the boundary data to an internal sphere, followed by the solution of the corresponding spherical problem for the disturbing potential which finally is upward continued by harmonic continuation to the original boundary surface in the external gravity field. While downward continuation is related to an improperly posed problem, being unstable for a rough field of boundary data, smoothing operations are performed in the subsequent steps. Thus, high-frequency components in the boundary data are amplified in the first step, but damped in the subsequent steps, providing a stable solution of the GBVP on and outside the Earth's surface. This fact has often been shown up in practical solutions of the GBVP.

The paper aims at a numerical evaluation of the solution mechanism within a controlled case study, referring to the fixed GBVP using gravity disturbances as boundary data. For this purpose, the Earth's figure and external gravitational field are represented by an ellipsoid of revolution and a global geopotential model, respectively. Following Heck and Seitz (2003), the complete solution of the GBVP can be decomposed into the solution of a spherical problem plus an "ellipsoidal correction", summarizing the effect of downward continuation of the boundary data to an internal sphere and upward continuation of the respective constituents within the disturbing potential. Based on this decomposition a procedure for the solution of the GBVP is proposed and numerically investigated which avoids the evaluation of unstable operators.

IAG (Geodesy)

G02a - G02 Static Gravity Field Models and Observations

IUGG-3283

Uncorrelated a priori noise in gravity data: A study by Restricted Maximum Likelihood (REML) and cross-validation

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Least Squares Collocation (LSC) of gravity is based on the covariance matrices, which describe the correlation of signal and noise. Spatially uncorrelated noise is quite common in many kinds of geodetic data and therefore is often investigated and modeled. LSC is applied with the a priori noise matrix in order to give optimum prediction in the least-squares sense. The proper a priori noise matrix has a significant influence on the prediction, especially if the data are sparse or the noise is heterogeneous. The heterogeneity of the noise often applies in the data combination. The estimation of reliable a priori noise variance is, however difficult via typical covariance model fitting, especially in the case of its heterogeneity. This work implements restricted maximum likelihood (REML) method and cross-validation for the estimation of different covariance parameters in LSC, however, a special attention is focused on the variance of uncorrelated noise. Different spatial resolutions of the data have been used in the numerical investigations, which provide additional observation, because the spatial resolution of the gravity data determines the range of the interpolated gravity spectrum. The work provides some observations on the relations between the spatial resolution of the data and a priori error. This relation is inspected and compared to the regularization problem that frequently occurs in the data modeling.

IAG (Geodesy)

G02a - G02 Static Gravity Field Models and Observations

IUGG-4852

The upwind scheme of the oblique derivative boundary condition in GBVP

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Our aim is to present upwind scheme for solving oblique derivative boundary-value problem by the finite volume method. The main idea is to understand the oblique derivative boundary condition as a stationary advection equation for the unknown disturbing potential. We combine this approach on the bottom boundary with the finite volume approximation of the Laplace equation outside the Earth. In our approach, the computational domain is a finite space bounded by two spatial boundaries. The bottom boundary represent an approximation of the Earth's surface and an the upper boundary approximation of the chosen satellite orbit.On the upper and side boundaries the Dirichlet boundary conditions are generated from GOCE satellite geopotential model.We present the practical numerical experiments dealing with the global and local gravity field modelling.

IAG (Geodesy)

G02a - G02 Static Gravity Field Models and Observations

IUGG-5236

Elementary potentials and Galerkin's matrix for an ellipsoidal domain in the recovery of the gravity field

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The aim of this paper is to discuss the use of elementary potentials for constructing Galerkin's approximations in solving the linear gravimetric boundary value problem. The approach follows the concept of variational methods and the notion of the weak solution. In the first part a mathematical technique is developed for the solution of Neumann's problem in the exterior of an oblate ellipsoid of revolution. The focus is on Galerkin's matrix and its elements. Ellipsoidal harmonics are applied as a natural tool. The problem, however, is the summation of the series that represent the elements. It is difficult to reduce the number of summation indices since in the ellipsoidal case there is no analogue to the addition theorem known for spherical harmonics. This makes the computation of Galerkin's matrix rather demanding. Therefore, the series representation of the elements is analyzed. Hypergeometric functions and series are used. The elements are split into parts. Some of the series may be summed relatively easily, apart from technical tricks. For the remaining series the summation needs more complex tools. It was converted to elliptic integrals. In the second part the use of successive approximations for the solution of the linear gravimetric boundary value problem is discussed. This particularly concerns the possibility to take effects caused by the obliqueness of the derivative in the boundary condition and the departure of the real boundary from the ellipsoid into account. The discussion is added extensive numerical simulations. The use of the EGM2008 gravity field model and ETOPO or SRTM terrain data in closed loop tests demonstrates the convergence of the process and thus also the applicability of the method.

IAG (Geodesy)

G02a - G02 Static Gravity Field Models and Observations

IUGG-5540

Numerical solution of the geodetic boundary value problem using the finite element method

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Geopotential model of the Earth is usually calculated using the Stokes coefficients. The objective of this work is to design an alternative method of calculating the potential, which is based on the finite element method. For the purpose of numerical solution a computational algorithm was designed and was subsequently implemented in the program in C ++. The success of the proposed method is demonstrated on several test problems, that are discretized using isoparametric finite element with trilinear shape functions. After evaluating the results, the finite element method was found to be a suitable method for solving the geodetic boundary value problem.

IAG (Geodesy)

G02b - G02 Static Gravity Field Models and Observations

IUGG-1074

Gravity anomalies derived from Cryosat-2 and Jason-1 altimetry and ship gravity for the BOHAI and YELLOW sea of CHINA

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We have employed least-squares collocation to derive a gravity field BOHAI and YELLOW sea of CHINA using Cryosat-2 and Jason-1 altimeter data combined with ship gravity. To avoid the crossover adjustment to correct for orbital errors we used mean geoid gradients. which were obtained by averaging gradients over 3 and 275 repeat cycles for Cryosat-2 and Jason-1, respectively. The average standard deviations for the Cryosat-2 and Jason-1 mean gradients are 2.28 and 3.05 microrad respectively. The standard deviations of the ship gravity, which were assigned based on weightings derived from an analysis of crossing differences. range from 2.82 to 12.33 mgal. The necessary covariances for the least-squares collocation computations were derived using the law of covariance propagation. Before merging with the altimeter data, the ship gravity for each leg was adjusted by removing a quadratic polynomial in time in order to match a satellite-only gravity field in a least-squares sense. The rms difference between the satellite-only gravity, derived using least-squares collocation. and the adjusted ship gravity is 6.32 mgal, smaller than the rms difference of 12.33mgal between the satellite-only gravity derived by a Fourier transform method and the adjusted ship gravity. The rms difference between the combined gravity field. derived from both altimetry and ship gravity, and the adjusted ship gravity is 2.42 mgal. suggesting that the former has successfully absorbed the high-frequency component of the gravity signal provided by the latter. The combined gravity field thus features a regionally uniform medium resolution from altimetry and a locally high resolution from ship gravity. The average accuracy estimate given by least-squares collocation for the combined gravity is 4.36 mgal.

IAG (Geodesy)

G02b - G02 Static Gravity Field Models and Observations

IUGG-1111

Impact of coloured noise in satellite altimetry data on a regional quasi geoid using spherical radial base functions

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We study the impact of coloured noise in satellite altimetry data when computing a regional quasi-geoid. The test area comprises the North Sea region including the UK, the Netherlands, Belgium, and parts of Germany, France, Denmark, and Norway. We perform the study in the context of radial base functions using the traditional remove-compute-restore procedure with a recent GRACE/GOCE gravity field model. Apart from satellite altimetry data, we use terrestrial, airborne, and shipboard gravity data. Radar altimeter data are used in the form along-track geoid height differences and corrected for instantaneous dynamic topography with a shallow-water hydrodynamic model. Different quasi-geoids are computed with and without taking coloured noise of radar altimeter geoid height differences into account. We quantify the impact of coloured noise by studying the difference between the two computed quasi-geoids. The computed quasi-geoids are assessed with independent GPS/levelling and shipboard GNSS data. We demonstrate a better fit of the quasi-geoid to the control data if coloured noise is taken into account. Moreover, we show that the impact of incorporating coloured noise may be up to several centimetres. We conclude that the incorporation of coloured noise in satellite altimetry data in the quasi-geoid modelling is necessary to realize a high-accuracy high-resolution quasi-geoid in marine and/or coastal areas, which is nowadays becoming more important for a broad range of applications. For coastal areas, which rely more heavily on radar altimeter data and where dynamic topography has larger gradients with respect to the quasi-geoid, e.g., due to prevailing winds, the impact of a proper handling of coloured noise in these data in the quasi-geoid modelling may even be higher.

IAG (Geodesy)

G02b - G02 Static Gravity Field Models and Observations

IUGG-1227

Accurate Approximation of the Anomalous Vertical Gravity Gradient using point mass method

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Due to the fact that measurement of the vertical gravity gradient is a hard work on the Earth's land surface, the paper tries to develop a new approximation method of the anomalous vertical gravity gradient. In the paper, a theoretical analysis was made on the computation of the vertical gravity gradient firstly, and then two existing methods, the gravity potential model method and the remove-restore method were introduced and discussed, from which the formulae of the anomalous vertical gravity gradient were derived. In order to fully utilize the rich ground gravity observations and terrain data, the paper tries to use the point mass method that is developed from the theory of Bjerhammar boundary value problem to accurately approximate the anomalous vertical gravity gradient, and a layered point mass model for the computation of the anomalous vertical gravity gradient was also constructed. Tests of the three methods were made using some actual measurements of vertical gravity gradient in China, and analyses were also made. Comparisons among the three methods were made and results show that the point mass method and the remove-restore method have advantages respectively. At the end of the paper, some issues on the vertical gravity gradient to be further investigated were proposed.

IAG (Geodesy)

G02b - G02 Static Gravity Field Models and Observations

IUGG-2818

The spherical wavelet analysis of regional gravity field data

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The gravity anomalies derived from Earth's gravitational field models are used to establish local spherical wavelet model in Tibetan Plateau. The Difference of Gaussia (DOG) and Poisson spherical wavelets are compared. The Earth's gravitational field models derived from GRACE, GOCE and EGM2008 and grid of gravity anomalies of WGM2012 are used. The multiscale structures of gravity anomalies are compared and analyzed.

IAG (Geodesy)

G02b - G02 Static Gravity Field Models and Observations

IUGG-3911

Estimation of degree variances for covariance modeling by Monte Carlo simulated annealing

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In physical geodesy covariance models are typically parameterized by degree variances. This modeling originates from a global spherical harmonic representation of the gravity field and from the hypothesis that the field is homogeneous and isotropic. However degree variances are often used also for local covariance modeling. This requires first to compute an empirical covariance function from the gravity data available over the study area and then to estimate a set of degree variances so that the resulting covariance function fits the empirical one. In this paper we propose to perform this estimation step through a stochastic optimization. The objective function does not only consist in the minimization of the residuals between empirical and modeled covariance functions, but includes also some regularization conditions on the unknown degree variances. The optimization is performed by a Markov Chain Monte Carlo method, and in particular by a Gibbs sampler nested into a simulated annealing. The method is tested on simulated data showing its capability of well fitting the empirical covariance function. It is also used to estimate a degree variance model that is simultaneously consistent for empirical covariances of different functionals of the gravity field. Finally, comparisons with other estimation algorithms are performed too.

IAG (Geodesy)

G02b - G02 Static Gravity Field Models and Observations

IUGG-4768

Global static gravity field model obtained from combined processing of the GOCE and terrestrial gravity data using point masses modelling

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We present high-resolution global gravity field modelling based on combined processing of the GOCE measurements and terrestrial gravity data. The method of fundamental solutions (MFS) and singular boundary method (SBM) are used to process heterogeneous input data, namely the second derivatives observed by the GOCE satellite mission and available surface gravity disturbances or altimetry-derived gravity data. Both methods, MFS and SBM, as mesh-free collocation techniques based on point masses modelling, use the fundamental solution of the Laplace equation as their basis functions. Hence, the system matrix depends solely on geometrical configuration, i.e. on 3D positions of the input measurements and source points. At the source points, unknown coefficients need to be evaluated. It requires to isolate singularities of the fundamental solution or its derivatives using appropriate regularization techniques proposed by SBM.

In our experiments almost 13 million of source points are regularly distributed over the Earth's surface with the high-resolution of 0.05 deg (3 arc min). The same number of input data is chosen for processing in our collocation scheme. The radial components T_{zz} from GOCE are filtered using the nonlinear diffusion filtering. Discrete gravimetric measurements are transformed into the surface gravity disturbances. Large-scale parallel computations are performed on the cluster with 1.2 TB of the distributed memory while an iterative elimination of far zones contributions is used to reduce enormous memory requirements. Finally, the obtained global static gravity field model is compared with the SH-based combined geopotential models, e.g. EGM2008 or EIGEN-6C4.

IAG (Geodesy)

G02c - G02 Static Gravity Field Models and Observations

IUGG-0930

Determining astro-geodetic deflections of the vertical using digital zenith camera system

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Astro-geodetic deflections of the vertical are crucial measurements in geoid determination studies and density investigations. Digital Zenith Camera Systems (DZCS) have been developed since the 2000s, which have been equipped with precise electronic tiltmeters, GPS receivers and CCD technology. After the first studies on DZCS in Germany, Switzerland, and Austria, recently some other studies in Poland, Serbia, Latvia, and China are performed, and all of these projects aimed to make improvements in measurement accuracies and system configurations. Design and tests of the DZCS introduced in this study were started in 2012 and developments are still ongoing.

In this study a transportable system is produced by mechanically integrating CCD/Telescope system, electronic tilt sensors and a GPS recievers. Star images that are captured by CCD camera and tilt values of the system are synchronized with GPS time to calculate the latitude and the longitude of the station point. The results of the observations indicate that the accuracy of the system is about ±0.20’’ in latitude and ±0.42’’ in longitude determination. The observation and calculation processes are fully automated.

In this respect, this study introduces the recently developed DZCS in Istanbul, Turkey in order to determine deflections of the vertical. We will also present some details about data acquisition, instrumentation and processing technique that focuses on the observations performed on a specific test site located in Istanbul. The system is also tested on a network of 4 station points and the results were compared with global models. Furthermore in this study the first results of astro-geodetic observations of the test station, and the test network of DZCS in Istanbul will be presented and evaluated.

IAG (Geodesy)

G02c - G02 Static Gravity Field Models and Observations

IUGG-1288

Impact of geological surface density information and seismic 3D density models for high precision regional geoid computation

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High precision regional geoid determination is a challenging task. Besides the quality of the input data, the quality of the density information is essential for a consistent treatment of the gravity field quantities within the remove-compute-restore procedure.

In this investigation a geological based surface density model and a 3D-density model based on seismic data are introduced, replacing the usually used constant standard crustal density within central Europe. In a first step, only the geological surface density information is used for the computation. Afterwards the two models are combined into a new hybrid density model and the geoid is recalculated.

The improvements due to the newly introduced density information can be clearly identified in the different solutions which are based on a Gauss-Markov model with radial basis function parametrization. As final outcomes a new geoid and the xi and eta components of the deflections of the vertical are computed on a regular grid.

The achieved results are primarily validated with independent GPS/Leveling observations. Secondary validation has been carried out through deflections of the vertical, obtained from precise zenith camera and astronomical measurements. Furthermore, differences between the current official Austrian geoid solution based on data from 2008 and the new estimated geoid are shown.

IAG (Geodesy)

G02c - G02 Static Gravity Field Models and Observations

IUGG-1650

Fast computation of general direct gravitation problems

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In this work, we derive a fast algorithm for the computation of the gravitation effects of a general volumic mass distribution. The algorithm consists in first computing a tetrahedral mesh modeling the sources. Then, the gravitation effects, namely the gravity potential and its first and second derivatives, are computed using a quadrature formula when the observation points are far away from the sources, and the Okabe analytical formulae when the observation points are close to the sources.

The novelty of this work consists in the use of a fast algorithm that accelerates the long-range interactions: the Fast Multipole Method (FMM).The algorithmic complexity is reduced from quadratic to linear, with respect to the data (sources and observation points), making available large test cases that are intractable with classical methods. Our implementation makes use of Scalfmm [1], a powerful parallel implementation of the FMM developed by INRIA, and is ready to use of large clusters. The approximations made in this algorithm are controllable.

When the observation points are far enough from the sources, all the interactions can be computed using a one-point quadrature formula, leading to fast execution times. This was applied to the computation of the global topographical effect on gravity at the GOCE satellite altitude. After building -- in linear complexity -- a mesh of the difference between the real Earth and the WGS84 reference ellipsoid composed of 100 million tetrahedrons, any componentof the gravitation effects over 2 million observation points are computed in 6min30s on a 16 processors cluster.

[1] O. Coulaud, B. Bramas, and C. Piacibello.Fast Multipole Method Library for HPC.public.gforge.inria.fr/doc/.Scalfmm, C++http://scalfmm-public.gforge.inria.fr/doc/

IAG (Geodesy)

G02c - G02 Static Gravity Field Models and Observations

IUGG-5085

Least squares downward continuation, fusion and gridding of airborne and terrestrial gravity observations

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Many downward continuation applications use the Poisson integral to express gravity anomalies on a regular grid at the Earth's surface as a function of those on a regular grid at the geoid. This relationship is then inverted to determine gravity anomalies on the geoid.

Alternatively, the Poisson integral may be used to represent gravity values where they are observed—at scattered points, predominantly on or above the topography—as a function of a regular grid of gravity anomalies at the geoid. The resulting system of equations may be solved, if the number of observed anomalies exceeds the number of grid cells on the geoid, in a least-squares sense. This formulation allows use of the many well-understood techniques available for solving least squares problems, including adding constraints, weighting observed values according to their precision, and efficient numerical methods. It also simultaneously grids the anomalies, and combines observations from varied sources according to assigned accuracies. This is especially useful in computations based on airborne gravimetry, where observations at flight height are plentiful, but must be combined with sparse but more accurate terrestrial observations observed on the Earth's surface.

We present results from real and synthetic data sets for a least-squares Poisson downward continuation technique, developed by Fugro Geospatial in collaboration with the University of New Brunswick. Closed-loop testing using EGM2008 indicates that the method has a maximum error of less than 2 mGal, in areas where gravity coverage is sufficiently dense; even if gravity observations are collected at heights over 10 km.

IAG (Geodesy)

G02c - G02 Static Gravity Field Models and Observations

IUGG-5574

Precise geoid models from GOCE, terrain models, and airborne/surface gravimetry – challenges and results

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The challenge of accurate gravity field modelling and geoid determination in large, often mountainous, regions is primarily related to the use of digital terrain models, harmonic downward continuation, and how to combine airborne and in situ data with high resolution global reference models in a consistent way – in practice often implemented with spherical Fourier transformation with modified Stokes function kernels. With the new GOCE R5 models, showing excellent fits to terrestrial and airborne gravity data up to harmonic degrees in the 200-220 range, special challenges are related to the use of terrain reductions, where terrain effects may leak well into the GOCE wavelength bands, and thus provide lack of consistency in the application of remove-restore methods for geoid determinations, a consistency violation which may limit the power of GOCE bias corrections for surface and airborne gravimetry data.

In the presentation we will outline some problems of the RTM method in connection with high-resolution GOCE fields, and indicate solutions to the problems based on geoid comparison in regions with good GPS-levelling control. We will also assess the impact on a number of recent large-scale airborne and surface gravity-based geoid determination projects in the Arctic, Africa and Asia, as well as use available regional airborne data for an independent error assessment of GOCE.

IAG (Geodesy)

G02d - G02 Static Gravity Field Models and Observations

IUGG-0230

Non-linear corrections in orbital perturbation equations for CHAMP-like satellite

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Orbital perturbation equations including non-linear effects are presented for CHAMP-like satellite, and their accuracies are discussed. Using GRACE and GOCE's SST data, non-linear effects are estimated, and the results illustrate that the established orbital perturbation equations can preserve the measurement accuracy of the non-gravitational force in a long time-arc such as at least seven days even if the reference orbit is imitated by the normal gravitational field like EGM08. In addition, solving method for the established orbital perturbation equations is discussed, and observation equations of the spherical harmonic coefficients of Earth gravitational field can be established for CHAMP-like satellite based on the solutions of orbital perturbation equations. Finally, some examples recovering Earth gravitational field from SST data are given, and the results illustrate that the established orbital perturbation equations are more efficient in computation than linearization orbital perturbation equations in recovering Earth gravitational field.

IAG (Geodesy)

G02d - G02 Static Gravity Field Models and Observations

IUGG-1549

Resolvability of gravity field parameters in a repeat orbit – based on global ground track density

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One of the limiting factors in the determination of gravity field parameters is the spatial sampling, namely during phases when the satellite is in a repeat orbit at a low order resonance. This often happens when it is freely passing (drifting) through the atmosphere and encountering various repeat orbits or when it is not drifting but is placed into a preselected repeat orbit to perform specific measurements. This research was triggered in 2004 by the significant but only temporary (2–3 months long) decrease of the accuracy of monthly solutions for the gravity field variations derived from GRACE. The reason for the dip was the 61/4 resonance in the GRACE orbits in autumn 2004. At this resonance, the ground track density decreased and large (mainly longitude) gaps appeared in the data-coverage of the globe. The problem of spatial sampling has been studied repeatedly and simple rules have been derived to limit the maximum order for unconstrained solutions (inversions) for gravity field parameters or their variations. Previous results have been based only on the equatorial track coverage. We extend this insight over all achievable latitudes and investigate the ground track density and maximum distances between subsatellite points at arbitrary latitude (specifically for CHAMP, GRACE, and resonant tuned GOCE). We demonstrate clearly how latitude is important and affects the choice of an order resolution limit. A new order resolution rule is presented, based on the average maximum distance between subsatellite points integrated over achievable latitudes.

IAG (Geodesy)

G02d - G02 Static Gravity Field Models and Observations

IUGG-1880

Mathematical foundations for the next generation of global gravity models from satellite gravity missions of CHAMP/GRACE types

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Satellite gravity missions of CHAMP/GRACE types play a key role in precise recovery of global Earth's gravity models. The standard mathematical foundation to reconstruct any precise global Earth's gravity model from satellite tracking measurements is the numerical integration method, which was first proposed by three authors from Hughes Aircraft Company and Aerospace Corporation, namely, Riley JD, Bennett MM, McCormick E, in: Math Comput (1967). As a basic component of this method, the authors claimed without mathematical proof or physical evidence that the partial derivatives of a satellite orbit w.r.t. the force parameters (unknown harmonic coefficients) can be computed by setting the initial values of partial derivatives to zero. We design simple mathematical examples to show that setting the initial values of partial derivatives to zero is erroneous mathematically. We prove that it is prohibited physically. In other words, setting the initial values of partial derivatives to zero violates the physics of motion of celestial bodies. To conclude, the numerical integration method, as is widely used today by major institutions to produce standard satellite gravity models, is incorrect mathematically. More details can be found in Xu (2009, Sci China D-Earth Sci). Bearing in mind that gravity satellites can be precisely tracked almost continuously by using global navigation satellite systems, we develop a new, measurements-based perturbation method for precise reconstruction of global Earth's gravity model from satellite tracking measurements. Since the new method is uniformly convergent mathematically, it is applicable to orbital arcs of any length and can theoretically be used to recover small gravity forces from long arc measurements with a very high resolution.

IAG (Geodesy)

G02d - G02 Static Gravity Field Models and Observations

IUGG-5602

Parameter estimation in dynamic orbit analysis of GOCE and GRACE satellite gravity missions

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The mathematical model of parameter estimation in the frame of dynamic orbit determination includes numerical integration of the equation of motion and implementation of the explicit form of the variational equations. We focus on Gravity Field and Steady-State Ocean Circulation (GOCE) and Gravity Recovery And Climate Experiment (GRACE) orbit analysis based on real orbital data and a force model that considers both gravitational and non-gravitational effects. The availability of a number of different satellite-only and combined gravity models permits a thorough survey of their role in representing the dynamical contribution of the observed gravity field in the equation of motion. The non-gravitational effects are computed through rigorous data processing of the GRACE on-board accelerometers, while in the case of the GOCE mission we use the common-mode accelerometer data which capture the residuals of the drag-free control system and thus treat the remaining non-gravitational constituents. However, additional empirical parameters are required for the effects of force mismodeling and orbit resonances. We examine the detailed mathematical parameterization of dynamic orbit analysis by implementing numerically an adapted dynamic orbit determination algorithm. Since the primary goal of these satellite missions is the gravity field recovery, we apply empirical orbit modelling that avoids absorbing part of the gravity signal that may be included in the captured orbit residuals.

IAG (Geodesy)

G02e - G02 Static Gravity Field Models and Observations

IUGG-0293

An alternative method for computing vertical and radial gravity gradient using GOCE observations

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An alternative method for computing vertical and radial gravity gradient by using GOCE gradient observations is proposed, since some components of the gradient tensors are more accurate. The formula to compute the radial gravity gradient and the error propagation are firstly discussed; and then the correlation property of the residual gravity gradients during the measurement bandwidth of GOCE is analyzed; finally, the combination factors to compute the vertical and radial gravity gradient are derived by solving a question of conditional extremum, which can improve the accuracy of the radial gravity gradient. The advantage of the combination factor is validated by simulation data. In actual data processing for recovering a gravity field model, the geoid accuracy at degree 250 can be improved by nearly 2 cm with the new method. Since the radial gravity gradient can be not only used in recovering a gravity field model but also kinds of geophysical interpretation, the method would be helpful in the related researches.

IAG (Geodesy)

G02e - G02 Static Gravity Field Models and Observations

IUGG-1370

A cascade filtering method for GOCE satellite gravity gradiometry data processing

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The gravity gradient from GOCE SGG(satellite gravity gradiometry) is a very new type of data, which is expected to increase the quality of gravity field model significantly in the short and medium wavelengths. The measurement bandwidth of SGG is 5-100mHz, it was contaminated by an increased noise at frequencies below 5 mHz. Furthermore, some prominent peaks at the frequencies of 1cpr, 2cpr,…can be observed for all gradient components. So designing a proper filter for SGG data processing is important for GOCE gravity filed recovery. Due to the colored noise and systematic behavior in SGG data, a cascade filter is designed in this work. The cascade filter is a combination of high-pass filter and AR de-correlation filter, the former is designed for processing the systematic noise and the latter is designed for whiting the colored noise. As a test, 71-day of GOCE SGG data is processed using the cascade filtering, and SGG normal equations with 210 degree are established based on space-wise least squares method. Then, SGG normal equations are combined with GOCE SST normal equations that are established using acceleration approach. Finally, a model named WHU_GOCE01S is obtained by solving the SGG and SST combined normal equations with Kaula regularization strategy. And the model is evaluated through comparison with ESA's first released GOCE-only models, and also validated with independent GPS/Leveling data. The results show that our model is better than GOCE time-wise and space-wise models, which demonstrates the effectiveness of the cascade filtering method.

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IAG (Geodesy)

G02e - G02 Static Gravity Field Models and Observations

IUGG-2776

Calibration of GOCE accelerometers and SST gravity model by the combination of GRACE

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Because of the accelerometer configurations of the GOCE (Gravity field and steady-state Ocean Circulation Explorer) gradiometer, the non-conservative force of GOCE is provided by the so-called common mode accelerations. In this presentation, the calibration of the GOCE accelerometers are studied using the real data by processing the high-low satellite-to-satellite tracking data in individual accelerometer mode. To overcome the polar gap problem, or the deterioration on the low order spherical coefficients of the earth gravity model because of the data loss in the Polar Regions, the GRACE (Gravity Recovery and Climate Experiment) data in the same time span was introduced, and a model WHU-GRGO-SST was built complete to degree and order 100 with limited data. The analysis shows that the bias parameters of the GOCE accelerometers are not stable as the GRACE accelerometer bias and there exists drifts. The results also reveal that the combination of the SST data of two satellite gravimetry missions has the superiority for providing a more accurate inversion on the low and medium parts of the earth gravity model.

IAG (Geodesy)

G02e - G02 Static Gravity Field Models and Observations

IUGG-3052

GOCE gradient transformation in the framework of In Orbit Validation

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ESA's GOCE (Gravity field and steady-state Ocean Circulation Explorer) mission was in space from March 2009 to November 2013. During this period approximately 42 months of data had effectively been collected providing the Earth's gravity field in unprecedented accuracy and spatial resolution.

Regular data calibration and validation is carried out to ensure high data quality for further use (e.g. gravity field processing). In the framework of validation of the GOCE gravitational gradients at IfE Hannover, we work on strategies for gradient in orbit comparison. On the one hand, gradients are compared in satellite track cross-overs, on the other hand the collinear track technique is applied. In both applications, we are faced with the challenge of using gradient tensors that are 'measured' in slightly different satellite (i.e. gradiometer) orientation and altitude. Therefore, the transformation of one gravitational gradient tensor is necessary, which requires both a rotation and a translation. Such a transformation is not possible without further data pre-processing due to the gradient tensor properties.

In order to prevent mixing of the tensor elements of different accuracies during tensor rotation, certain parts (e.g. long wavelengths) of the gradient tensor are replaced with synthetic model information (similar to the official gradiometer product TRF, i.e. gradients in the terrestrial reference frame, NorthWestUp). To consider the differences in altitude between two satellite positions that can reach magnitudes of up to 16 km in a cross-over point, upward (or downward) continuation is used to 'introduce' the height-related gradient change.

Here, we focus on the challenges and limitations of tensor transformation and present some selected validation results.

IAG (Geodesy)

G02e - G02 Static Gravity Field Models and Observations

IUGG-4816

Investigations on the Quality of the GOCE Level 1b Gradiometer Data around the Magnetic Poles

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The latest Canadian Geoid Model was developed based on the combination of GOCE, GRACE, terrestrial and altimetry data. It is observed that the GOCE data have improved the Canadian geoid up to a few centimetres in some regions. Our preliminary investigations on the GOCE Level 1b gradiometer data have shown that GOCE data processing methodology still needs improvements. It is found that GOCE gravity gradients along the satellite track are affected by unknown external sources over Northern Canada and Greenland. These effects can disturb the gravity signal up to three times the expected noise level. In this study, we have attempted to understand the reasons behind these disturbances present in the gradients by using external and GOCE-independent space weather datasets. Solar satellites ACE (Advanced Composition Explorer) and WIND derived interplanetary magnetic and electric field data and magnetic activity data observed by the terrestrial CARISMA (Canadian Array for Real-time Investigations of Magnetic Activity) stations are used for this purpose. We found that GOCE was affected by the increasing short-term solar activity and its corresponding effects around the polar cusp regions. We have investigated both, the GOCE and magnetic activity observations in time, spectral and spatial domain and attempted to eliminate these disturbances from GOCE observations. We believe that any improvement on GOCE data processing can help scientists improve the quality of the global and regional geoid models as well as the processing of other missions' datasets.

IAG (Geodesy)

G02f - G02 Static Gravity Field Models and Observations

IUGG-1172

GOCE based gravity field models – Signal characteristics and error assessment

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In October 2013 the GOCE successfully completed its mission and delivered a unique data set of gravitational gradients of the Earth gravity field. During the final mission phase the satellite orbit was lowered in several steps by all together 30 km with respect to the operational orbit. By being closer to the attracting masses the sensitivity of the satellite to the Earth gravity field could be increased significantly. In July 2014 the 5th and ultimate release of the GOCE gravity field models were made available, which are based on the complete mission data set. Based on these GOCE models various combinations with other data sets like GRACE or terrestrial data were performed in order to further enhance their long wavelength quality or their spatial resolution. The paper provides an overview about the characteristics of the GOCE based gravity field models in terms of signals and errors and makes an attempt to derive absolute quality parameters in order to show that the GOCE mission goals have been achieved.

IAG (Geodesy)

G02f - G02 Static Gravity Field Models and Observations

IUGG-1199

Precise and fast computation of gravitational field of celestial body of general shape

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The Newtonian gravitational field of a celestial body of general shapeis a fundamental subject to be investigated both theoretically and practically, especially in geodesy and planetary science. Reviewed aresome recent developments in theircomputation for several types of body: (i) uniform ring and disk likethose of Saturn (Fukushima, 2010a, Celest. Mech. Dyn. Astron., 108, 339),(ii) nearly-spherical bodies covering the Earth, the Moon, majorplanets, and massive satellites (Fukushima, 2012a, J. Geodesy, 86, 271; Fukushima, 2012b, J. Geodesy, 86, 745; Fukushima, 2012c, J. Geodesy, 86, 1019; Fukushima, 2012d, Comp. Geosci., 49, 1; Fukushima, 2014a, Comp. Geosci., 63, 17),(iii) flattened bodies including Ceres and other dwarf planets as well as major asteroids (Fukushima, 2013a, J.Geodesy, 87, 303), and (iv) elongated bodies such as Eros, Itokawa,1999 JU3, and small peculiar-shaped asteroids (Fukushima, 2014b, Astron. J., 147, 152). The main techniques used are (i) the recursive computation of associated Legendre functions of the first and second kinds, and (ii) the precise and fast computation of complete and incomplete elliptic integrals and Jacobian elliptic functions as well as their derivatives and iverses (Fukushima, 2009, Celest. Mech. Dyn. Astron., 105, 245; Fukushima, 2010b, Numer. Math., 116, 687; Fukushima, 2011a, Math. Comp., 80,1725; Fukushima, 2011b, J. Comp. Appl. Math., 235, 4140; Fukushima, 2012e, J. Comp. Appl. Math., 236, 1961; Fukushima, 2012f, Math. Comp., 81, 957; Fukushima, 2013b, Numer. Math., 123, 585; Fukushima, 2013c, J. Comp. Appl. Math., 237, 43; Fukushima, 2013d, J. Comp. Appl. Math., 249, 37; Fukushima, 2013e, J. Comp. Appl. Math., 253, 142; Fukushima, 2013f, Appl. Math. Comp, 221, 21; Fukushima, 2015, J. Comp. Appl. Math., 282, 7).

IAG (Geodesy)

G02f - G02 Static Gravity Field Models and Observations

IUGG-2015

Spherical harmonic analysis of third-order gravitational tensor components and its implications for future gravity-dedicated satellite mission designs

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One of the fundamental physical manifestations of the Earth is the gravitational field. Its global representation in the form of a global gravitational model is usually based on spherical harmonic series of the gravitational potential. From such a model any functional of the gravitational potential may be evaluated. Significant improvements in modelling the global gravitational field have recently been made due to new satellite data provided by the gravity-dedicated satellite missions CHAMP, GRACE and GOCE. New global gravitational models have consequently allowed for many applications in geodesy, geophysics, oceanography, glaciology or climatology. Far reaching applications, progress in technology and the need for better understanding of the Earth system stimulates for proposals of future satellite missions. In this study we assume a third-order gravitational tensor would potentially become observable at satellite altitudes. Such a tensor composed of 10 different components may be divided into vertical-vertical-vertical, vertical-vertical-horizontal, vertical-horizontal-horizontal and horizontal-horizontal-horizontal parts. Firstly, we derived new integral formulas between spherical harmonic coefficients of the gravitational potential and the four parts of the third-order gravitational tensor. Secondly, we studied possible improvements of the gravitational field due to observations of the third-order gravitational tensor in a closed-loop simulation. For simplicity, we assume global grids of the corresponding observables are available on a spherical (mean orbital) surface. Sensitivity of the third-order gravitational tensor for the global gravitational field recovery is tested for various orbital altitudes and different levels of the white observation noise.

IAG (Geodesy)

G02f - G02 Static Gravity Field Models and Observations

IUGG-2176

Gravity gradient grids at GOCE satellite altitude for lithospheric modelling

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We explore how GOCE gravity gradient data can improve modelling of the Earth's lithosphere and thereby contribute to a better understanding of the Earth's dynamic processes. We study the use of gravity gradient grids to provide improved information about the lithosphere and upper mantle in the well-surveyed North-East Atlantic Margin. In particular, we present the computation of gravity gradient grids at GOCE satellite altitude combining GOCE with GRACE gravity information. It is shown that regional solutions based on a tesseroid approach may contain more signal content than global gravity field models do. The patchwork of regional grids is presented as well as the subsequent error reduction through iterative downward and upward continuation using the Poisson integral equation. The promises and pitfalls are discussed of using grids at nominal altitude of 255 km and a lower altitude of 225 km for lithospheric modelling.

IAG (Geodesy)

G02f - G02 Static Gravity Field Models and Observations

IUGG-4326

Space-wise grids of GOCE gravity gradients by processing the full mission dataset

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The space-wise approach has been applied to the processing of the whole dataset acquired by the GOCE mission, from November 2009 to October 2013, corresponding to about one hundred million epochs of data. This period includes both the mission phase at nominal satellite altitude of about 255 km and the orbit lowering phase when the satellite slowly went down to about 224 km passing through intermediate measuring stages. Before the processing, all these data have to be subdivided into subsets between two subsequent in-flight calibrations and outliers have to be detected and possibly repaired. After that, the space-wise approach can be applied to produce global grids of the full gravity gradient tensor at 0.2°x0.2° resolution.

The key idea of this approach is to filter the original data both in the time domain, namely along the orbit, by taking into account the time correlation of the observation noise, and in the space domain by exploiting the spatial correlation of the gravity field. Whereas the latter filtering is more consolidated and it is performed by a local collocation gridding procedure, the former is newer and it requires to couple a Wiener filter with a White filter to better recover the different parts of the harmonic spectrum.

The output grids are delivered together with their associated error standard deviations, which are computed by Monte Carlo simulation. Moreover, from the grids a set of spherical harmonic coefficients is straightforwardly derived by numerical integration and global regularization, again together with the corresponding full error covariance matrix. The information content of the obtained results is assessed by comparing them with other global grids and spherical harmonic models based on the same observation time span.

IAG (Geodesy)

G02g - G02 Static Gravity Field Models and Observations

IUGG-0739

Stabilized static gravity field solution with the normal equation derived by short arc approach from GRACE data

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In the modified short arc approach, all the positions of the twin GRACE satellites, including the boundary positions, are expressed as the kinematic orbits plus their corrections, and the observation equations are linearized with respect to the kinematic orbits. This modified short arc approach was used to derive the Tongji-GRACE01 static gravity field model complete to degree and order 160 from GRACE data spanning from 2003 to 2007, which has been published on the website (http://icgem.gfz-potsdam.de/ICGEM/).The final normal equation for solving Tongji-GRACE01 static model is seriously ill-conditioned, since its condition number is up to $3.0*10^9$. However, the Tongji-GRACE01 static model was computed by least squares adjustment without using any method to stabilize the solution. Thereby, the final normal equation is used in this paper to derive the stabilized static gravity field solution by using the regularized method constraint to Kaula’s rule. The regularized parameter is estimated by minimizing the mean squared error of the geoid height of the gravity field model. The results indicate that our stabilized solution is significantly better than the Tongji-GRACE01 static model. When the EIGEN6C2 model is taken as the reference model, the cumulative geoid errors up to degree and order 160 are about 6.9cm and 14.1cm for our stabilized solution and Tongji-GRACE01 static model, respectively. The degree geoid errors of our stabilized solution are obviously smaller than those of Tongji-GRACE01 static model for the degree over 85, especially over 120.

IAG (Geodesy)

G02g - G02 Static Gravity Field Models and Observations

IUGG-0802

Extension of the SHTOOLS-Software-Package for ultra-high spherical harmonic computations – a step towards potential modelling to degree and order 21,600

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The freely available software package SHTOOLS by Mark Wieczorek provides readily usable functions for spherical harmonic computations and transformations. Among others it provides functions for two spherical harmonic analysis (SHA) and spherical harmonic synthesis (SHS) methods (Driscoll/ Healy (DH), Gauss-Legendre-Quadrature (GLQ)) that are able to calculate the surface spherical harmonic coefficients (SHCs) for a gridded function on the sphere by Fast-Fourier-Transforms. Surface SHCs are essential for the computation of the topographic potential and geopotential. In its current version SHTOOLS (v2.8 / v2.9) proofs to deliver accurate spherical harmonic transforms up to spherical harmonic degree ~2800, corresponding to a spatial resolution better than 4 arc-min.

In this contribution we will show that SHTOOLS can be modified for ultra-high spherical harmonic analysis by implementing the algorithms to compute the Associated Legendre Functions (ALFs) as described by Fukushima (2012a, b). Using a perfectly bandlimited 1 arc-min gravity grid, we achieve a closed loop error < $2.5 * 10^{-6}$ mGal for degree 10800 SHA and SHS. In order to achieve feasible computation times, parts of the code can be parallelised using OpenMP standards. Doing so, non-parallelized computation times can be reduced to $1/5^{th}$ (~1.3h) for GLQ and $1/4^{th}$ (~3.3h) for DH using 8 cores.

IAG (Geodesy)

G02g - G02 Static Gravity Field Models and Observations

IUGG-1149

5'×5' global geoid GG2015 and its evaluation

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We provide an updated 5′×5′ global geoid GG2015, which is determined based on the shallow layer method (Shen 2006). First, we choose an inner surface S below the EGM2008 geoid by 15 m, and the layer bounded by the inner surface S and the Earth's geographical surface E is referred to as the shallow layer. The Earth's geographical surface E is determined by the digital topographic model DTM2006.0 combining with the DNSC2008 mean sea surface. Second, we determine the 3D shallow layer model using the refined 5′×5′ crust density model, CRUST1.0-5min, which is an improved 5′×5′ density model of the CRUST1.0 with taking into account the corrections of the areas covered by ice sheets and the land-ocean crossing regions. Third, based on the shallow layer model and the gravity field EGM2008 that is defined only in the region outside the Earth's geographical surface E, we determine the gravity field EGM2008S defined in the whole region outside the inner surface S, where the gravity field's definition domain is extended from the domain outside E to the domain outside S. Fourth, based on the gravity field EGM2008S and the geodetic equation W(P)=W0 (where W0 is the geopotential constant on the geoid and P is the point on the geoid G), we determine a 5′×5′ global geoid, which is referred to as GG2015. Comparisons show that the GG2015 fits the globally available GPS/leveling points better than the EGM2008 geoid. This study is supported by National 973 Project China (grant Nos. 2013CB733301 and 2013CB733305), NSFC (grant Nos. 41174011, 41210006, 41429401, 41128003, 41021061).

IAG (Geodesy)

G02g - G02 Static Gravity Field Models and Observations

IUGG-1529

An oblate ellipsoidal approach to update geopotential models over the oceans

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As the global high-resolution geopotential models are released usually once per decade (OSU89, EGM96, EGM2008), satellite, airborne and terrestrial techniques provide new data sets every year (e.g., in polar and ocean areas). In this contribution we develop an idea of updating high-degree gravity field models with satellite altimeter data in terms of the geoid, which can be determined from several solutions of MSS (satellite altimetry) and MDT (oceanography). The approach is suitable for end users of altimeter and gravity data (commonly distributed in grids), who can update models such as EGM2008 in a particular area in order to work with latest gravity data. The approach is based on a pure ellipsoidal methodology since the problem has to be solved near a reference ellipsoid. We test this novel methodology and illustrate it numerically step by step.

IAG (Geodesy)

G02g - G02 Static Gravity Field Models and Observations

IUGG-4309

Comparison of computational methods for ultra-high degree spherical harmonic series

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The very last years, spherical harmonic series, used to represent the Earth's gravitational field, are expanded to a very-high degree (~2190). In that range the associated Legendre functions cannot be computed with high precision due to the arithmetic overflow or underflow based on the floating point arithmetic system that is used in modern computer programs. Therefore, new methods, based on extended range arithmetic or even on approximations and computational approaches, have been presented over the last decade, trying to solve the aforementioned problem and compute the associated Legendre functions to ultra-high degree. In the present study we assess all of these methods comparing their precision and their time limitations. Additionally, we thoroughly examine the performance of many recursion formulae for the computation of Legendre functions carefully adopting new schemes in our computations. Finally, we transform the above methods, making them efficient for their inclusion in Spherical Harmonic Synthesis and Analysis programs, while assessing their computational time performance and efficiency.

IAG (Geodesy)

G02h - G02 Static Gravity Field Models and Observations

IUGG-1364

The GGM05 Mean Earth Gravity Models

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More than 11 years of satellite-to-satellite ranging data from the joint US/German GRACE mission, and nearly four years of gravity gradient measurements from the ESA GOCE mission have been assimilated into a mean Earth gravity model. While the data processing is a challenge, the validation of the resulting products is an equally great challenge. This paper reviews the preparation of the GGM05 suite of mean Earth gravity models, and presents insights into their quality at the regional and global scales, with attention to applications on ocean and land.

IAG (Geodesy)

G02h - G02 Static Gravity Field Models and Observations

IUGG-1736

The Earth's gravity field model WHU_IGT_GOCE_01s from the combination of GOCE gravitational gradient tensor invariants and ITG-GRACE2010s

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Compared to the traditional methods which are affected by measuring error of GOCE attitude indicator, the invariants of gravitational gradient tensor are independent from gradiometer reference frame (GRF), and can be used to recover the Earth’s gravity field for avoiding inaccurate transformation matrix effectively. In the study, the invariants of gravitational gradient tensor along the GOCE orbits are employed to recover the Earth’s gravity field by least squares method. For this purpose, the linearization formulae of gravitational gradient tensor invariant and its error estimate formula are derived. The determination of high truncated order/degree gravity field model by least squares method is a time-consuming task, considered the symmetrical feature of normal equation, a supper parallel algorithm combining MPI and OpenMP technology has been developed to effectively reduce the amount of calculation. The spherical cap regularization approach (SCRA) is applied to deal with polar gaps of GOCE GGs, and the forward and backward finite impulse response band-pass filter are used to process color noise of GGs. Considering that the low degree parts of gravity field model cannot be recovered precisely only from GGs of GOCE, we combine the normal equation of ITG-GRACE2010s by the parametric covariance approach (PCA) to improve the Earth’s gravity field. Finally a gravity field model named WHU_IGT_GOCE_01s with complete degree and order 240 is established from the combination of two month GOCE GGs and ITG-GRACE2010s, and validated by GPS/leveling data and other published Earth’s gravity field models.

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IAG (Geodesy)

G02h - G02 Static Gravity Field Models and Observations

IUGG-1919

A global gravity field model up to degree/order 720 combining satellite and terrestrial data

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Global gravity field models are a key instrument for many scientific disciplines dealing with the description of static and dynamic processes on the planet Earth. Geophysicists use gravity field information for constraining density models of the Earth’s interior, oceanographers need a geoid solution as a reference surface. To fulfil the various requirements of all users, gravity models should be of high accuracy and high spatial resolution.

A combined high-resolution global gravity field model up to degree/order 720, including a full variance-covariance matrix, is estimated. Measurements of the gravity field satellite missions GRACE (Gravity Recovery And Climate Experiment) and GOCE (Gravity field and steady-state Ocean Circulation Explorer), which are highly accurate in the low to medium wavelength range (degree/order 240), as well as terrestrial and altimetric gravity anomalies, which are due to their full signal content able to enhance the spectral resolution of the model, serve as data base.

To achieve an optimal result, relative weighting among single data sets and individual observations is applied. The use of individual weights per observation generates strong correlations among all parameters. This is why full normal equations are used. Handling of full normal equations (>2 TByte) with corresponding 520000 unknown parameters requires a large amount of computational resources, which makes the use of supercomputing inevitable.

The quality of the result is analyzed by comparisons with independent gravity field models and GPS-leveling data, orbit validation and in the frame of the computation of a mean dynamic topography. The result shows, that the final model achieves at least the quality level of established high resolution models.

IAG (Geodesy)

G02h - G02 Static Gravity Field Models and Observations

IUGG-2096

EIGEN-6S4: A new satellite-only gravity field model to d/o 300 based on LAGEOS, GRACE and GOCE data

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This presentation deals with the global satellite-only gravity field model EIGEN-6S4 from the cooperation of GFZ Potsdam and GRGS Toulouse. This new model is a time variable version of release 5 of the GOCE gravity field model by means of the direct approach. It was computed including the Satellite Gravity Gradiometer data from the entire GOCE mission. The GOCE gradiometer provided gravity gradients that are measured with a high accuracy only within its measurement bandwidth of ~ 0.005 to 0.1 Hz. Therefore, the gravity gradients must be filtered. Here this has been done using a band pass filter of 8 - 120 sec. That means the GOCE gravity signal is filtered out below degree 50.

The low-to-medium degree spherical harmonic coefficients of EIGEN-6S4 are determined using 10 years of GRACE data as well as 25 years of LAGEOS SLR data from the CNES/GRGS release 3 processing.

All data are combined at normal equation level and solved using Cholesky decomposition. We apply the spherical cap regularization to stabilize the low-order spherical harmonic coefficients for the GOCE polar gaps and used Kaula regularization at the high degrees.

EIGEN-6S4 contains time variable components for all spherical harmonic coefficients up to degree/order 80. This comprises annual and semi-annual oscillations as well as yearly trends. These time variable components were adjusted from GRGS’ release 03 monthly gravity fields.

Our evaluations of EIGEN-6S4 show the improved performance of this model w.r.t. previous time variable as well as static global gravity field models like EIGEN-6S2, GOCO03S, DGM-1S and others. We present orbit adjustment fits for various satellites, GPS-leveling comparisons and independent oceanographic evaluations.

EIGEN-6S4 is available for download at icgem.gfz-potsdam.de.

IAG (Geodesy)

G02h - G02 Static Gravity Field Models and Observations

IUGG-3647

An improved version of the GOCE-only model EGM_TIM_RL05

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In August 2014 the fifth releases of the official global GOCE models were made available. These models were already based on the entire mission data set, i.e. the data collected between November 2009 and October 2013. One of the official Earth's gravity field model series are the models computed with the so called time-wise approach. One special property of the model series is that it is based on GOCE observations only. Since the fifth release was presented, effort was spent into detailed studies on remaining potential in the GOCE data, which can be exploited to further improve the quality of the time-wise models. Two major points in the overall processing were identified, which allow for improvements in the final solution. Firstly, the processing of the GPS observations used for high-low satellite-to-satellite tracking was adopted. A systematic error which occurred around the magnetic equator was significantly reduced. Secondly, the estimation of decorrelation filters for the observed gravity gradients was robustified. As a consequence, the accuracy estimates for sub-solutions and for individual components are even more realistic, which improves the relative weighting in the final combination of normal equations (of the different gradient components and of different parts of the measurement time series). Both updates applied yield an improved gravity field model. Within this contribution, an updated gravity field model of the fifth release of the time-wise method (EGM_TIM_RL05) is presented. The entire mission data set is reprocessed and a new gravity field model in terms of a spherical harmonic series is derived. Details on the improved processing are shown, the consequences of the updates are highlighted and the improved solution is presented.

IAG (Geodesy)

G02h - G02 Static Gravity Field Models and Observations

IUGG-3812

Synthesis report on assessments of GOCE global geopotential models

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The Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite by European Space Agency (ESA) was launched on March 17th, 2009, and re-entered the Earth's atmosphere falling into the ocean on November 11th, 2013. Its objectives were to measure the Earth's gravity field with an accuracy of 1 mGal (one millionth of the Earth's gravity) and geoid with an accuracy of 1-2 cm at the spatial resolution of 100 km. Five generations of GOCE-only and GRACE and GOCE-combined models have been released by a number of development teams since 2010. In order to achieve a complete, inclusive and realistic assessment of the GOCE models, the Joint Working Group (JWG 2.3) between the International Gravity Field Service and the IAG Commission 2 was established in 2011. Key questions for the assessment to answer are what new and improved gravity information GOCE has brought in, how accurate GOCE satellite-only models are in terms of both commission and omission errors, and how the combined models with other satellite and terrestrial data have improved our overall knowledge on the Earth's gravity field. This report synthesizes assessments that were published in the past four years and highlights GOCE contributions to the determination of the Earth's gravity field.

IAG (Geodesy)

G02i - G02 Static Gravity Field Models and Observations

IUGG-0559

African Geoid Model AFRgeo2015

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The paper presents an attempt to compute a geoid model for Africa in the framework of the IAG African Geoid Project. The available gravity data set consists of land point gravity data as well as shipborne and altimetry derived gravity anomaly data. The available gravity data set has a lot of significant gaps allover the continent. The reduced gravity anomalies are gridded on a 5' × 5' grid using an iterative process employing a tailored reference model, to fill in the data gaps, and weighted least-squares prediction technique. The tailored reference model, up to degree and order 2160, has been used to compute a geoid model for Africa within the window remove-restore technique (Abd-Elmotaal and Kühtreiber, 2003) employing Stokes' integral in frequency domain by the 1-D FFT technique. For the sake of comparison, another geoid model for Africa has been computed using a different approach. This approach renounces the use of the topographic-isostatic reduction and uses the most recent global combined geopotential model EIGEN-6C4, complete to degree and order 2190, serving as the reference model. The computed geoids are scaled using the GO_CONS_GCF_2_DIR_R5 GOCE satellite-only model, which represents the best available global geopotential model approximating the African gravity field. An extensive comparison between the geoids computed within the current investigation has been carried out.

IAG (Geodesy)

G02i - G02 Static Gravity Field Models and Observations

IUGG-2788

Towards a continent-wide gravity anomaly grid in Antarctica to support global and regional gravity field modelling

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The IAG Subcommission 2.4f "Gravity and Geoid in Antarctica" has been established to foster gravity measurements in Antarctica and to work towards the objective of a continent-wide regional geoid solution. A variety of ground-based and especially airborne gravimetry surveys have been accomplished in recent years. Especially aerogravimetry proved to be a powerful technique to survey vast areas and to reliably operate in that hostile environment. Those recent surveys will be discussed with respect to resolution, accuracy, systematic effects, and reference issues. An updated map will be presented showing a gridded gravity anomaly data set in Antarctica. The method to infer this grid will be discussed in detail, mainly based on a remove-compute-restore technique. Finally, this Antarctic gravity anomaly data grid shall be published and, thus, be made available to the scientific community. Eventually, these data are indispensable to infer global, high-resolution combined geopotential models. In Antarctica, the currently processed gravity data grid will help to close the polar data gap. This is especially crucial, since the GOCE mission (2009 – 2013) delivered high-quality data but left – due to the orbit inclination of 96.5 degree – a data gap with a diameter of about 1,400 km. Also, it should be discussed how the ground-based gravity data help to improve regional geoid solutions in Antarctica. Finally, an outlook will be given how to infer further functionals (like Bouguer anomaly) as well as what future plans exist to proceed towards the above mentioned goal.

IAG (Geodesy)

G02i - G02 Static Gravity Field Models and Observations

IUGG-3355

Results of analysis of the geoid slope Validation Survey 2014 in Iowa

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After the successful completion of the Geoid Slope Validation Survey of 2011 (GSVS11) in Texas, the National Geodetic Survey (NGS) conducted the second GSVS in 2014 (GSVS14) along a 325 km line crossing the Midcontinent Rift in Iowa. The following data were collected on passive control marks along the line at a 1 mile (1.6km) sample spacing: leveled height, GPS coordinates, astrogeodetic deflections of the vertical, and terrestrial gravity. Airborne gravity was also collected over the entire survey. The goal of the survey was to quantify differential geoid accuracy over various distances, both with and without the use of GRAV-D airborne gravity. This was possible because geoid slopes were determinable independently through terrestrial surveying techniques with well-defined error budgets. The location for GSVS14 was chosen for its combination of medium-high elevation (average 350 meters), generally flat terrain, but complicated geophysical structure (the Midconenent Rift). This paper presents the analysis of the GSVS14 data sets and its accuracy estimation. At the end, gravimetric geoid models with/without the airborne gravity will be compared and the results will be shown.

IAG (Geodesy)

G02i - G02 Static Gravity Field Models and Observations

IUGG-3922

IAG sub-commission 2.4c report: Gravity field and geoid for north and central America

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The practical unification of the vertical datums in North and Central America is progressing well. Over the last year, Mexico held a workshop that brought together participants from countries in Central America, the Caribbean and USA. Furthermore, Canada had the opportunity to meet with Mexico and USA during conferences. These meetings brought open collaboration among the governmental agencies and research centers with the commitment to determine regional standards. One key standard recently agreed on by Mexico, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, Panama and Dominicana is make use of the same geopotential value (Wo = 62636856.0 m2/s2) as agreed between Canada and USA back in April 2012 for the realization of geoid models.

In terms of recent activities, Canada adopted formally a geoid-based vertical datum in November 2013 based on the agreed geopotential value while Denmark produced a new geoid model for Greenland. The main effort in the USA, Mexico, El Salvador and Panama is presently the collection of gravity data for improvement of geoid models. The USA is principally collecting gravity by airborne technique (see GRAV-D project and the beta-version geoid model xGEOID14B) while the other regions are collecting data at ground level. Furthermore, the new geopotential models derived from the satellite missions GRACE and GOCE have been tested through several studies across North And Central America and the analysis demonstrated the usefulness of these missions for the improvement of the long and middle wavelength components of the geoid models.

For the years to come, it is expected that these initial progress will bring together

nearly 30 national agencies for the realization and adoption of a common vertical reference system.

IAG (Geodesy)

G02i - G02 Static Gravity Field Models and Observations

IUGG-3962

The GEOMED 2 project: A high resolution geoid of the Mediterranean Sea

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The Mediterranean Sea has always been of economic and ecological importance to its surrounding countries. A better understanding of its currents is necessary for the management of fishery resources, potential pollution, and maritime security. Currents can be derived from the Mean Dynamic sea surface Topography (MDT), which can be estimated by subtracting the geoid from the Mean Sea Surface obtained by radar altimetry. The main scope of the GEOMED 2 project is the determination of a high-accuracy and high-resolution geoid model for the Mediterranean Sea employing land and marine gravity data, GOCE/GRACE based Global Geopotential Models and SRTM/bathymetry terrain models. The processing methodology will be based on the well-known remove-compute-restore method following both stochastic and spectral methods for the determination of the geoid. The estimated geoid model will form the basis for height-system unification and MDT determination for the estimation of the circulation in the Mediterranean Sea. In this work, the pre-processing steps consisting in merging and validating all the available gravity observations for the wider Mediterranean are presented and discussed. Furthermore, in selected test areas, geoid undulations are estimated from the validated gravity data by using different methods such as collocation and Stokes formula. These preliminary computations will serve as a basis for assessing and refining the methodology to be applied in the final geoid computation over the entire Mediterranean basin.

IAG (Geodesy)

G02i - G02 Static Gravity Field Models and Observations

IUGG-5273

Regional gravity field from GOCE and new airborne data. Cases from the SE-Asian region and the effect on the geoid

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The new GOCE R5 model provides an excellent backbone for the development of local/regional high resolution gravity field models for various applications. The unbiased behavior from the lowest harmonics and up to degree 200 or more facilitates the combination of heterogeneous data sets.

This paper describes the development of regional gravity field models for geoid modeling over major parts of the Eastern Indonesian Archipelago and over Philippines. The effort included the measurement of more than 150,000 line kilometers of airborne gravity data. The region is characterized by very strong variations in the gravity field stemming from mountain ranges, volcanos and subduction zones (The Ring of Fire) and rather large differences between GOCE and airborne data are observed, in some places up to 200 mGal. The accuracy of the new airborne data is accessed by comparison to existing terrestrial data.

It is also an area with a very active atmosphere (humid and hot) so it can be a challenge to collect airborne gravity data of a good quality. Methods to secure the quality of the data from the airborne measurements are described.

Comparisons of the resulting geoid models to new GPS/leveling control points show that five to ten centimeter geoid accuracy can be achieved even in a region with very strong lateral variations in the gravity field.

IAG (Geodesy)

G02j - G02 Static Gravity Field Models and Observations

IUGG-3291

Effect of lakes og glaciers on the gravity field and geoid

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Mapping the gravity field across Norway, with it's deep fjords and high mountains, is not an easy task. The fjords, seen as long scars through the mountainous western part of Norway, is as deep as 1300 m, and together with mountains as high as 2500 m makes it difficult to achieve a good map of the gravity field. In addition, more than 450 000 fresh water lakes and 1 600 glaciers add challenges to the scene. The glaciers covers a total area of 2 595 square km (Norway covers 385 178 square km), a volume of 164 qubic km, and the thickest glacier, Jostedalbreen, is more than 600 m thick.
Just a small part of all the glaciers and lakes have their thickness and depth measured, respectively. At two of the lakes, with depth data, we have measured the gravity signal using a marine gravimeter.
Adding the gravity information obtained from depth information of the lakes give similar results as information obtained from the marine gravimeter. For the lake Mjøsa a geoid change of 2 cm is observed.
The estimated changes in the gravit fieldy and, subsequently, geoid, due to lakes and glaciers, is compared to GPS/leveling points. However, in comparison to GPS/leveling points changes may be hard to detect even with 2000 points available. It is crucial that the points are located close to lakes and glaciers to see the changes.

IAG (Geodesy)

G02j - G02 Static Gravity Field Models and Observations

IUGG-3602

On the development of the new Nordic gravimetric geoid model NKG2015

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A previous Nordic Geodetic Commission (NKG) geoid model was computed in 2004. Since then, the amount of gravity and other relevant data within the Nordic-Baltic region has increased considerably, high quality satellite-only Global Geopotential Models have become available and there have been methodological developments in the geoid modelling process. Also, the Nordic and Baltic countries have new national height systems, which are realisations of EVRS.

In order to take advantage of the above mentioned possibilities for further geoid modelling improvements, the NKG Working Group of Geoid and Height Systems started a project to compute a new NKG geoid model in 2010, involving all the Nordic and Baltic countries. Since then, the NKG gravity database has been modernized, quality of existing data checked and updated with new gravity data, from all the 7 participating countries. A new regional Digital Elevation Model (DEM) has been compiled and an ice thickness model derived for the Norwegian glaciers. A new GNSS/levelling database has also been created. Much effort has been spent on transforming the different data sets to common reference systems/frames, as well as to the common postglacial land uplift epoch 2000.0 and

the zero permanent tide system. The GNSS-derived ellipsoidal heights have also been transformed from the national ETRS 89 realisations to the ETRF2000 frame, using the transformations from the common NKG2008 GNSS campaign. Gravimetric models have then been computed by several computation centers, using different regional geoid modelling methodologies and strategies.

It is the purpose of this presentation to describe the different components of the NKG2015 geoid model project and to analyse the computations leading to the final NKG2015 gravimetric geoid model.

IAG (Geodesy)

G02j - G02 Static Gravity Field Models and Observations

IUGG-4608

Geoid Determination in Turkey after GOCE

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GOCE mission led to a crucial improvement on middle-to-long wavelength part of the gravity field of the Earth. A new gravimetric geoid model for Turkey is determined using the latest combined global gravity field model, EIGEN-6C4, including complete satellite gravity gradiometry data of the GOCE mission, terrestrial gravity measurements and an altimetry-derived marine gravity model, DTU10. We used the Least Squares Modification of Stokes' Formula technique for the gravimetric geoid determination and 3590 GNSS/levelling geoid heights for the assessment. GRACE and GOCE based model EIGEN-6C4 is also used to estimate and remove the middle-to-long wavelength errors in the GNSS/levelling geoid undulations. The results show that using available data sets in Turkey, a gravimetric geoid can not be determined and assessed below the accuracy of 8-9 cm. New terrestrial absolute and relative gravity measurements will be carried out through the “Improving the Turkish gravity infrastructure and Height System Modernization Project” funded by Turkish Ministry of Development for the period 2015-2020 by collaboration of five Turkish institutions (General Command of Mapping, Mineral Research & Exploration General Directorate, Turkish Petroleum Corporation, TÜBITAK Marmara Research Center, TÜBITAK National Metrology Institute). The current status of this project aiming to determine a 2-3 cm accurate gravimetric geoid model in Turkey will also be described.

IAG (Geodesy)

G02j - G02 Static Gravity Field Models and Observations

IUGG-5583

Geoid modelling in Turkey using remove-compute-restore and least squares modification of Stokes method

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With the contribution of dedicated gravity field satellite missions and improved methodologies, one centimeter accuracy geoid modelling is possible today. Some countries adopted geoid-based vertical datum which facilitates the use of GNSS technologies to derive orthometric heights from ellipsoidal heights precisely. In fact, it is quite convenient to use a vertical datum that is compatible with the GNSS/Levelling and is less dependent on geodynamic activities. Currently, there are ongoing height modernization efforts to re-define the vertical datum in Turkey. Through this modernization, methodological developments and new approaches are needed to be investigated as well as acquiring the optimum dataset to determine a centimeter accuracy geoid model. In this study, it is aimed to obtain precise geoid model in Turkey using the classical Remove-Compute-Restore (RCR) and KTH approach, also known as the Least Squares Modification of Stokes' formula (LSMS). The theoretical differences of the two geoid modelling methods are provided with their performance comparisons based on numerical results. Hence the advantages and drawbacks of both techniques are clarified from an extended perspective. The geoid models are tested using homogeneously distributed thirty GNSS/Levelling data in Turkey, beside their local validations using denser control data in region. In conclusions, the results are compared with the recent official release of regional Turkey geoid model, TG03.

IAG (Geodesy)

G02j - G02 Static Gravity Field Models and Observations

IUGG-5584

Local geoid modeling using various interpolation approaches for vertical control with GNSS

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The Global Navigation Satellite System (GNSS) based positioning techniques provide three-dimensional coordinates in all conditions and economically. However the heights, obtained through GNSS observations are typically defined according to a reference ellipsoid and they typically lack of reflecting Earth gravity field reality. In order to overcome this drawback of GNSS positioning in many geodetic and surveying applications, the conversion of heights from ellipsoidal system into regional vertical datum using transformation surface models, so called local geoid models, is applied. The accuracy of the surface model depends on the modelling method as well as the density and distribution of the data points. The concentration of this study is on the performance validation of Akima's Bivariate (BIVAR) interpolation algorithm, based on Finite Elements principles, in fitting a height transformation surface based on irregularly distributed geoid data. Hence clarifying the appropriateness of BIVAR algorithm in spatial discrete data modeling with comparison of the numerical results, which are obtain through applying Least Squares Collocation and Wavelet based methods in terms of prediction accuracies in the same validation area.

IAG (Geodesy)

G02j - G02 Static Gravity Field Models and Observations

IUGG-5606

Recent results of gravimetric quasi-geoid in China

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Based on the Helmert's second condensation method, the direct effects of terrain attraction and the indirect effects of topographic potential on the gravimetric geoid determination are investigated. For precise calculation of various terrain/topographic effects, a series of rigorous spherical integral formulae is derived in which the curvature of the Earth is taken into account. For effective avoiding the leakage of high-frequency terrain signals, a method for recovering the high-frequency components of the geoid is presented by use of high-resolution terrestrial elevation data. Considering high-frequency terrain effects, SRTM digital terrain model data is reprocessed to increase its resolution. Using topography data with superhigh resolution and combining the terrestrial gravity data with the marine gravity anomalies inversed from satellite altimeric data, a recent results of 2'×2' China mainland-sea unified quasi-geoid are achieved. The accuracy of the results is of ±0.11m estimated from an independent comparisons with the national-wide 649 GPS/leveling points which are distributed over China continent. The accuracy of the new geoid is significantly improved because of the collection of the terrestrial gravity data from Tibet area, consequently, the original accuracy of ±0.22m is increased to ±0.15m, and the accuracy of the geoid over the China East Sea area is better than ±0.05m.

IAG (Geodesy)

G02k - G02 Static Gravity Field Models and Observations

IUGG-2165

Gravity surveys and quasi-geoid model in South America - extra efforts

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In the last 20 years a constant effort has been undertaken in the establishment of fundamental gravity networks (FGN), terrestrial and airborne gravimetric surveys, absolute gravity measurements and the calculation of the geoid (quasi-geoid) model for South America. The old FGN is being substituted by new absolute measurements in different countries. Recent efforts of gravity surveying involved Argentina, Bolívia, Brazil, Chile, Ecuador, Paraguay, and Venezuela. Airborne gravity are available in Brazil and in Chile. Taking advantage of as much data as possible the South America geoid model (GEOID2015) was computed. It was based on EIGEN-6C4 up to degree and order 200 as a reference field. The oceanic area was completed with the mean free-air gravity anomalies derived from a DTU10 satellite altimetry model. The short wavelength component was estimated via FFT. The GGMs EIGEN-6C4, DIR_R4, TIM_R4 out of the new geoid model

have been evaluated against 1,861 GPS observations on Bench Marks (GPS/BM), where 1113 located in Brazil and the remaining points in other countries. Preliminary RMS difference between GPS/BM and GEOID2015, in the whole South America and just in Brazil, are 55 cm and 44 cm, respectively, the mean values are 17 cm and 2 cm. New activities are starting with the support of Instituto Geográfico e Cartográfico (IGC) under the coordination of EPUSP/LTG and Center for Geodetic Studies (CENEGEO). The new project aims to establish fundamental gravity points with A-10 absolute gravitymeter in South America. It has been working already around São Paulo State and Argentina. In the future, the absolute surveys will be undertaken along Brazil, Peru, Venezuela and Ecuador. On the other hand, BGI/IRD carried out several measurements in Chile and Argentina.

IAG (Geodesy)

G02k - G02 Static Gravity Field Models and Observations

IUGG-2324

Gravity anomalies and ice mass movements around the Japanese Antarctic stations in East Antarctica

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The region from Dronning Maud Land to Enderby Land in East Antarctica, where a Japanese Antarctic station Syowa is located, is a key area for investigating the formation of Gondwana, because reconstruction models suggest a junction of the continents locates in the area. There is Shrase Glacier, one of the major glaciers in Antarctica, which controls the ice sheet floor of the area. Moreover, recent investigations using GRACE, IceSat/Envisat, and other geodetic and/or glociological measurements show the mass increase in the area. Therefore the area is also important for glaciological and GIA studies.

To contribute to these investigations as well as enhancing gravimetric networks, the Japanese Antarctic Research Expedition (JARE) has been conducting gravity measurements in the area for a long time. Combining these in-situ gravity data and GOCE EGMs recently released, gravity fields in the area have been newly determined by means of Least Squares Collocation. In addition, JARE has been conducting absolute gravity measurements for provideing acculate gravity values at the gravity base stations and detecting the temporal gravity changes. In particular, the 55th JARE conducted the absolute gravity measurements at Princess Elisabeth Station (PES) near the Sor-Rondane Mountains and on the Seal rock near the Asuka station, where a gravity base point is located. These absolute gravity values are employed to reevaluate the gravity anomalies in the area.

In this paper, we report the results of these studies. In addition, because the surface and basement topography of the ice sheet should play an important role to control the ice sheet flows and the consequent mass movements, we discuss the relation between the gravity anomalies and the mass changes in the area.

IAG (Geodesy)

G02k - G02 Static Gravity Field Models and Observations

IUGG-3315

The benefit of quantum gravimetry and relativistic geodesy with clocks for geodetic applications

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Novel developments in physics can excellently be used for geodetic applications, where new technology and concepts may lead to enhanced capabilities for terrestrial gravimetry. Here, we will present new sensor measurement concepts that apply atomic interferometry for gravimetry and relativity for observing potential values. On one hand, gravity anomalies can be determined by observing free-falling atoms (quantum gravimetry). On the other hand, highly precise optical clocks can be used to measure differences of the gravity potential over long distances (relativistic geodesy). Principally, also inter-satellite ranging between test masses in space with nanometer accuracy belongs to these novel developments.
We will show how the new concepts are connected to classical geodetic concepts, e.g. geopotential numbers and clock readings. We will illustrate the application of these new methods for geodesy, where local and global mass variations can be observed with unforeseen accuracy and resolution, mass variations that reflect changes in the Earth system.

We will present a few examples where geodesy will potentially benefit from these developments. The novel technologies might be applied for defining and realizing height systems in a new way, but also for fast local gravimetric surveys and exploration.

IAG (Geodesy)

G02k - G02 Static Gravity Field Models and Observations

IUGG-4491

Absolute gravity datum: Should it be "modernized"?

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The international gravity datum is defined today by the International Gravity Standardization Net of 1971 (IGSN-71). The data supporting this network was measured in the 1950s and 1960s using pendulum and spring-based gravimeter ties (plus some new ballistic absolute meters) to replace the prior protocol of referencing all gravity values to the earlier Potsdam value.

Since this time, gravimeter technology has advanced significantly with the development and refinement of the FG5 absolute gravimeters (the current standard of the industry) and will again with the starting-to-be-available cold atom interferometric absolute gravimeters. This latest development is anticipated to provide improvement in the range of two orders of magnitude as compared to the measurement accuracy of technology utilized to develop IGSN-71. In this presentation, we will explore how gravity datums might best be “modernized” given today’s requirements and available instruments and resources, within the United States. NOAA’s National Geodetic Survey (NGS), along with other relevant US Government agencies, is concerned about establishing gravity control to establish and maintain high order geodetic networks as part of the nation’s essential infrastructure. The need to modernize the nation’s geodetic infrastructure was highlighted in “Precise Geodetic Infrastructure, National Requirements for a Shared Resource” National Academy of Science, 2010. The NGS mission, as dictated by the US Congress, is to establish and maintain the National Spatial Reference System, which includes gravity networks. If undertaken, NGS would want to coordinate this effort with other nations.

IAG (Geodesy)

G02k - G02 Static Gravity Field Models and Observations

IUGG-4714

Strategy for definition and realization of a global absolute gravity reference system

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In recent years, it has become increasingly evident that it is necessary to resolve discrepancies between accuracies in modern absolute gravity determination and the valid gravity reference system of the IAG (IGSN71).

Scientists from metrology and geosciences agreed on a proposal to base the absolute gravity reference upon repeated instrument comparisons following metrological rules for traceability to SI quantities. A strategy paper proposes continuation of the comparisons as suggested by the International Committee for Weights and Measures (CIPM) in four-yearly intervals at alternating locations followed by distribution of the results to a global network of gravity reference and comparison sites. Their gravity variations are recorded by a combination of repeated absolute gravity measurements and continuously operating superconducting gravimeters. The results of comparisons and gravity variations at the reference stations will be documented in a registry of the “AGrav” database, maintained jointly by the International Gravity Bureau (BGI) and the Federal Agency for Cartography and Geodesy (BKG).

A network of comparison and gravity reference stations would make it possible to establish a global gravity reference system covering the needs of geodetic and metrological communities, capable of integrating observations of the new cold atom gravimeters. Recorded gravity variations in an absolute reference system will complement the Global Geodetic Reference Frame and be used for combination with other geoscientific data in investigation of mass transports and global change processes in the context of the Global Geodetic Observing System, GGOS.

The implementation of the new gravity reference system will be based upon the international standards and conventions of the IAG.

IAG (Geodesy)

G02k - G02 Static Gravity Field Models and Observations

IUGG-4984

The return of relative gravimetry

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The opportunity of determining the instrumental offsets (degrees of equivalence) of absolute gravimeters in international comparisons is now leading to the application of those offsets, not only for harmonizing measurements by different instruments in geophysical campaigns, but also when reference values for gravity are provided. The recently established document "Consultative Committee for Mass and Related Quantities – International Association of Geodesy (CCM-IAG) Strategy for Gravimetry" which outlines a clear hierarchical calibration structure for absolute gravimeters will no doubt formalize and accelerate this tendency. In the future a large number of absolute gravimeters may thus primarily be transmitting the Key Comparison Reference Values to other locations and epochs. In this way, they will be used as relative gravimeters – albeit with "absolute" scale and (ideally) without drift, but relative all the same. Many error components in their original uncertainty budgets (as absolute gravimeters) will become irrelevant in this activity (i.e., are eliminated from the differences), and what remains are principally questions of reproducibility (i.e., instrument stability). I discuss the consequences in view of the size of the different contributions to uncertainty, as seen in time series of gravity results and in typical estimates of the total uncertainty as provided for comparisons of gravimeters.

IAG (Geodesy)

G02l - G02 Static Gravity Field Models and Observations

IUGG-2214

Study of the restitution of submarine geological structures thanks to a new underwater moving gravimeter and gradiometer sensor

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A gravimetric measurement system operating in underwater environment allows the measure of the gravity field very close to the geological sources where permanent instrumentation is not feasible due to the high seismic activity and volcanism such as encountered in subduction zones and oceanic ridges. Some marine geophysicists argue that the hydrothermal sources located in oceanic ridges should hold considerable mineral resources. Whereas bathymetry over oceanic ridges is commonly determined with a resolution of a few meters up to a depth of 3,000 meters from Autonomous Underwater Vehicles, gravity is still acquired from the sea surface using on-board marine gravimeters, located far from the geological sources. The resolution of the gravity map is therefore so low that such gravity data cannot be used to visualize the finest structures of oceanic ridges where precious mineral resources may be located.

The LDO has on charge the development of the instrumental part which is based on the LiMo-g system improved by the use of six electrostatic accelerometers divided into two triads both installed in a waterproof sphere. The latter is intended to be embedded in a Autonomous Underwater Vehicle. Through numerical simulations, the L2G laboratory studies the accuracy and resolution of the gravity field recovery we can hope to achieve with this type of system.

After an overview of the instrument and the carrier, we will focus on the assessment of the system's performances which consists of determining the best compromise in terms of spatial resolution and restitution of geological structures after filtering. The performances have been studied by simulation with reference data calculated from actual submarine geological structures, on which different noise models have been added.

IAG (Geodesy)

G02l - G02 Static Gravity Field Models and Observations

IUGG-2250

Towards the Sub-mGal Level: Latest Results of Strapdown Airborne Gravimetry

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Based on two airborne gravity campaigns in 2013 and 2014, latest results of strapdown airborne gravimetry are presented. The data coverage includes areas of high-mountain terrain and ocean. For both campaigns, a LaCoste and Romberg stable-platform gravimeter (LCR) was flown side-by-side with an off-the-shelf iMAR RQH inertial measurement unit (IMU). A focus is set on the IMU processing using an integrating IMU/GNSS Kalman filter. Different stochastic models for the gravity disturbance are compared. Also, a thermal correction method for the accelerometers is shown, yielding a substantial reduction of long-term drifts. Results are compared against the expected gravitational terrain-effect in the short-wavelength spectrum, and against satellite-based geoid models for the longer wavelengths. A cross-over point analysis shows an excellent overall IMU performance, with estimated standard deviations of 1.3 mGal (without adjustment) and 0.6 mGal (after a constant-bias cross-over adjustment), which is a greatly improved performance for strapdown airborne gravimetry using a commercial off-the-shelf IMU. A strapdown IMU also enables the determination of the deflection of the vertical (DOV). The relative accuracy (after adjustment) can be shown to be of the order of 1 - 2 arc seconds, while the absolute level is difficult to determine due to the strong correlation with attitude errors.

IAG (Geodesy)

G02l - G02 Static Gravity Field Models and Observations

IUGG-2258

Progress in airborne gravimetry by combining strapdown inertial and new satellite observations via dynamic networks

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We revisit the concept of scalar gravity anomaly determination by an airborne strapdown INS/GNSS system. We built on the previously investigated concepts (mainly within 1995-2005) while trying to decrease the error spectrum of the system caused by accelerometer biases at lower frequencies and GNSS-position/velocity noise at shorter wavelengths. We claim that the determination of the random long-term accelerometer bias is possible through combination of GRACE + GOCE data that provide an unbiased field with 80 km resolution while the decrease in velocity noise is expected by precise-point-positioning (PPP) method that merges satellite-phase observations from GPS and Galieo. In the absence of Galileo constellation we focus our practical demonstration on the gravity-anomaly determination via INS/GNSS data filtering. We present first the modeling of an extended Kalman filter/smoother that determines the gravity anomaly together with the trajectory, which is a preferred method over the cascade determination (i.e. separate estimation of trajectory and specific forces, GNSS acceleration and low-pass filtering of the merged signal). Second, we show how to incorporate the same modeling within the concept of dynamic network. This approach allows imposing crossover conditions on the state of gravity anomaly at trajectory intersections while estimating the sensor and trajectory errors at the same time. This is indeed rigorous formulation of the problem that is expected to surpass the conditioning via crossover adjustment that in previous investigations followed the filtering/smoothing. Despite the remaining challenges of the method of dynamic network caused by large number of parameters (i.e. >10e6), we present first practical results obtained within European FP-7 GAL project.

IAG (Geodesy)

G02l - G02 Static Gravity Field Models and Observations

IUGG-3827

Experiences from airborne gravimetry in the frame of the GEOHALO project

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In 2012 the GEOHALO flight mission was carried out as a joint project of several universities and research institutions using the German research aircraft HALO. Amongst other geodetic/geophysical equipment we participated with our air/sea gravimeter Chekan-AM. The surveyed zone covers the major part of Italy. Seven longer tracks (NW to SE) with a spacing of about 40 km and four perpendicular cross tracks were surveyed at a speed of approximately 130 m/s from an altitude of 3,500 m. Hence, in contrast to geophysical exploration, our aim was not to achieve the maximum resolution at the lowest flight speed and altitude possible, but to cover a relatively wide region in realistic time. The chosen region is very favorable for such a test, because combined satellite-terrestrial global gravity field models are very good there (in addition to satellite observations, high-quality terrestrial gravity data were included too). Hence, the airborne results can be cross-checked with them.

The results of the improved processing are presented. Different low-pass filters have been investigated showing the importance of the choice. Furthermore, the importance of accurate determination of the vertical component of the non-gravitative acceleration from GNSS observations was clearly shown. It seems that this is the main limiting factor for the obtainable accuracy. If all such details are paid an appropriate attention, the main conclusion is that with this type of mission it is possible to obtain the resolution and accuracy needed to improve global (satellite-terrestrial) gravity field models in regions with sparse terrestrial data coverage.

IAG (Geodesy)

G02l - G02 Static Gravity Field Models and Observations

IUGG-4587

Developments in airborne gravity collection and processing with the Gravity for the Re-Definition of the American Vertical Datum (GRAV-D) Project

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The U.S. National Geodetic Survey is collecting airborne gravity with the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) Project to produce a geoid supporting heights accurate to 2 centimeters, where possible, with a modernized U.S. vertical datum in 2022. Data collection started in 2008 and covers over 40% of the U.S. and territories. The blocks of data are processed and minimally trimmed for release, with further trimming performed specifically for geoid creation. This presentation will discuss variations in data quality among blocks and discuss potential causes as well as touching on demonstrated improvements. Research and technical developments will also be presented.

IAG (Geodesy)

G02l - G02 Static Gravity Field Models and Observations

IUGG-5214

Using an ixSea Inertial Navigation System for airborne gravimetry

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Airborne gravimetry systems, based on the integration of Strapdown Inertial Navigation Systems (SINS) and GNSS, proved to be quite efficient in the recovery of the gravity anomalies, either as a complement to the more traditional scalar airborne gravimetry techniques or as a standalone method. Depending on the type of Inertial Measurement Unit (IMU), accuracies can range from several mGal (5/6), for spatial resolutions of 6 to 10 Km, down to 1 or 2 mGal, with spatial resolutions below 2 km. The characteristics of the IMU are naturally crucial for the performance of the SINS based airborne gravimetry systems.

Accuracies better than 1 mGal for spatial resolutions below 2Km have been reported using the very expensive navigation grade IMUs with Ring Laser Gyro (RLG). Inertial technology and algorithm developments made possible to achieve good results using less expensive Fiber Optic Gyros (FOG) IMUs.

This work shows the results obtained with an ixSea navigation grade FOG IMU during a campaign done around Madeira, Portugal, in the scope of the GEOMAD (GEOid over MADeira) project, which was funded by EUFAR.

The results show that with this iXSea it is possible to derive gravity estimates with an accuracy of approximately 2 mGal with a spatial resolution near the 2.0 km (half-wavelength). This type of performance, similar to what is achieved with spring gravimeters, makes the ixSea an interesting sensor to recover the medium to short wavelength signals of the Earth's gravity field, with impact on regional geoid improvement. The Madeira regional geoid is presented as example.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-398

Modelling Moho depth in ocean areas based on satellite altimetry using Vening Meinesz-Moritz method

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An experiment for estimating Moho depth is carried out based on satellite altimetry and topographic information using Vening Meinez-Moritz (VMM) gravimetric isostatic hypothesis. In order to investigate the possibility and quality of satellite altimetry in Moho determination, the DNSC08GRA global marine gravity field model and the DTM2006 global topography model are used to obtain a global Moho depth model over the oceans with a resolution of 1 by 1 degree. The numerical results show that the estimated Bouguer gravity disturbance varies from 86 to 767 mGal, with a global average of 747 mGal, and the estimated Moho depth varies from 3 to 39 km with a global average of 19 km. Comparing the Bouguer gravity disturbance estimated from satellite altimetry and that derived by the gravimetric satellite-only model GOGRA04S shows that the two models agree to 13 mGal in RMS. Similarly, the estimated Moho depths from satellite altimetry and GOGRA04S agree to 0.69 km in RMS. It is also concluded that possible mean dynamic topography in the marine gravity model does not significantly affect the Moho determination.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-399

Recent Earth gravitational models to determine the accurate geoid and gravity field at mountain of Kilimanjaro in Tanzania .

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Mt Kilimanjaro, Africa’s highest mountain (5895m), is a large, young (<1.6Ma) stratovolcano at the southern end of the East African Rift, in northern Tanzania. This area is bounded by minimum latitude -3.57 degree, maximum latitude -2.85, minimum longitude 37.02 degree and maximal longitude 37.67 degree. Since the publication of the Earth gravitational model OSUU91A1f and EGM96 considerable improvements in the observation techniques resulted in the development of new improved models. The improvements are due to the availability of data from terrestrial and altimetry derived gravity anomalies. It is expected that the use of new EGM2008 will further contribute to the improvement of the resolution and accuracy of the gravity and geoid modeling in local and regional scale. To prove this numerically, three representative Earth gravitational models are used for the reduction of several kinds of data related to the gravity field in the MT Kilimanjaro. The results of the reduction are discussed regarding the corresponding covariance functions which might be used for modeling using the least squares collocation method. The contribution of the EGM2008 model in this case is comparable to EGM96. In this case the variance and the correlation length of the covariance functions of data reduced to this model up to its maximum degree are only a few percentages of corresponding quantities of the same data reduced up to degree 360. Furthermore, the mean value and the standard deviation of the reduced gravity anomalies in extended area of the Earth vary between −1 and +1 and between 8 and 10×10^{-5} ms^{-2} , respectively, reflecting the homogenization of the gravity field on regional scale.

This is very important in using least squares collocation for local and regional applications.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-400

Viscosity of mantle inferred from land uplift rate and mantle gravity field in Fennoscandia

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One potential application of post glacial rebound is the determination of mantle viscosity. In this study we use a geodetic method to determine the viscosity from CRUST1.0 seismic model, an Earth gravitational model (EGM) and a crustal thickness model based on Vening Meinesz-Moritz' (VMM) gravimetric–isostatic theory. Our model estimates the rebound induced peaks rates of change of surface gravity and geoid height to -1.9 μGal/yr and 1.6 mm/yr, respectively, the former being consistent with absolute gravity observations. We derive the viscosity of the mantle from the land uplift rate and different mantle gravity field models namely: **a)** a spectral window of an EGM, **b)** a crust corrected Earth's gravity field applying the VMM Moho model and **c)** using the gravity effect of upper mantle density contrast through an isostatic model. In optimizing model "a" the aim is to find the optimum harmonic window which best fits to land uplift. In model "b" EGM is filtered by the Earth's crustal thickness model. Finally, in model "c" disturbing gravity signals (non-isostatic effects) in gravimetric Earth's crustal thickness modelling will be used. In the central part of Fennoscandia the mean values of mantle viscosity of 0.4, 9.3 and 5.2 $\times 10^{22}$ Pa.s are obtained using the above models.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-401

The feasibility analysis of land-based INS/GNSS gravimetry system for groundwater resource detection

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Although the annual rainfall is abundant in Taiwan, the supply of water to human, agriculture, or industry is deficient since the water follow to oceans directly and quickly due to the topographic slope is steep. An alternative source for supplying water is groundwater when surface water is in the shortage. For this reason, this research aim to develop an efficient method to detect the groundwater resource. Moving base gravimetry system integrating Inertial Navigation System with Global Navigation Satellite System (INS/GNSS) has been proved to perform well in estimating gravity. In order to achieve gravity in mGal-level, high accuracies of dynamic accelerations derived from Inertial Measurement Unit (IMU) and kinematic accelerations from GNSS are the basic demand. In this research, an investigation of a land-based INS/GNSS gravimetry system containing a navigation grade IMU is conducted to verify the performance and to improve the spatial resolution. The measured gravity, derived directly by differencing the smoothed kinematic accelerations from GNSS and dynamic accelerations from IMU, is compared to the measurements of the relative gravimeter and the comparison shows both agree reasonably. The gravity disturbance estimated from proposed system shows the mean differences is 2.46 mGal with a standard deviation of 1.32 mGal. In addition, a comparison of the preliminary estimates of kinematic velocities and accelerations using GPS, GLONASS, and BDS indicates that three-system GNSS performed better than two-system GNSS in the computation of kinematic accelerations. Finally, the feasibility of the proposed land-based INS/GNSS gravimetry systems for groundwater resource detection is analyzed and discussed.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-402

Estimating degree variances and omission errors at ultra-short scales - 2D-DFT spectral analysis of topographic potential based GGMplus gravity maps

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Recently released Global Gravity Maps Plus (GGMplus, Hirt et al. 2012) gravity maps provide short-scale gravity as forward modelled from the topographic masses at near-global scale in the space-domain. In this work, these maps are analysed spectrally via a 2D-DFT approach dating back to Forsberg 1984. A new degree variance model, valid for Earth's landmasses only, is created, allowing to calculate approximate signal powers and omission errors up to degree 90,000. The new model is supported by over 3 billion GGMPlus gravity estimates over Earth's land areas.

The work shows that at short scales the gravitational signal is underestimated by the spherical harmonic degree variances based on an ellipsoidal mass approximation – while a spherical mass approximation in spherical harmonics shows a spectrum similar to the ellipsoidal harmonic spectrum. Degree variances from the new model are found to be situated "between" those from the classical Kaula and Tscherning-Rapp models.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-403

Syncretic processing of GOCE satellite's SST and SGG data based on spectral combination method

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The general expressions of the spectral weight and spectral combination of the united-processing of various types of gravimetric data are shown. What's more, based on spherical harmonic analysis method, the detailed expressions of spectral combination formulae and the corresponding spectral weights in the Earth's gravitational field model (EGM) determination using satellite-to-satellite tracking (SST) data and satellite gravity gradient (SGG) data of GOCE satellite are derived. Experimentation results show that the EGM computed by SGG data is improved by SST data in the low degree, whatever the data are simulated or surveyed. Consequently, as many types of gravimetric data as possible should be combined together in the data processing in order to strengthen the quality and reliability with widening scope and improve the precision and spatial resolution of the computational results.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-404

The Development of the Argentinean Gravimetric Geoid Model GEOAR

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A new gravimetric geoid model for Argentina named GEOAR was developed using the remove-compute-restore technique and combining an optimal GGM with approximately 230,000 land and marine gravity observations. Several GGMs (e.g. EGM2008, GOCO03S and EIGEN-6C2) were tested for the identification of the best fitting model. Terrain corrections were calculated for all gravity observations using a combination of the SRTM_v4.1 DTM and SRTM30_Plus bathymetric models. For those regions that had gravimetric observations within a distance of 20 km, the observed gravity anomalies were gridded using the inverse square distance weighting method, while for all the regions that lacked such observations, the world gravity model WGM2012 was utilised to derive gravity data. The resultant gravity anomaly grid was evaluated in the Stokes's integral using the spherical multi-band FFT approach and the deterministic kernel modification proposed by Wong and Gore. The accuracy of GEOAR was assessed by comparing its geoidal undulations over more than 1,300 GPS/levelling benchmarks, which have both orthometric and ellipsoidal heights. Results showed that an accuracy of better than 10 centimetres was achieved by the new geoid model.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-405

The comparison of bathymetry prediction methods using the altimetry derived gravity anomalies and models comprehensive

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The 1′×1′ grid bathymetry models of one 7°×8° region are predicted by gravity-geologic method (GGM) and Smith&Sandwell (SAS) method respectively. The results compared to the ship-derived data indicated that the standard deviations are 60.08m and 60.07m for GGM and SAS respectively, the relative precision are both about 1.87%. Due to the short wavelength components for both methods were calculated by the same ship data, the two model's precisions are comparative. The power spectral density, the precision and the depths in shipboard cruises of ETOPO1, SIO, GGM and SAS models were compared and analyzed. The results showed that the GGM and SAS models can gain more bathymetry information of short wavelength component and had better precision. As a final result, we presented a comprehensive bathymetry model by weighted averaging method, in which the weighted factors were determined by precisions of ETOPO1, SIO, GGM, SAS bathymetry models respectively

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-406

The new detailed gravity model for Antarctica

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At present there are a number of gravity models, obtained different methods. The considering in this work models are the following: (1) the spherical harmonics expansion, obtained from the composition of satellite, altimetry and observed data, and (2) gravity field, derived from altimetry data (for ocean).
This work presents the result and analysis of the comparison of these models between themselves and with available observed data for Soutn Polar region.

In this work considered the combined gravity models of Sandwell, published in 2008, Sandwell 1996, which widely used in geophysical research, and danish model KMS, produced by Knudsen and Andersen and published in 1996. In addition was considered reference gravity models EGM96 (expansion on spherical functions to degree and order 360) and EGM2008 (expansion on spherical functions to degree and order 2159, this new model used in gravity field model of Sandwell 2008.).
For analysis of these models were calculating their discrepancy and made statistical analysis of it.
From this study the conclusion was drawn, that these gravity models may be used in geologo-geophysical study of Antarctica, but very carefully on account of the level uncertainty.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-407

The determination of external disturbing gravity potential with ground boundary observations based on Green Integral

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In the series solution for the Molodensky boundary value problem with ground as boundary surface, the higher order terms represent the corrections of ground observations to some smooth surface. The application of the series solution encounters some calculation problems, such as complexity and stability, and the requirements on data intensity is hard to fulfill. In order to find a solution to the problem for the approximation to the external disturbing gravity field, the paper applies the Green formula in the solution of boundary value problem, and derives a solution where gravity anomaly and height anomaly difference are boundary values with kernel being distance reciprocal and Poisson integral kernel. The result provide a direct analytical solution of the external disturbing gravity potential from ground boundary values. Compared with conventional solution, the new solution avoids the complexity in both expression and data processing, and what's more, the kernel is simple for practical calculations. Numerical experiments show that the proposed method has better accuracy than the existing methods for the approximation of disturbing gravity potential.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-408

Assessment of GOCE-based Global Geopotential Models and their use for modelling gravity field over Poland

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The GOCE (Gravity field and Ocean Circulation Explorer) satellite gravimetry mission, launched by the European Space Agency (ESA) in 2009, has remarkably improved the modelling of the Earth gravity field. Several global geopotential models (GGMs) based on GOCE satellite mission data have been developed and released for the scientific use by ESA and other institutions. In this paper the accuracy of the consecutive releases GOCE-based GGMs developed with the use of the direct solution and the time-wise solution strategies as well as the recent high resolution combined GGM, i.e. EIGEN solution, has been assessed over the area of Poland.

Free-air gravity anomalies and height anomalies determined from GOCE-based GGMs have been compared with the corresponding ones obtained from the EGM08. Moreover, height anomalies determined from GOCE-based GGMs were compared with the corresponding ones obtained from different GNSS/levelling data sets with the use of the spectral enhancement method. The results of the comparison reveal clear improvement of the consecutive releases of GOCE-based GGMs investigated. The use of GOCE-based GGMs for modelling the gravity field over Poland is discussed.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-409

Traceability of the Hannover FG5X-220 to the SI units

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The absolute measurement of g is currently realized through the laser interferometric measurement of a free falling retroreflector. The Micro-g LaCoste FG5X is a free-fall gravimeter with a laser interferometer in Mach-Zehnder configuration which uses simultaneous time and distance measurements to calculate the absolute value of g. The instrument itself contains the necessary standards of length and time and operates independent of external references. The timing is kept with a 10 MHz rubidium oscillator with a stability of 5x10^-10. The length standard is provided by a iodine stabilized Helium Neon Laser with a wavelength of 632nm and accuracy of 2.5x10^-11. In 2012 the FG5-220 was upgraded to the FG5X-220. The upgrade included a new dropping chamber with a longer free fall and new electronics including a new rubidium oscillator. The traceability to the Système International d'unités (SI unit) is ensured by two complementary and successive approaches: the comparison of frequencies with standards of higher order and the comparison of the measured g to a reference. Since the upgrade of the absolute gravimeter the instrument participated in several international comparisons, which showed no measuring offset between the instrument prior and after the upgrade. Measurements at well observed stations and the comparison with specific instruments, however, point to an offset of about 20 nm/s^2. A number of experiments to test the rubidium oscillator were performed. The oscillator showed a linear drift of 0.2x10^-3Hz/month (=0.3nm/s^2/month) in the first 18 months of use. A jump in the frequency of 0.01Hz (=20nm/s^2) was revealed recently and the drift rate changed to -0.5x10^-3Hz/month.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-410

A highly accurate absolute gravimetric network for Slovenia

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The main task of the project was to perform very highly accurate absolute gravity measurements at 6 established absolute gravity stations in the Republic of Slovenia.

Previous absolute gravity measurements (AGMs) in Slovenia were performed from 1996 to 2000 with different types of absolute gravimeters, like: IMGC, JILAg5, JILAg6 and FG5-101. The complete basic gravimetric network of Slovenia has been tied to these absolute gravity points and therefore depending from the measurement uncertainty of AGMs.

In Austria the BEV (Federal Office of Metrology and Surveying) maintains the national standard for gravimetry. The present AGMs in Slovenia were performed by the Physico-Technical Testing Service of the BEV in autumn 2014. The absolute gravity measurements were performed with the absolute gravimeter FG5-242 of the BEV over approximately two days at each of the 6 stations.

The vertical gradients were measured at all 6 stations with the relative gravimeter Scintrex CG5. Compared to previous AGMs the results of the AGMs 2014 show large deviations up to 30 microgal (1 microgal = 10^{-8} m/s^2) at some stations. Especially the IMGC absolute gravimeter shows larger deviations than the other absolute gravimeters. The measurement uncertainty of the AGMs 2014 by the FG5-242 varies between 2.5 and 3.1 microGal.

In this presentation the AGMs 2014 in Slovenia and their results will be presented and the comparison to previous measurements will be analysed.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-411

A comparative assessment of Stokes integration, collocation, and radial basis functions for regional gravity field modeling

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Three methods for regional gravity field modeling have been investigated; Stokes integration, least-squares collocation, and spherical radial basis functions. While Stokes integration and least-squares collocation may be regarded as classic methods for regional gravity field modeling, radial basis functions may still be regarded as a modern approach.

Spherical harmonics is a common spectral representation of the global gravity field. Gravity field representation in terms of radial basis functions may also be interpreted as spectral representations (they are based on spherical harmonics), but are limited to a certain spatial region. Therefore, they are deemed suitable for regional gravity field modeling.

In the global case, Shannon low-pass radial basis function is equivalent to spherical harmonics. In addition, when applied globally, both Stokes integration and least-squares collocation are also equivalent to spherical harmonics. As all methods are theoretically equivalent when applied globally, we expect them to give comparable results in applications.

We perform a comparative assessment of Stokes integration, least-squares collocation, and radial basis functions in a closed-loop environment using synthetic data, to verify their equivalence numerically. As we have observed an increased use of radial basis functions for regional gravity field modeling, a comparative assessment will increase confidence in radial basis functions as a suitable method.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-412

Regional gravity field modeling using a two-step point mass method applied to the IAG JSG0.3 test data

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A two-step method has been developed for regional gravity field modeling using point mass radial basis functions (RBFs). In contrast to the standard point mass method, where the point mass RBFs are defined beforehand in a regular grid, the new method starts with initially unknown locations of the point mass RBFs and also the total number of RBFs is to be determined during the computation process. In the first step, the point mass RBFs are searched and optimized one by one by solving a series of small-scale bound-constrained nonlinear problems, resulting in a certain number of point mass RBFs beneath selected observation points at different depths. The magnitudes of these point mass RBFs are considered as preliminary after the first step. And therefore within the second step, a readjustment of all the magnitudes takes place, keeping the positions fixed. In the case of ill-posedness, Tikhonov regularization is applied in conjunction with variance component estimation. Furthermore, the method is capable of combining heterogeneous gravity field data sets. Finally, practical results are presented based on synthetic test data created by the IAG ICCT Joint Study Group JSG0.3 'Comparison of Current Methodologies in Regional Gravity Field Modeling'. The results include comparisons with independent gravity field data to prove the effectiveness of the entire procedure.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-413

Combination of GOCE SGG data and surface gravity anomalies for local/regional geoid determination

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Different approaches have been applied for downward continuation of GOCE gradient data and the consecutive combination with Earth surface gravity data. This presentation demonstrates the abilities of Monte Carlo (MC) annihilation together with the Multiple-Input Multiple-Output System Theory (MIMOST) for combining GOCE gradient data and surface gravity anomalies for local/regional geoid determination. MC is used in combination with MIMOST to iteratively downward continue and convert all six GOCE SGGs to gravity anomalies on the global geoid and further to refine the local/regional geoid. The experiments presented focus over the Mediterranean Sea, where refined values of regional geoid are predicted for both marine and land areas. 18 months of GOCE SGG data are employed, while TIM-R4 is used as a reference field for the reduction of the original GOCE observations. The improvement brought by GOCE is viewed against EGM2008, especially over regions with high-terrain, where local gravity data are scarce. Finally, insight on the use of Tzz only, Txx, Tyy, Tzz and Txz as well as all six SSG components are presented to investigate possible contributions to the improved representation of the geoid and gravity field spectrum. Finally, the external evaluation is performed with local collocated GPS/Leveling data as well as the latest DTU2013 altimetry-derived geoid at sea.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-414

GOCE/GRACE GGM evaluation over Attika and Thessaloniki, Greece and local geoid modeling in support of height unification

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Within the frame of the "Elevation" project, supported by the action "Archimedes III – Funding of research groups in T.E.I.", co-financed by the E.U. and Greek national funds, an extensive evaluation of the latest GOCE, GOCE/GRACE and combined GGMs has been carried out. The evaluation was performed using a set of collocated GPS and leveling BMs covering the regions of Attika and Thessaloniki. To this extent all available satellite-only and combined GOCE/GRACE GGMs were evaluated to conclude on the possible improvement brought by GOCE, given the various methodologies used for the GGM development (DIR, TIM, SPW, GOCO, EIGEN) and the various releases of GOCE data (Release 1, 2, 3, 4 and 5). For the latest GGMs, local height transformation parameters have been determined to accommodate surveying and engineering applications. Moreover, local geoid models have been determined for the two areas under study through the well-known Multiple-Input Multiple-Output System Theory (MIMOST) method, employing GOCE GGMs and the local GPS/Levelling data. The so-determined geoid models are validated against the latest gravimetric geoid for Greece and conclusions are drawn w.r.t. the improvement brought by GOCE in resolving the lower and medium band of the gravity field spectrum with higher accuracy.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-415

Two validation schemes for gravity field interpretation at different scales and altitudes

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Two independent validation schemes have been developed in terms of closed simulation procedures in order to perform a detailed band limited analysis of the abundance of currently available Earth gravity models both in the space and spectral domains. The first procedure performs a comparative analysis of the models by computing standard spectral quantities, such as correlation or smoothing coefficients per order and degree, signal to noise ratio, gain, degree variances and error degree variances. The second scheme investigates the role of the dynamic contribution resulting from the Earth's gravity field in precise orbit determination. We present characteristic implementations using the most recent gravity models and applying both procedures. As both modules lead to a degree-wise quantification of different features of the observed gravity field at different altitudes, we investigate the possibilities of their joint exploitation, especially in the frame of regional applications, where they could serve the task of relating the observed field with known tectonic features or characteristic density distributions in the Earth's interior.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-416

Comparison of third order potential derivatives based on recent satellite-based GGMs and on global isostatic topographic models

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Validation of GOCE-based global geopotential models (GGMs) is a significant topic for both modelers and users. There have already been many studies performed on this topic based on different methods. This study deals with comparison of GOCE-based GGMs with topographic-isostatic models using third-order derivatives of the geopotential. The third-order geopotential derivatives are calculated from various releases of time-wise (TIM) and direct (DIR) GGMs in a regular coordinate grid. New non-singular formulas for spherical harmonic synthesis of third-order potential derivatives are used for this purpose. Third-order derivatives of the gravitational potential generated by isostatically-compensated topography are also computed from topographic-isostatic models. Then the two sets of the third-order derivatives are compared and their correlation is studied in both spatial and spectral domains. Special attention is given to higher-degree spherical harmonics. Also the improvement of various TIM and DIR releases is assessed.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-417

Enhanced GOCE gravity gradients along the orbit

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GOCE gravity gradients are known to be very accurate in the measurement bandwidth of the on-board gradiometer. We asses the combination of GOCE gravity gradients with GRACE information. Therefore we take into account the along track projection of the GRACE field information along the GOCE orbit frequencies to lower the influence of the less accurate sectorial information present in GRACE gravity field products. In addition we account for systematic errors in the cross track gradients close to the magnetic poles applying an adapted filter approach. These products (GGC-GRF) are validated for the complete GOCE mission duration and are analyzed in terms of their signal content in comparison with latest published global gravity field models.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-418

Improving New Zealand's Geoid-Based Vertical Datum with Airborne Gravimetry

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Land Information New Zealand (LINZ) is midway through a project to improve the accuracy of the quasigeoid-based New Zealand Vertical Datum 2009 to 3cm in developed areas. Much of the geoid accuracy improvement is expected to be attributed to the incorporation of recent airborne gravity data, re-analysis of existing terrestrial gravity observations and newer satellite gravity models. In this paper we outline the results of the recent airborne gravity collection campaigns (2013-14) over New Zealand and their contribution to an improved national geoid. The airborne data and the resultant geoid model are validated by comparisons with terrestrial gravity and GNSS-levelling data along two 35-50 km calibration lines. We also evaluate the potential of the resulting geoid to form the basis of the updated New Zealand Vertical Datum.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-419

The new Earth2014 suite of shape, topography, bedrock and ice-sheet models: available as 1-arcmin gridded data and degree-10,800 spherical harmonics

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We present a suite of new 1 arcminute models of Earth's topography, bedrock and ice-sheets constructed as a composite from up-to-date topography models: Earth2014. Our model suite relies on SRTM30_PLUS v9 bathymetry as base layer, merged with SRTM v4.1 topography over the continents, Bedmap2 over Antarctica and the new Greenland Bedrock Topography (GBT v3). As such, Earth2014 provides substantially improved information of bedrock and topography over Earth's major ice sheets, and more recent bathymetric depth data over the oceans, all merged into readily usable global grids. To satisfy multiple applications of global elevation data, Earth2014 provides different representations of Earth's relief. These are grids of (1) the physical surface, (2) bedrock (3) bedrock and ice, (4) ice sheet thicknesses, (5) rock-equivalent topography. These models have been transformed into ultra-high degree spherical harmonics, yielding degree 10,800 series expansions of the Earth2014 grids as input for spectral modelling techniques. As further variants, planetary shape models were constructed, providing distances between relief points and the geocenter. The Earth2014 model suite shall be released mid 2015 via www.ddfe.curtin.edu.au/models/Earth2014.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-420

MODERN GLOBAL MODELS OF QUASIGEOID: ANALYSIS OF RESOLUTION AND ACCURACY

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Great progress has been achieved lately as regards improvement and development of new techniques for space geodesy and their application for determining the Earth figure parameters and its gravity field. On the basis of space gravimetric missions results foreign specialists developed a number of models for the Earth gravity field of high resolution and improved accuracy characteristics of geopotential harmonic coefficients. Thirty three modern global models of quasigeoid are presented, with twenty three of them being combined models and ten satellite models based on the space gravimetric missions of GRACE, CHAMP, and GOCE.

The Earth gravity field models have been investigated by the program modules developed by the authors.

The models developed for the quasigeoid heights were compared with the heights anomalies obtained by GNSS-leveling and geometric leveling (for two different regions of Russia).

The research results show that high resolution global combined models (of gravity field) EIGEN-6C3stat and EIGEN-6C4 have minimum standard deviation of 0.199 m. Satellite models have standard deviation 0.254 m that exceeds the errors of high resolution models by 22%. The mean value of quasigeoid (all models) height difference is of a minus sign in the range of - (0.262 - 0.326). That reveals the systematic error which may result from noncoincidence of the height system and the chosen ellipsoid. The research of high resolution global combined model (of gravity field) EIGEN-6C4 showed 5% improvement of quasigeoid heights spatial resolution and accuracy (on territories under study) as compared with the data of EGM2008 model.

The research has been conducted within the framework of Russian Science Foundation Grant (Project ?14-27-00068).

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-421

The effect of lateral topographical density variations on the geoid in Auvergne

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Uncertainty of the topographical density distribution affects the accuracy of all geoid results. In Stokes-Helmert's approach, topography (i.e., Earth's masses above the geoid) is removed to help create the Helmert model (space). What is usually done is that the average constant density value of 2.67 g/cm^3 is assumed for the whole topography. However, this approximation prevents us from reaching the geoid accurate to one centimeter. The effect of topographical density variations on the geoid has been showed by many researchers to be significant and we come to a similar conclusion in this study.

The effect of lateral topographical density distribution on gravity anomaly and the geoid in the Auvergne (France) area, 43°<?<49°, -1°< λ<7°, was investigated using Stokes-Helmert's geoid computation package of University of New Brunswick. Topographical density values were estimated on 5′×5′ grid from publicly available geological maps of this area using ARCGIS software; then, the effect of lateral density variations on gravity anomalies on the surface of the earth was computed. These gravity anomalies were then continued down to the geoid and passed through Stokes's integration to derive the effect (Direct Density Effect) on the geoid. Also, the primary indirect effect of these variations on the geoid (Primary Indirect Density Effect) has been added to the derived co-geoid as part of the transformation of Helmert's co-geoid to the real space geoid.

Our results show that lateral topographical density variations should be considered and their effect on gravity anomalies and thus on the geoid must be evaluated as part of the "one centimeter geoid computation" process.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-422

Compact absolute gravimeter with a homodyne quadrature laser interferometer

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Monitoring of absolute gravity variations in the difficult accessible areas requires robust and compact instrumentation. For this purpose a compact free-fall corner-cube absolute gravimeter is developed. Such instrument is based on interferometric displacement measurement during repeated free falls of a target mirror in a high vacuum. A distinctive feature is that the homodyne quadrature laser interferometer is complemented with a digital demodulation of the fringe signal based on the Hilbert transform. Specific measurement errors coming from non-identical frequency-dependent phase delays in the used photo-detectors are revealed and corrected. As a result, the prototype can detect gravity variations in the volcanic areas with the resolution better than 1 microgal over 1-2 days. The details of the prototype's performance will be reported.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-423

RWI_TOPO_2015: An update of the Rock-Water-Ice topographic gravity field model of the Earth up to degree and order 2190

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Global high-resolution digital terrain models provide precise information of the Earth’s topography. By applying gravity forward modelling this data can be used to determine the high-frequency constituents of the Earth’s gravity field that can be used in various applications, e.g., the smoothing or spectral extension of gravity ?eld-related quantities.

This contribution provides an update of the Rock-Water-Ice (RWI) topographic gravity field model that is characterized by a three-layer decomposition of the topography. In contrast to condensation methods, e.g., the use of rock-equivalent heights, geometry changes are avoided due to a rigorous separate modeling of rock, water, and ice masses with layer-specific density values. In a first step, gravity forward modelling is performed in the space domain using tesseroid mass bodies arranged on the GRS80 ellipsoid. In the second step, global gridded values of topographic effects are transformed to the frequency domain by applying harmonic analysis.

While the previous model, RWI_TOPO_2012, was based on the 5′×5′ global topographic database DTM2006.0, the updated version, RWI_TOPO_2015, uses the new 1′×1′ global Earth2014 model as topographic input. This terrain model combines information of SRTM3, SRTM30_PLUS, Bedmap2, and GBT_V3. Furthermore, in the case of RWI_TOPO_2015, the representation in spherical harmonics is extended to degree and order 2190 (formerly 1800).

The characteristics and differences of both versions of the RWI model are described in detail. Additionally, their performance is compared with respect to their reduction rate of high-frequency signals in observed GOCE gravity gradients and derived gravity field models.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-424

A new European Gravimetric (Quasi)Geoid EGG2015

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A series of European geoid and quasigeoid models was computed at Institut für Erdmessung (IfE) with support of the International Association of Geodesy (IAG), presently in the form of IAG Sub-Commission 2.4a "Gravity and Geoid in Europe". The last major re-computation was performed in 2008 and is denoted as EGG2008 (European Gravimetric Geoid 2008). Since that time, several important developments have taken place, including five releases of GOCE global gravity field models, the availability of a number of new gravity field data sets, as well as some improvements in the modeling approach, especially regarding the rigorous linearization of the observation equations with respect to a high-degree reference model.

The present contribution takes the aforementioned refinements into account and discusses the results of corresponding re-computations of the quasigeoid in Europe. The new models are evaluated by different national and European GPS and levelling data sets, where emphasis is put on the effect of the data updates and the modeling refinements. Furthermore, applications of the quasigeoid models are outlined regarding vertical datum connections and the delivery of ground truth data for high-precision optical clock comparisons. The latter topic relates to the presently developed new generation of optical clocks with a projected relative accuracy of 10^{-17} to 10^{-18}, which (according to the laws of general relativity) corresponds to a sensitivity in the gravity potential equivalent 0.1 m to 0.01 m in height, respectively. Once such optical clocks become operational, this would open several interesting applications in geodesy, such as the large-scale control of height systems and gravity field models as well as the interconnection of tide gauges.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-425

Towards a high-resolution modeling of the Earth's topographic potential: A case study

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Discrete 3D density distribution between Moho boundary and daylight surface of the Earth has been generated from a combination of CRUST1.0, GEMMA and ETOPO1 models. To compute the gravity effect of these structures, harmonic analysis has been applied to a sequence of global equi-angular grids of lateral density variations within thin layers of a constant depth. Gravity models of different resolution have been accumulated from harmonic coefficients of these layers. Possible augmentations of existing high-resolution gravity models (EGM2008, EIGEN-6C, DTU13) with the models computed in this study are discussed.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-426

The effect of topographic and atmospheric masses on inversion of a satellite third-order gravitational tensor onto gravity anomalies

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Gravitational effects of topographic and atmospheric masses play an important role in precise downward continuation of satellite gravity data. In this contribution we study the effect of topographic and atmospheric masses on recovery of regional ground gravity anomalies from a satellite third-order gravitational tensor (assumed to be observable in the future). Firstly, we calculate the atmospheric and topographic gravitational effects on the third-order gravitational tensor simulated along a satellite orbit at 250 km elevation above Europe. These effects are applied in the traditional remove-compute-restore scheme. Secondly, new integral formulas for transformation of ground gravity anomalies onto the satellite third-order gravitational tensor defined in the local north-oriented frame are decomposed in the spatial domain into the near and distant zones. The effect of gravity data in the distant zones is synthesized from a global geopotential model with spectral weights given by truncation error coefficients. In numerical experiments, we assess the numerical accuracy of associated inverse problems in closed-loop simulations. Thirdly, we evaluate numerical properties of closed and spectral (band-limited) forms of respective integral kernels, and possible improvements of the inverse problems when combining various components of third-order gravitational tensor with and without topographic and atmospheric gravitational effects are presented. Finally, we combine the third-order gravitational tensor components contaminated with the white noise with atmospheric and topographic gravitational effects computed from available spherical harmonic models of isostatically-compensated topography and standard atmosphere.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-427

Results from IAG's Joint Study Group JSG0.3 on Regional Gravity Field Modeling

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For the period 2011-2015, the International Association of Geodesy (IAG) has established under the roof of its Inter-Commission Committee on Theory (ICCT) a Joint Study Group (JSG0.3) on the Comparison of Current Methodologies in Regional Gravity Field Modeling. The main objectives of JSG0.3 are (1) to collect information of available methodologies and strategies for regional modelling, (2) to analyze the collected information in order to find specific properties of the different approaches and to find, why certain strategies have been chosen, (3) to create a benchmark data set for comparative numerical studies, (4) to carry out numerical comparisons between different solution strategies for estimating the model parameters and to validate the results with other approaches, and (5) to quantify and interpret the differences of the comparisons with a focus on detection, explanation and treatment of inconsistencies and possible instabilities of the different approaches.

As one of the outcomes the group has provided a set of synthetic gravity field observations representing data from terrestrial, airborne and satellite sensors for specific regions with different signal character. In addition a global data set of satellite data exists. These benchmark data sets are publicly available (http://jsg03.dgfi.badw.de) and free to all interested researchers to test and validate their modelling procedures. The aim of this presentation is the comparison of results from various groups using different methodologies for regional gravity field modeling as the title of the study group implies.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-428

Refinement of the geoid model on the islands with sparse terrestrial gravity data

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Croatia has more than five hundred islands majority of which has the surface smaller than one km square, while the largest island exceeds even 400 km squares. In accordance to the large differences of the islands' surfaces, 10 % of the islands are permanently inhabited while the rest of the islands record an increasing rate of the real estate transactions making them a subject of a great scope of the construction works, which reflects on higher demands for the geoid model on the islands to rely on. Since 2011, current Croatian geoid model have been implemented in the online service of national positioning system in order to allow the real time height transfer between ellipsoidal and orthometric heights. Its accuracy of +/- 4 cm was validated on the Croatian mainland stations while the estimation of its reliability on the islands was not possible due to the lack of gravity and levelling data on the islands. Regarding the new avenues that have occurred in the meantime such as more detailed bathymetric and gravity global models as well as new sparse terrestrial gravity data on the islands, the subtle gravity field modelling have been applied on the Croatian islands, within which the refinement of the geoid model for the islands and part of the Adriatic sea have been evaluated in this paper.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-429

New Zealand's primary gravity network

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Until recently, the few absolute gravity observations that had been acquired in New Zealand were geographically constrained to a small area of the South Island. This deficiency was remedied in early 2015 through a collaborative absolute gravity campaign between GNS Science, Land Information New Zealand and Geoscience Australia. Observations were acquired at seven sites located across New Zealand, included the Warkworth Radio Astronomy Observatory which includes co-located GNSS and VLBI stations. The results of this survey will be used to define an updated primary gravity network.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-430

Efficient computation of topographic effects for a new German Combined Quasigeoid

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The German Combined Quasigeoid (GCG) is the official height reference surface adopted by the German land surveying authorities. The next update, which will form a major part in the modernization of the height system in Germany, is to be released in 2016.

For the new GCG very large and still increasing sets of gravity data (up to 1 million points) need to be processed. This requires the use of robust and efficient numerical methods. The computation of the GCG is based on the remove-restore principle incorporating residual terrain effects of a 25 meter (1 arc-sec) DEM of Germany and the surrounding areas. In this regard, the performance on modern computers of the prism-based GRAVSOFT/TC software used so far is limited.

During the last years, the benefit of topographic modelling by means of tesseroids has been widely discussed, and optimized numerical formulas have been derived (e.g., Grombein et al. 2013). This motivated us to investigate the feasibility of this approach for the GCG. Reasonable computation times could be realized on the available Linux cluster (64 cores, 512 GB memory) without the need for any further simplifications or restrictions, such as far-zone approximations, coarse grids or subdivision of tiles. However, it is known that the numerical accuracy of the expansion formulas is critical in the near zone, which requires special treatment. In this regard, the feasibility of a horizontal and vertical densification strategy in the direct vicinity of the computation point, rather than reverting to prisms, was systematically investigated and confirmed.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-431

Gravity field modelling for optical clock comparisons

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A coordinated programme of clock comparisons is carried out within the EMRP-funded project "International Timescales with Optical Clocks" (ITOC), aiming at a validation of the uncertainty budgets of the new optical clocks in view of an optical redefinition of the SI second. Based on Einstein's general relativity theory, clocks are affected by the gravitational field and the velocity of the clocks. For an Earth-bound clock at rest, the corresponding relativistic redshift effect is directly related to the (geodetic) gravity potential. As optical clocks are now targeting a relative accuracy of 10^{-18}, corresponding to a sensitivity of about 0.1 m^2/s^2 in terms of the geopotential or 0.01 m in height, precise knowledge of the gravity potential is required at the respective clock sites. Alternatively, optical clocks may also be employed for deriving the gravity potential (denoted as "chronometric levelling" or "relativistic geodesy") and hence offer completely new options for geodetic height determination.

The ITOC project involves clock sites at the national metrological institutes in France, Germany, Italy and the United Kingdom. In order to determine the gravity potential with best possible accuracy at these sites, two approaches are considered, namely geometric levelling and GNSS ellipsoidal heights in combination with a gravimetric (quasi)geoid model. Additional absolute and relative gravity observations were carried out around the clock sites and then used to compute an updated quasigeoid model. The general strategy, the work undertaken so far, the update of the quasigeoid models as well as corresponding differences and accuracies are presented.

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-432

Gravimetric and LiDAR data integration to determine the residual effect of topographic masses

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This paper aims to present a case study that uses gravimetric and LiDAR data for calculating the residual effect of topographic masses. In the calculation of the local gravity, its value is affected by topographical masses close to the points where it is required to determine its value. The present study used LiDAR data to model the topographic region. The calculation of the effect of residual topographic masses was performed using gravity data, digital surface model (DSM), digital terrain model (DTM) , density and classification of man-made and natural elements sites. The procedures were applied in an urban área. The chosen scenario consists of populated areas occupied by buildings, regions with predominant vegetation and mixed areas. The results are promising and indicate the possibility of further research in the future, given the technological development of the gravimetric apparatus.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-433

The IFE global gravity field model from GOCE-only observations

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GOCE was the first satellite mission that combined SST-hl (high-low Satellite-to-Satellite Tracking) and SGG (Satellite Gravity Gradiometry) techniques to measure the Earth's gravity field. During its lifetime, hundreds of millions of measurements were delivered, which poses a great challenge to recover a global gravity field model from such a huge dataset. The GOCE HPF (High level Processing Facility) made remarkable achievements in this respect. But also the worldwide users have the opportunity to derive their own gravity models as a result of ESA's open-access policy for GOCE data. In this study, we will present an independent GOCE-only gravity field model, which is obtained from our own IfE software package.

We applied the acceleration approach to process the orbit data. The accelerations are computed from the satellite positions by numerical differentiation and they are balanced with the derivatives of the gravitational potential. The gravity gradients are processed in the framework of the remove-restore technique by which the low-frequency components of the original gradients are replaced by modeled ones. To avoid introducing external information, the long-wavelength gravity field recovered from the GOCE SST-hl data is used to model the gradients at low frequencies. In a combination analysis, the normal equation systems of the SST-hl and SGG analysis are summed by the Variance Component Estimation approach.

About 500 days (from November 2009 to April 2011) of GOCE observations are used for our present solution. The model is recovered with a maximum degree of 240, which contains 58,077 unknown gravity field coefficients to be estimated. In order to evaluate our model, a comparison with the GOCE official models and external validation by GPS leveling is carried out.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-434

Gravity anomalies and geoid undulation from strapdown airborne gravimetry: Outcomes from the GAL project

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The GAL (Galileo for Gravity) project, founded by the European GNSS Agency (GSA)in the framework of the FP7 Transport theme aims to study and develop a state of the art methodology for the determination of precise and high-resolution gravity field models from strapdown kinematic airborne gravimetry.
In this work the procedure applied in order to retrieve gravity anomalies and geoid undulations as well as the final results are discussed.
Basically the applied algorithm is a classical remove-restore strategy consisting on four main steps: in the first one a Wiener filter is applied to the airborne observations removing biases and systematic errors potentially present in the data and improving the low frequencies of the observed signal. After that the low and high frequencies of the gravitational field are removed from the observations. The former are obtained from the harmonic synthesis of a global Earth gravitational model (for this study an ad hoc model obtained by combining GOCE and EGM2008 has been used), the latter are derived from a residual terrain correction. The third step consists in the gridding of the residual field; this operation can be performed either by a unique 3D collocation or by downward continue the residual signal (using the Abel-Poisson integral) and by gridding it with a classical 2D least squares collocation. Finally the restore of the signal removed in the second step, in terms of free air anomaly or geoid undulation is performed.
The results obtained from the GAL project test case shows that strapdown airborne gravimetry can give useful information on the gravity field in terms of free air anomalies (errors standard deviation of 3.4 mGal at 1 km spatial resolution) and in terms of geoid undulation (errors standard deviation of 4 cm).

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-435

High-resolution modelling of altimetry-derived gravity data by solving the altimetry-gravimetry boundary-value problem

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We present a numerical solution of the altimetry-gravimetry boundary-value problem using the finite volume method (FVM). Such a numerical approach discretizes the 3D computational domain between an ellipsoidal approximation of the Earth's surface and an upper boundary at the mean altitude of the GOCE orbits. A parallel implementation of FVM and large-scale parallel computations on clusters with distributed memory allow high-resolution modelling of the altimetry-derived gravity disturbances over oceans. The key idea is to generate precisely the Dirichlet boundary conditions over oceans that are prescribed in form of the disturbing potential. For this purpose the geopotential on the mean sea surface is generated from the GRACE/GOCE-based satellite-only geopotential model and afterwards filtered by nonlinear diffusion filtering. On the upper boundary, the Dirichlet boundary conditions generated from the same satellite-only geopotential model are prescribed as well. Numerical experiments present high-resolution modelling of the gravity disturbances over oceans derived from the DTU13 mean sea surface model and the GO_CONS_GCF_2_DIR_R5 geopotential model up to degree 300. Their comparison with the DTU13_GRAV altimetry-derived gravity data indicates an importance of a-priori information about the mean dynamic topography, especially in zones of main ocean geosprophic surface currents.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-436

Improving regional gravity field and geoid modelling by various use of global geopotential models

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Regional enhancements in gravity field and geoid modelling are still needed despite the improved quality and availability of high-resolution global geopotential models (GGM) from several computation centres. Sufficient density and distribution of terrestrial gravity data are necessary to meet the demand for sub cm geoid modelling. Although such data may be available, these need to be complemented with information from GGMs to account for the far zone effect and possible data voids. This contribution investigates different use of contemporary satellite-only and combined high degree GGMs in combination with terrestrial gravity data. The resulting geoid models are evaluated with high precision GNSS/levelling data in common reference frames and time epoch.
First, recent high-resolution GGMs (EGM08, EIGEN-6c3stat, EIGEN-6C4) are analysed, evaluated and experimented with as additional information within a large area of little to no terrestrial data available. In the study area, filling a data void with GGM data has an effect as large as 20 cm to the geoid model.
Second, satellite-only GGMs are used in a least squares modification of Stokes' formula to attribute for the far zone effect in regional geoid modelling. Different spherical harmonic expansion limits of the GO_CONS_GCF_2_DIR_R5 satellite-only model are tested to find the expansion limit that fits the local GNSS/levelling data best.
These investigations are motivated by and will be used in the Nordic Geodetic Commission's (NKG) regional geoid modelling project covering an area of 53-73 °N and 0-34 °E. It is an area of varying gravimetric data coverage and quality due to complications of marine gravity data collection over the Baltic Sea.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-437

RAGA - AAGN (Argentine Absolute Gravity Network)

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The zero order Argentine gravity network was stablished in 1991 and is formed of five absolute gravity stations. Modern geodesy, integration of geodetic regional frames and improvements in vertical reference systems, among other factors, require gravity networks with better precision parameters.

In 2013, the National Geographic Institute, the National Universities of Rosario, San Juan and La Plata in Argentina, together with the University of Sao Paulo (Brazil) and de Institut pur le développement (France) initiate the RAGA – AAGN project in order to constitute a new absolute gravity network formed of 35 stations well distributed along the Argentine territory.

This work shows the results of realization, execution and calculation of this gravity network.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-438

Calculation of gravity terrain effects for the correction of sub-surface gyroscope observations

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Deflections of the vertical (DOV) at the 1” accuracy level are an unconditional pre-requisite to correct high-quality geodetic observations like zenith distances and azimuths for the high- and low-frequency topographic effects. Unfortunately the observation of astro-geodetic DOVs is time-consuming and expensive and even the calculation of gravimetric deflections depends on a dense network of observed gravity anomalies and an accompanying topographic and density model. The problem becomes more intense if not only surface DOVs are requested but also sub-surface DOVs along given tunnel trajectories for the reduction of gyroscope measurements. These reductions are also required at the 1”-2” accuracy level to account for systematic topographic effects.

Therefore the software TOPOGRAV was created at TU Vienna, which is able to calculate both the topographic DOV and gravity effects (terrain corrections) from a given terrain and density model. By importing station coordinates and utilizing the well-known remove-restore technique absolute surface and sub-surface DOVs can be established either by introducing available sparse observed deflections or by evaluating the earth gravity model EGM2008 for the long-wave-length effects. Two calculation methods have been implemented, the prism integration method and the discrete Fourier transformation for calculating the terrain attraction. Besides also related quantities, like the height anomaly, the Bouguer anomaly, Geoid undulations and orthometric corrections can be calculated for a given trajectory. This poster presentation shall introduce the functionality of TOPOGRAV and provide comparisons to DOV surface observations and sub-surface gyro-corrections on the basis of a huge railway-tunnel project in the Austrian Alps.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-440

Exploitation of marine gravity measurements in the validation of global gravity field models

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Over the oceans, data from altimetry are currently the only input data for the latest global geoid models such as EGM08 or EIGEN6C. Over the Mediterranean Sea, satellite altimetry does not give good results for gravity models, in particular because of the high ocean variability, and in the vicinity of the coast in some areas. A marine gravity data compilation and screening was conducted as part of an international project GEOMED2 for calculating the geoid of the Mediterranean Sea (Barzaghi et al., 2015).

Marine gravimetric data will be described. Comparisons with models inferred from satellite altimetry and satellite gravity have been done and the results showed differences according to spatial wavelength. Some recommendations on the use of marine data in the processing chain will be given especially for the global models validation and for their integration in global Earth models.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-441

Sub-crustal stress determined using gravity and crust structure models

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The sub-crustal stress induced by mantle convection has been traditionally computed using the Runcorn formulae of solving the Navier-Stokes problem. The main disadvantage of this method is a limited spectral resolution (up to degree 25 of spherical harmonics) due to a divergence of the spherical harmonic expression. To improve the spectral resolution, we propose a new method of computing the horizontal components of the sub-crustal stress based on utilising the stress function with a numerical differentiation. According to the proposed method, the stress function is functionally related to the gravity and crust structure models expressed in terms of spherical harmonics, instead of directly relating the stress components with partial derivatives of these spherical harmonics. The stress components are then computed from the stress function by applying a numerical differentiation. This modification increases the degree-dependent convergence domain of the asymptotically-convergent series and consequently allows computing the stress components to a higher spectral resolution, which is compatible with currently available global crustal models. We further utilise the solution to the Vening Meinesz-Moritz inverse problem of isostasy in definition of the stress function. This definition facilitates a variable crustal thickness instead of assuming only a constant value adopted in the Runcorn formulae. The crustal thickness and sub-crustal stress are then determined directly from gravity data and a crustal structure model. We apply this numerical approach to compute the sub-crustal stress globally. Regional results are also presented and discussed over study areas of oceanic subduction zones, convergent continent-to-continent collision zones and hotspots.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-442

Determination of crust-mantle density contrast by combination of seismic and satellite gradiometry data

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The density contrast between the Earth's crust and mantle can be determined using the isostatic theories. Vening Meinesz-Moritz inverse problem is the recent development of this theory and have been used by several geoscientists for computing the Moho depths based on the assumption of having a constant density contrast between the crust and mantle, which is not a fully realistic assumption. Here, we assume that the deviation between the gravimetric Moho model, determined using this theory, and the seismic one is due to this assumption and we try to estimate the deviation of the density contrast from the considered constant value. We develop a spherical harmonic approach for using an Earth's gravity and seismic models and also an integral approach for using the satellite gradiometry data in combination of seismic Moho model of CRUST1 and CRUST2 for regional applications. The methods will be applied and tested over Himalaya area.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-443

Towards a high resolution geopotential model using clock-based geodesy

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Current methods to determine the geopotential are mainly based on indirect approaches using gravimetric, gradiometric and topographic data. Satellite missions (GRACE, GOCE) have contributed significantly to improve the knowledge of the Earth's gravity field with a spatial resolution of about 90 km, but it is not enough to access to the geoid variation in hilly regions. While airbone and ground-based gravimeters provide the high resolution, the problem of these technics is that the accuracy is hampered by the heterogeneous coverage of gravity data (ground and offshore). Recent technological advances in atomic clocks are opening new perspectives in the determination of the geopotential. To date, the best of them reach a stability of 1.6x10^-18 (NIST, RIKEN+University of Tokyo) in just 7 hours of integration, an accuracy of 2x10^-18 (JILA). Using the relation of the relativistic gravitational redshift, this corresponds to a determination of geopotential differences at the 0.1m^2 /s^2 level. This present work aims at evaluating the contribution of optical clocks for the determination of the geopotential at high spatial resolution. To do that, we have chosen to study a test area from the French Alps to the Mediterranean Sea. Located at the limit between different countries, this region is very interesting because, the gravitational field strength varies greatly from place to place at high resolution due to the mountains and the bathymetry; and there is a surface gravity data coverage of heterogeneous quality. Here we describe the synthetic tests methodology: generation of synthetic gravity and potential data, then estimation of the potential from these data using the least square collocation, and assessment of the clocks contribution. We discuss our preliminary results.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-444

Airborne gravity data in Alaska: contributions to xGEOID15 and Arctic gravity models.

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By 2022, The U.S. National Geodetic Survey [NGS] intends that all orthometric heights in the USA will be determined in the field by using a reliable national gravimetric geoid model to transform from geodetic heights obtained from GPS. Towards this end, the NGS Gravity for the Redefinition of the American Vertical Datum [GRAV-D] program, continues to update its gravimetry holdings by flying new airborne gravity surveys over a large fraction of the USA and its territories. Several airborne campaigns have already been flown over Alaska and its coastline. All available Alaskan data has been incorporated into a new NGS experimental geoid model - xGEOID15. The xGEOID15 model is the second in a series of annual experimental geoid models that will incorporate NGS GRAV-D airborne data. This series provides a useful benchmark for assessing and improving current techniques by which the airborne and land-survey data are filtered and cleaned, and then combined with satellite gravity models, elevation data (etc.) with the ultimate aim of computing a geoid model that can support a national physical height system by 2022. Here we will examine the NGS GRAV-D airborne data in Alaska, and assess its contribution to xGEOID15. Contributions to new Arctic gravity models will also be considered.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-445

Analysis of the repeated gravity measurements in China (1998 -2013) and its implication on the gravity variations of China continent

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Over the last three decades there has been an increased effort to analyze precise geodetic measurements of various types to determine global and regional gravity variations. In China, we have already built three national repeated gravity networks: the Crustal Movement Observation Network of China? (CMONOC?, 1998-2008), Digital Earthquake Observation Network of China (DEONOC, 2006-2007), and the Crustal Movement Observation Network of China ? (CMONOC ?, 2010 - present). We have nearly 30000 relative gravity observations obtained over a period of 16 years on those Chinese national gravity networks, using primarily LaCoste-Romberg gravimeters that have a typical precision of about 20 μGal. We also conducted the repeated absolute gravity measurements during the last three decades, which could provide the absolute gravity constraints on the national relative gravity network with a high precision of about 1-2μGal. In this paper, we process and analysis all the repeated gravity measurements in China mainland from the period of 1998-2013, and attain the dynamic change of gravity field in China continent. The results suggest that: (1) there existed significant inhomogeneity in the spatial-temporal distribution of gravity changes in China and partition phenomenon; (2) significant gravity changes appear to be concentrated in regions with active faults and associated with the preparation of large earthquakes; (3) the majority of large earthquakes in mainland China occurred in areas that exhibited significant differences of gravity changes of $90\times10^{-8}ms^{-2}$ or greater, and these earthquakes typically ruptured around the time when the trend of gravity change in the region showed signs of reversal.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-446

The research on the variation characteristic of the gPhone's scale factor

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The gPhone is essentially a LaCoste & Romberg, model G meter, but with an improved thermal system (a double oven) for increased temperature stability. To validate the variation of the gPhone's scale factor at different geographical position, we report on the results of a comparative analysis carried out on more than one month of co-located records collected at the Wuhan(SG-C053), Lasha(SG–C057) and Lijiang (SG-C066) SG stations with gPhone(113) and CG5(843,852). The precise scalce factor of SG-C057 is -77.1144uGal/V(Xiaodong Chen 2014), and that value of SG-C053 is -76.960uGal/V(Lelin Xing 2009). To acquire the accurate scale factor of SG-066, we use FG-5(232) calibrate it from August 23 to 25, 2014. The preliminary results show that the scale factor of gPhone(113) at lasa is 0.13% lower than it at Wuhan. The accuracy of the scale factor's difference value is better than 0.05%. Further study of observation data is process, we will give detailed results in the near future.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-447

Approximation of the Earth gravity field by the point mass model

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The formulation and the advantages of the virtual point mass model used in the earth gravity approximation are analyzed and the key issues for the construction of the point mass model are discussed in this presentation. Then, the method on the structure of the virtual sphere used in the point mass method will be formatted. The analysis on the model error transformation is given and the analysis is taken as a base condition to derive the virtual sphere radius. Point masses model sometimes may require that the area of gravimetry be larger than the study area, thus a method for the criteria of the expanding is proposed. And the efficiency of the method is verified by the simulation data. Based on a geo-potential model as the reference, the point mass model is studied through the simulated gravity anomalies. Then, the vectors of gravity disturbance computed by the geo-potential model and the point masses model are used to study the precision of the virtual model.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-448

Comparison of simultaneous gravity-recordings by the gravimetric atom interferometer (GAIN), the FG5X and superconducting gravimeters

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Atom interferometers have demonstrated a high sensitivity to inertial forces. This enables their application in gravimetry, creating a new type of instrument for continuous absolute gravity measurements. The Gravimetric Atom Interferometer (GAIN) is a mobile atom interferometer based on interfering ensembles of laser-cooled Rubidium atoms in an atomic fountain configuration. It has been specifically designed for on-site measurements of the absolute value of g as well as continuous recordings. The current state of the art of commercial absolute gravimeters (AG) is represented by optical interferometers like the FG5X while the most precise continuously operating relative gravimeters are superconducting gravimeters (SG). GAIN aims at combining both applications in a single instrument. We present the results of simultaneous gravity recordings of GAIN and two superconducting gravimeters. The first was conducted with the SG-30 at the Geodetic Observatory Wettzell (Germany), operated by BKG, in November 2013. The second measurement was carried out with the OSG-054 at the Onsala Space Observatory (Sweden), operated by Chalmers University of Technology, in February 2015 after improvements of GAIN. This campaign also included simultaneous operation of an FG5X operated by IfE. The comparison of the recorded time series of GAIN and the SG shows an excellent agreement between both instruments. This enables the GAIN sensor to be used to determine the scale factor of the SG. During a 5 day measurement in Wettzell this factor was determined with an uncertainty of 0.4‰, which is an improvement by a factor of 2-3 with respect to the previous value determined by a set of FG5 measurements.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-450

Towards a highly accurate quasigeoid for the Czech Republic

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The paper discusses some of the possible contributions important to further development of a highly-accurate quasigeoid model for the territory of the Czech Republic. The present quasigeoid realization QGZU-2013 of accuracy ca 10 mm (relative, inland) provides a springboard for the investigation of various sources of residual errors. The focus is put on available terrestrial gravimetric data, their systematic and random errors and possible improvements achievable with re-observations of the gravity. Furthermore, temporal changes of local mass distribution (mostly of anthropogenic character – like mines, quarries or water damps) have to be modelled in order to compare observations of different epochs and justify the data to certain reference. The impact of gravity data error and its propagation to the solution (quasigeoid) is thoroughly studied. We focus also on terrain model inaccuracies and theirs influence on the solution. Last but not least, systematic effects present in the realization of the national vertical reference system (normal heights of Kronstadt-57) are analysed and modelled too. Taking all the effects into account, we believe that the accuracy of the national quasigeoid solution can be improved to the level better than 5 mm. The work could be of interest for other studies of detailed geoid/quasigeoid modelling.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-451

Advanced post-processing of absolute gravity measurements - Verification of the correction due to the finite speed of light

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New script (AGDAS) in Matlab has been developed for post-processing of raw absolute gravity data (time and distance pairs related to the interferometric signal generated during the free-fall). Objectives of the AGDAS are on the one hand to verify the standard 'g' software used for processing of FG5 gravimeters and on the other hand to allow more complex analysis of gravity data including advanced outputs related to the measurement results and their quality. Among others, the analysis includes accurate definition of the effective measurement height using a numerical method, analysis of gravity residuals in spectral and time domain, evaluation of the quality of solution of the free-fall motion.

The AGDAS has been employed for the experimental verification of the questionable correction due to the finite speed of light (SOL). Theoretical and experimental results published in 2012 and 2014, respectively, have demonstrated that the present treatment of SOL correction is insufficient and modern gravimeters as FG5s overcorrect the influence of the finite speed of light by about 4 μGal. Therefore, new independent experiment and analyses have been carried out through the careful processing of gravity data for variable drop length. Measurements of two gravimeters (FG5 and FG5-X) at 5 sites with well known gravity gradients have been used for this purpose. Presented are the results of this experiment.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-452

RFCAG2013: Russian-Finnish Comparison of absolute gravimeters in 2013

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In June-July 2013, we performed a comparison of five absolute gravimeters of different types. The gravimeters were the FG5X-221 of the FGI, the FG5-110 and GBL-M 002 of the TsNIIGaiK, the GABL-PM of the IAE SB RAS, and the GABL-M of the NIIMorGeofizika (Murmansk, Russia). The three last-mentioned are field-type portable gravimeters made by the Institute of Automation and Electrometry in Novosibirsk. The comparison was conducted at four sites with different characteristics: in Pulkovo and in Svetloe near St. Petersburg, at the TsNIIGaiK laboratory in Moscow, and in Zvenigorod near Moscow. At the TsNIIGAiK site and in Zvenigorod two piers were used, such that altogether six stations were occupied. The FG5X-221 provides a tie to the International Comparison of Absolute Gravimeters ICAG-2013 in Luxembourg in November 2013. We present the comparison results and discuss the performance characteristics of the different gravimeters.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-453

Use of numerical weather models for atmospheric gravity corrections in terrestrial gravity measurements

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The atmosphere is the main source of noise in high precision terrestrial gravity measurements. Usually we can deal with this phenomena by means of local pressure recordings utilizing simple atmosphere models or standard or site dependent admittance factors. Despite of their great simplicity this method performs very well. As this methods do not reflect the physical phenomena of atmosphere impact on gravity they limit the accuracy of high precision superconducting and ballistic gravimetric measurements. This can be important obstacle in terms of interpretation of subtle geodynamic processes.
We present here not yet very well known so-called 3D atmosphere modelling with minor improvements using recent numerical weather models. The calculation of gravity corrections using this advanced method is verified using large data set of superconducting gravimeter data. The improvement of atmospheric corrections is confirmed with reduced gravity residuals (in time and frequency domain), better agreement of tidal gravimetric factors (mainly for long-period awes) and polar motion gravimetric factor with values predicted with Earth models. Within this work the on-line service for computing 3D atmospheric gravity measurements is also presented.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-454

Accurate gravity data processing using the real definition of Bouguer correction

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Gravity data correction is a very important step to get the highest precision on a Bouguer anomaly. In this way, topography correction is a crucial step, which is very complex in areas of steep topography. Until now, this correction was made using a predefined reticular cylinder (e.g. Hammer), in which a gravity effect of the topography is assessed. At this time and with available computational means, we can recover the numerical topography from any Digital Terrain Model (DTM), which can be handled by a PC in a reasonable calculation time, and then compute the gravity effect of the whole topography area.

New accurate topography correction for gravity measurements using a forward modeling approach and based on DTM of different resolution, has been developed and proposed in the new concept. The accurate correction is based on the subdivision of the area around the measurement point to four zones with increasing radius. Each zone has a specific weight following its distance from the observed gravity station. On the one hand this is achieved by using two DTMs with different resolutions. The high resolution DTM is used for the innermost zone, while for the other three zones, sensitivity analyses show that lower resolution DTMs are sufficient. While the cell size in the innermost zone can be < 5x5 m, in the outermost zone the cell size is enlarged to about 1x1 km.The computed topography effect using this approach is comparable to the plateau and topography effect assessed by the old approach, but computed in the same run and without using plateau assumption. The final computed Bouguer anomaly is improved compared to that obtained using the classical approach. Its accuracy is higher and the improvements are clearly visible in the area of high topography gradient.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-455

Geoid of Saudi Arabia (KSA GEOID) from surface and satellite altimetry gravity

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General Commission for Geodesy (GCS) is mandated to provide an accurate KSA Geoid in the kingdom. Land gravity points of 446488 from ARAMCO covering the eastern kingdom and 169180 marine ship-borne gravity points over Arabian Gulf and Red Sea from NOAA/NGDC and ARAMCO are obtained. Free gravity anomalies in IGSN71 referring to GRS80 ellipsoid are computed at those points. DTU13 satellite altimetry gravity anomalies on a 0.05x0.05 degree over Red Sea and Arabian Gulf are extracted from DTU13 global solution. The ship-borne data are checked against both DTU13 gravity and GOCE Earth Geopotantial Model (EGM) (go_cons_gcf_2_dir_r5). These consistent data sets are used in the KSA geoid computation by a remove-restore technique. A composite EGM model of GOCE and EGM08 up to degree 720 is used for the EGM effects. The RTM effects are computed based on the SRTM30 DTM. Mean of the reduced anomalies is -1 mGal for land, -1 mGal and -2.8 mGal over Arabian Gulf and Red Sea, respectively, whereas -0.4 mGal for DTU13 anomalies. Spherical FFT with optimized kernels is used for the gravimetric geoid from residual anomalies interpolated on a grid. Restoring EGM and RTM effects to the geoid reveals the gravimetric KSA Geoid on a grid of 2x2 km resolution. The KSA Geoid, fitted to 286 GPS/BMs, reveals differences of about 80 cm increasing from Red Sea to Arabian Gulf maybe caused by systematic effects in the level network originated to Jeddah MSL on Red Sea, and uncertainty of ± 9 cm.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-456

Introduction to gravity calibration baseline between Jeddah and Taif in Saudi Arabia

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Relative gravimeters are calibrated properly before performing a geodetic survey and regularly when used to over extended periods of time for calibration constant(s) relating observable units to µGal. The calibration correction factor(s) with respect to the instrument calibration constant(s) are constrained by calibration baseline measurements where large known differences in gravity are compared to those measured by the relative gravimeters. Jeddah and Taif sites, installed in 2013 by FG5(#111) and A10(#029) absolute gravity measurements, has gravity difference of about 431000 µGal within short horizontal distance of about 200 km. Between these two sites 12 new sites were installed and measured by two A10X(#021, #023) absolute and four CG5 relative gravimeters from December 21014 to January 2015. At each site, absolute gravity, gravity gradient and gravity differences between the sites are observed. Recently developed A10X(s) provide set scatter of less than 3 µGal and total uncertainty ±6 µGal. Absolute gravity by two A10Xs at the same site differs in +/- 6 µGal. A10X and CG5 measured gravity differences between sites, vary from 3865 µGal to 63278 µGal, are coincident in +/- 10 µGal. Sum of CG5 gravity differences between sites differs 2.81 µGal from the end sites gravity difference by FG5 whereas it is -3.64 µGal for the sum of A10X differences. Furthermore the sum of gravity differences by A10X and CG5 differ 6.45 µGal. These preliminary results indicate appropriateness of the Jeddah Taif calibration baseline for calibration of relative gravimeters available in the market.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-457

Domain transformation and the iteration solution of boundary value problems in gravity field studies

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In this paper, when treating boundary value problems in gravity field studies, the geometry of the physical surface of the Earth is seen in relation to the structure of the Laplace operator. This approach may be applied to classical problems as well as to combinations of terrestrial and satellite data. Similarly as in other branches of engineering and mathematical physics a transformation of coordinates is used that offers a possibility to solve an alternative between the boundary complexity and the complexity of the coefficients of the partial differential equation governing the solution. For instance the Laplace operator has a relatively simple structure in terms of spherical or ellipsoidal coordinates which are frequently used in geodesy. However, the physical surface of the Earth substantially differs from a sphere or an oblate ellipsoid of revolution, even if these are optimally fitted. The situation may be more convenient in a system of general curvilinear coordinates such that the physical surface of the Earth is imbedded in the family of coordinate surfaces. The structure of the Laplace operator, however, is more complicated in this case and in a sense it represents the topography of the physical surface of the Earth. The Green's function method together with the method of successive approximations is used for the solution of geodetic boundary value problems expressed in terms of new coordinates. The structure of iteration steps is analysed and if useful, it is modified by means of the integration by parts. Subsequently, the individual steps are discussed and interpreted.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-458

Spectral improvements of recent GOCE GGMs through spatial selective filtering using wavelet-based multi-resolution approximation

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The gravity-field dedicated satellite mission of GOCE offered a wealth of data towards improved representation of the Earth's gravity field, especially in the medium band of the spectrum. The spectral and spatial correlation of the available GOCE/GRACE data can be thoroughly investigated using Wavelets (WL) as a multi resolution analysis (MRA) tool. In this work we focus on the improvement of the spectral behavior of low resolution GOCE global geopotential models (GGMs) targeting the shortest resolvable wavelengths of their spectrum, i.e., at the limits of GOCE measurement waveband at d/o ~220-260. At these spatial scales, the gravity field signal derived by GOCE is usually contaminated by noise. Therefore, spatial selective filtering using WL-based MRA is carried out at the first levels of WL decomposition in order a) to retrieve as much as possible of the useful GOCE signal, especially from the low-orbit GOCE data, and b) remove the inherent noise in the GOCE GGMs at the highest d/o of the GGM expansion. This process results in the improvement of the spectral behavior at the higher bands of the spectrum. The GGMs evaluated refer to the latest releases of GOCE GGMs, DIR-R5, TIM-R5m SPW-R4 and GOCO03s, while EGM2008 is used as reference. Moreover an investigation of the coherence and the correlation between the GOCE GGMs and land topography is carried out, the latter being represented by the latest SRTM digital terrain model. The estimation of the power spectral density for each spatial scale is used in order to detect the noisy GOCE wavebands, which are then filtered by selecting filtering. Finally, correlation and coherence between the filtered GOCE levels and SRTM also takes place, to quantify the improvement, compared to EGM2008, brought by the filtering process.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-459

Absolute gravity measurements in Canary Islands

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Canary Islands (Spain) are located at east of the African continent, just off the southwest coast of Morocco. Its volcanic origin and evolution make them crux of countless studies in the field of geodesy and geophysics. Several of these studies entail the need of knowledge of the gravity field among other issues.

Traditionally, the absolute gravity reference for these islands was located at Gran Canaria, belonging to The International Gravity Standardization Net 1971 (IGNS71). Subsequent connections to the rest of the islands where developed later by the Spanish National Geographic Institute (IGN) as part of its National Gravity Base Net (RGFE73). These values were obtained through connections performed with relative gravimeters. An absolute gravity value was obtained using an IMGC absolute gravimeter model in 1995 at Las Mesas Observatory (Santa Cruz de Tenerife) but it has been only used for the very precise leveling network.

Here, we present the new set of absolute gravity measurements obtained during 2014 with the absolute gravimeter A10 # 006 (10 μGal) in all the islands. These data will expand the information provided by the geodetic and geophysical networks that IGN and other Institutions have already deployed on the islands. Moreover, it will be used to complement the study and monitoring of volcanic activity in the area, ground deformations and even tectonic movements

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-460

"Regional gravity field exploration with self-reliant approach"

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During the last decades considerable improvement of global Earth gravity field models has been achieved due to successful satellite gravity field exploration missions. That allows us to improve control for local gravity data coverage and sequential applications for surveying and height determination, geophysical exploration and determination of crustal structures.

Nevertheless there is a technical progress in the classical determination of deflection of vertical (DoV) due to electronic sensor production and corresponding methodology. There are available modern digital zenith cameras with measurement accuracy up to 0.1 arc sec. It is an independent and alternative technique for gravity field exploration in especially recognized study areas.

In our case, as an eligible test field is used territory of Latvia due to implementation of new height system for updated EVRS realization and introduction of new geoid model. In this transition, we recognize very local pikes in comparison to global geopotential models in the range up to 50 cm. Also for localization of geological structures, a precise gravity data can be successfully used. For example, to define more exactly borders of old ancient meteorite impact crater near city Dobele or in the Gulf of Riga. There are different practical approaches that can be named where similar research work is necessary in chosen study areas.

Our work is carried out to demonstrate results from regional gravity field research with global Earth gravity field models, regional geoid models, DoV measurements and available geophysical data for theoretical and practical implementations.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-461

Feasibility and performance assessment of a new gravitational gradiometer for airborne surveys

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During the past decade, satellite missions such as GRACE and GOCE have considerably improved global gravitational field models. Albeit these models have been beneficial to various fields of geosciences, their accuracy at wavelengths shorter than 100 km is not sufficient to address many geodetic and geophysical questions. To overcome this limitation and access the short wavelengths of the gravitational field, the development of new sensors is crucial. In this respect, gravitational gradiometry is particularly appropriate as it enables to amplify the high-frequencies of the gravitational field spectrum.

Here, we put forward and analyze the adaptation to airborne conditions of electrostatic technologies developed at ONERA for space accelerometers. GREMLIT is a gradiometer concept specially designed for this purpose. The sensor is composed of an assembly of 4 planar electrostatic accelerometers which enables together with gyrometer data to measure the 3 horizontal gradients: V_{xx}, V_{xy} and V_{yy}. After an overview of its operational principle and main components, a detailed error budget on the final gravitational gradients is given. This error budget is based on the results of an end-to-end numerical simulation of a survey performed with GREMLIT under realistic airborne conditions. We show that after a calibration of the gyrometer's bias, it is possible to reach a precision below 2 E in the measurement frame of reference and in the local geodetic frame after, in the latter case, an along-track Gaussian filtering.

Finally, we briefly examine and discuss how the electrostatic accelerometer measurements can be enhanced thanks to the complementary use of laser interferometry, as a first step towards optical gradiometry.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-462

Absolute gravimetry in Greenland – a study on the tidal corrections.

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In connection with the absolute gravity measurements conducted in Greenland by DTU Space with their A10 absolute gravimeter (the A10-019), it has become evident that care must be taken when the tidal correction is applied to the data.

Long measurements (up to 48 hours) conducted in Greenland reveals that the standard models, e.g. Schwiderski and FES2004 which are built-in the commercial g8-software, leaves a residual signal after the tidal correction.

For long measurements this residual will average out, but in situations where only a short time period is available for the measurement, this residual could lead to erroneous results.

Here is presented the result of using other tidal models, e.g. DTU10, in the correction of absolute gravity data collected in Greenland. This study is of importance for the geodynamic studies in Greenland where absolute gravimetry is used, but could be of interest for all who is conducting gravity measurements in the Arctic region.

IAG (Geodesy)

G02p - G02 Static Gravity Field Models and Observations

G02p-475

Assessment of high-resolution digital terrain models in Turkey

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Digital Terrain Model (DTM) provides information on elevations of the bare ground except the upper surface of the landscapes. DTMs are important data sources for a range of applications in Geodesy science, as in gravity-field modeling. The released data set of the space-borne missions, such as SRTM (Shuttle Radar Topography Mission) and ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer) provided significant advances in global elevation modeling. In this study, a number of globally distributed high-resolution DTMs (e.g. SRTM (3 arc second), ASTER (1 arc second) and ACE2 (3 arc second) etc.), are assessed against the GNSS heights with EGM08 data and heights from regional vertical datum at control benchmarks in Turkey. They are tested using homogeneously distributed control data over Turkey and also at the locally distributed denser control data in smaller areas. The validations concerns clarifying the accuracies of the models as well as inspecting their possible systematic shifts among the models and regional data.
With this purpose, beside the comparison of heights at the control benchmarks, the statistical assessments of the selected DTMs include the slope and Gauss-bell comparisons as well. The correlations among the models and regional heights are mapped using the spatial and spectral analyses tools, such as FFT and Wavelet approaches. Hence a complete analyses of the elevation data are done in terms of spatial and spectral point of view as well. This investigation results specifically contributes the on-going investigation for regional gravity field determination and precise geoid modeling using hybrid data in Turkey. The conclusions includes the numerical results on their use in gravity field modeling.

IAG (Geodesy)

G03a - G03 Variations of the Gravity Field

IUGG-1366

A regularized sliding window time-variable gravity field from GRACE

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The Gravity Recovery and Climate Experiment (GRACE) mission has provided an unprecedented global, homogeneous observational dataset of the time variation in terrestrial water storage since 2002. The data product has evolved over this timeline, and it is now possible to produce daily, regularized fields that resolve higher frequency signals and more accurately capture the location and magnitude of time-variation in terrestrial water storage. The typical GRACE product uses approximately thirty equally weighted days of data to estimate a monthly mean gravity field with 300+ km resolution. Each regularized sliding window gravity field is composed of twenty-one days of observations differentially weighted to optimize the frequency retention while ensuring sufficient observability for a global solution. Tikonov regularization informed by RL05 error is applied in the estimation process to increase the amplitude and localization of signal retention. The effectiveness of these products will be assessed through comparison with high resolution and high fidelity models, independent in-situ datasets, and assimilation into land surface models.

IAG (Geodesy)

G03a - G03 Variations of the Gravity Field

IUGG-1588

Improved methods for estimating Earth's time variable gravity from GRACE using Bayesian constraints and surface spherical cap mascons

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The majority of the GRACE gravity solutions released to date have been obtained by fitting the data to spherical harmonic basis functions without apriori-conditioning of the solution. The resultant products are contaminated with longitudinal stripes, which are typically removed via empirical post-processing filters. JPL has developed a new solution strategy using spherical cap mass concentration blocks ('mascons') as the basis function and variance information derived from geophysical models to place realistic constraints on the solution. These solutions are therefore more "optimally" destriped than purely empirical posteriori filters. We compare the conditioned JPL RL05M mascon solution to RL05 spherical harmonic solutions and summarize key global mass flux results for cryosphere, hydrology, and ocean applications. Several advantages of using the mascon solutions over harmonics are discussed. We additionally discuss optional post-processing techniques which can be applied to the mascon solution, including regional scaling as well as a Coastline Resolution Improvement (CRI) filter which is used to distinguish between land and ocean mass variations within mascons that span coastlines.

IAG (Geodesy)

G03a - G03 Variations of the Gravity Field

IUGG-2356

GRACE mascon solutions: Validation and applications to hydrology, glaciers and earthquakes

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The GRACE mission is providing insight into mass redistribution in the solid earth, hydrology and cryosphere. However, numerical results from different processing strategies lead to inferences that differ particularly with respect to the spatial resolution. In this study we compare mass change derived from mascons, spherical harmonics and spherical cap harmonics (with and without forward modelling) based on the same geophysical and geodynamic models using simulated data and GRACE level 1b data (k-band range rates, accelerometer and attitude data, GNV1B orbits). The results confirm the efficiency of the mascon approach and demonstrate its advantage over spherical harmonics for separating basin-scale effects. Utilising the mascon solution derived at Newcastle we investigate geophysical inferences from the GRACE mission. GRACE results for Jan 2003-Dec 2013 will be presented for change in glacial mass (e.g. Alaska), hydrological applications in river basins (e.g. Amazon and Indus), terrestrial water storage over Africa and the effect of earth deformation observed in the vicinity of major earthquakes.

IAG (Geodesy)

G03a - G03 Variations of the Gravity Field

IUGG-3084

The GRACE Mission status and future directions

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The Gravity Recovery and Climate Experiment (GRACE) satellites were launched on March 17, 2002 and have operated continuously for over 15 years. The results from this mission are used in a wide range of contemporary studies of Earth System Dynamics. The mission objectives are to sense the spatial and temporal variations of the Earth's mass through its effects on the gravity field at the GRACE satellite altitude. The mission objectives are to measure: 1) the Earth's time-averaged gravity field over the mission life and 2) the monthly variations in the mean gravity field at wave lengths between 300 and 4000 km. The major cause of the time varying mass is water motion and the GRACE mission has provided a continuous decade long measurement sequences which characterizes the seasonal cycle of mass transport between the oceans, land, cryosphere and atmosphere; its inter-annual variability; and the climate driven secular, or long period, mass transport signals. Measurements of continental aquifer mass change, polar ice mass change and ocean bottom currents are examples of paradigm shifting remote sensing observations enabled by the GRACE measurements. In 2012, a complete reanalysis of the mission data, referred to as the RL05 data release, was initiated. The monthly solutions from this effort were released in mid-2013 and have been applied in numerous science and application related investigations. The RL05 mean and combined models, involving the GRACE/GOCE data combinations, are still in development. This presentation will review some of the science improvements from the RL05 data and the remaining tasks to be conducted in completing the solution, describe the current mission status and the current operations, which are focused on extending enhance the mission lifetime.

IAG (Geodesy)

G03a - G03 Variations of the Gravity Field

IUGG-3287

Improved GRACE preprocessing methodologies: Impact on monthly gravity field solutions

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The GRACE (Gravity Recovery and Climate Experiment) satellite mission provides K-band ranging (KBR) measurements between the two twin satellites GRACE-A and GRACE-B for the purpose of gravity field recovery. Although the accuracy of gravity field solutions has increased during the last years, there still remains an offset between the present error level and the predicted GRACE baseline accuracy. Therefore, efforts are ongoing identify the remaining error sources.

Potential contributors to the error budget are both unmodeled errors within the Level-1B data products related to the alignment and outliers within the GRACE observations.
As the precise inter-satellite pointing is one of the essential requirements for the KBR ranging, we combine both angular accelerometer and star camera data (ACC1B, SCA1B) in a least squares approach to improve the satellites' attitude determination. As a result, the high frequent noise of the attitude data is decreased significantly.
In order to benefit from the improvements on the sensor data level, other error sources and disturbances within the GRACE observations have to be identified. Based on these results, we show that improved preprocessing methodologies (sensor fusion, data screening & gap filling) contribute substantially to the overall accuracy of the recovered monthly gravity field solutions.
For some dedicated month the achieved improvements are validated against previous solutions and the official GRACE Level-2 products.

The purpose of the presented work is to understand and reduce the impact of possible error sources on the GRACE gravity field recovery. Proper understanding of the science data is essential not only for increasing the accuracy but also for the development of future gravity field missions.

IAG (Geodesy)

G03a - G03 Variations of the Gravity Field

IUGG-4896

Time-variable gravity field from SLR and combined GRACE-SLR solutions

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GRACE satellites provide substantial information about the temporal variability of the gravity field at long to medium wavelengths describing the mass transport in the system Earth. The GRACE solutions suffer, however, from the poor determination of the Earth's oblateness from GRACE K-Band data, due to the aliasing with the S2 tide. On the other hand, the Earth's oblateness and its temporal variability can be very well determined using the Satellite Laser Ranges (SLR) to spherical geodetic satellites, e.g., LAGEOS, Starlette, Stella, Ajisai, and LARES. We perform a combination of GRACE and SLR solutions at the normal equation level using the SLR monthly gravity fields from the combined analysis of up to 9 SLR geodetic satellites. A reduction of the influence of the S2 tide alias on some GRACE-derived coefficients by using a combination with SLR data will be addressed.

Over the past years, the K-Band tracking between GRACE-A/B satellites was deactivated several times, which caused gaps in the series of GRACE monthly gravity field solutions. The GRACE on-board GPS receivers were, however, active almost continuously and they provided uninterrupted observations. We investigate whether the combined SLR+GRACE GPS-only solutions can fill the gaps of monthly series of gravity field models for the months with none or sparse K-Band observations. Finally, we discuss the temporal variability of the SLR-derived Earth's gravity field for 1995-2014, thus including the period prior to the GRACE launch. The changes of the trends for selected regions, e.g., Antarctica and Greenland will particularly be addressed.

IAG (Geodesy)

G03b - G03 Variations of the Gravity Field

IUGG-1207

A comparison of seasonal and inter-annual crustal displacements from GPS and GRACE observations over Northern Indian region

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We present a comparison of crustal displacement derived from seventeen GPS observations and computed from GRACE mass signal over northern Indian region with focus to identify influence of continental hydrological signal present in the GPS data. We find that seasonal vertical deformations are in the order of 3.5-4 cm in the north eastern part of India and it is less (~ 1 cm) in the Laddakh, north western India. It is remarkable that seasonal crustal deformation measured from GPS is consistent with crustal deformation derived from GRACE data at almost all the observation locations. The GPS observations are recorded over different time periods during 2002 to 2010. Considering the uniformity in two data sets and continuous long GRACE data; time series of crustal deformation obtained from GRACE observations is utilized to find inter-annual variability in the vertical crustal deformation at GPS observation locations. The tectonic implication of the crustal displacement due to hydrological loading in the northern India had been explained in the terms of seasonal seismicity behaviour in the Himalayan region. In this study, we extend the spatial pattern of seasonal and inter-annual crustal displacement over a board region of northern India and discuss tectonic implications of them.

IAG (Geodesy)

G03b - G03 Variations of the Gravity Field

IUGG-1886

Small-scale hydrological signals: In-orbit validation by GRACE level 1B observations

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Here, GRACE level 1B observations and output from high-resolution hydrological models are used in order to compute K-band range rate (KBRR) residuals. The presented approach avoids the downward continuation and filtering process required for computing monthly gravity field solutions and, thus, enables to assess model-derived water storage variations with a high temporal resolution and at small spatial scales.

In a first step, KBRR observations are simulated from modeled water mass variations. Secondly, those simulated observations and a number of geophysical corrections are reduced from the original GRACE K-band observations to obtain the residuals. Smaller residuals imply that the model is able to better explain the observations.

In this study, a set of global to regional scale hydrological models are assessed including the high-resolution Community Land Model CLM3.5 over the European CORDEX domain and models dedicated to the estimation of groundwater storage variations. Key points are the analysis of hydrological signals occurring at time scales below one month and the interpretation of the residuals produced by storage changes in small scale (~100 km) groundwater systems.

Daily information from global hydrological models reduce the residuals with respect to monthly model output further by about 0.7% considering only the continents. As a reference: the application of AOD-RL05 leads to a reduction of 1.1% with respect to AOD-RL04. Over Europe, still a reduction of 0.2% is

obtained when daily CLM3.5 output instead of monthly output is used for the computation of the residuals.

In summary, the evaluation of KBRR residuals gives evidence about the sensitivity of GRACE KBRR measurements and provides detailed information about the model quality at different time scales.

IAG (Geodesy)

G03b - G03 Variations of the Gravity Field

IUGG-2386

Orbit and Gravity Field Solutions from Swarm GPS Observations

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Although ESA's Earth Explorer Mission Swarm is primarily dedicated to measure the Earth's magnetic field, it may also serve as a gravity field mission. Equipped with GPS receivers, accelerometers, star-tracker assemblies and laser retro-reflectors, the three Swarm satellites are capable to be used as a high-low satellite-to-satellite tracking (hl-SST) observing system, following the missions CHAMP (first single-satellite hl-SST mission), GRACE (twin-satellite mission with additional ultra-precise low-low SST and GOCE (single-satellite mission additionally equipped with a gradiometer). GRACE, dedicated to measure the time-variability of the gravity field, is the only mission still in orbit, but its lifetime will likely end before launch of its follow-on mission GRACE-FO in August 2017 primarily due to aging of the onboard batteries after meanwhile more than 12 years of operation. Swarm is therefore a good candidate to provide time-variable gravity field solutions and to close a potential gap between GRACE and GRACE-FO. The properties of the Swarm constellation are raising expectations at least compared to CHAMP derived time-variable gravity field solutions.

We assess the quality of more than one year of Level 1b data (excluding accelerometer data) for Swarm orbit determination and subsequent recovery of the Earth's gravity field. Special emphasis is made to further investigate and eliminate systematic errors affecting the gravity field solutions along the Earth's geomagnetic equator, as well as to assess the potential of Swarm to recover time-variable signals of the Earth's gravity field. The presented gravity field solutions are also compared to GRACE GPS hl-SST solutions based on the same amount of data and processing methods.

IAG (Geodesy)

G03b - G03 Variations of the Gravity Field

IUGG-2433

A high resolution map of linear trends in mass re-distribution from DMT-2: computation and evaluation

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We present a new high resolution model of linear trends in mass re-distribution (Delft Mass Transport model, DMT-2). It has been computed primarily from K-Band Ranging (KBR) data of the Gravity Recovery And Climate Experiment (GRACE) satellite mission. It consists of a time series of monthly solutions complete to degree 120. The degree-1 coefficients in the solutions are restored by the means of a modified procedure of Swenson et al. (2008). A unique feature of the designed methodology is the computation and usage of an accurate stochastic description of data noise using monthly auto-regressive moving average (ARMA) models. The unconstrained monthly solutions are used to estimate a trend function comprising linear, annual and semi-annual terms. The linear term is further processed with an anisotropic Wiener filter, which is based on estimates of the signal and noise covariance matrices. Given the fact that noise in the corresponding unconstrained model is reduced substantially as compared to a monthly solution, the Wiener filter associated with the trend is much less aggressive than the monthly Wiener filters. Consequently, the estimated linear trend has an enhanced spatial resolution. For instance, the computed trend model allows signals in relatively small lakes, such as Aral sea, lake Victoria, and lake Ladoga, to be detected clearly. Over the ice sheets, it allows for a clear distinction between signals associated with different glaciers. We also compute alternative models of the linear trends from commonly used monthly models and their noise covariance matrices. The quality of all models is assessed using independent satellite data.

IAG (Geodesy)

G03b - G03 Variations of the Gravity Field

IUGG-2501

Validation of GRACE time-variable gravity field by ICESat, GPS, WGHM and altimetry satellites orbits

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Since 2002 the Gravity Recovery And Climate Experiment (GRACE) mission has been measuring temporal variations of Earth's gravity field with unprecedented accuracy. The data provides valuable information on the distribution and variation of mass in the Earth's subsystems such as atmosphere, hydrosphere, ocean and cryosphere.

The current GRACE time-series of monthly gravity field spherical harmonic solutions generated at GFZ (RL05a) show significantly less noise and spurious artifacts compared to its predecessor. In addition, a regional method based on radial base functions is capable to compute models in regional and global representation. The present study makes use of both solutions in order to quantify recent ice-mass changes and their contribution to global sea-level rise. We further compare the ice-induced crustal deformation due to the dynamic (un-)loading of the crustal layer with GPS uplift measurements along Greenland's coastline. Mass/Volume changes derived from ICESat laser altimetry measurements both in Greenland and Antarctica are used to validate the GRACE results. A direct comparison with hydrological modeling for various basin extensions reveals overall high correlation to surface and groundwater in all compartments. The forward computation of satellite orbits for altimetry satellites such as ERS-2, TOPEX/Poseidon, Envisat and Jason compares the performance of GRACE time variable gravity fields with models including time variability, such as EIGEN-6S2.

IAG (Geodesy)

G03b - G03 Variations of the Gravity Field

IUGG-3013

Establishment of the International Geodynamics and Earth Tide Service (IGETS)

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We propose the establishment of a new IAG/IGFS service to monitor temporal variations of the Earth gravity field and deformation through long-term records from ground instruments such as gravimeters, tiltmeters or strainmeters.

IGETS' primary dataset is highly stable and precise gravity variations recorded by superconducting gravimeters. This new service will not only replace, but also continue and improve the running Global Geodynamics Project (GGP), which was established in July 1997. The main products to be generated by IGETS and hosted by its database are:

- Raw gravity and local pressure sampled at 1 or 2 seconds, and also decimated at 1 minute
- Gravity and pressure series, both corrected for instrumental perturbations, ready for tidal analyses
- Gravity residuals after geophysical corrections, including polar motion, solid Earth tides, tidal and non-tidal loading effects.

IGETS also acts as the main data center for long term series recorder from other geodynamic sensors, including the historical dataset from the ICET database. IGETS will continue the tradition of ICET and GGP by providing appropriate software for those wishing to do their own analysis.

We present here in details the different products of this new IAG/IGFS service, and its permanent components, especially the different analysis centers computing the different time series. In particular, the University of Polynesia (Tahiti, France) is in charge of producing corrected gravity series; EOST (Strasbourg, France) will produce the final gravity residuals, with the help of loading models computed by BKG (Germany) and EOST; the SG database is still hosted by ISDC at GFZ in Potsdam. BKG will also include Absolute Gravity data at the various stations for the determination of SG instrument drift, where available.

IAG (Geodesy)

G03c - G03 Variations of the Gravity Field

IUGG-0825

Land-ocean leakage effects on Glacier melting estimation in Antarctica from GRACE measurements

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The Gravity Recovery and Climate Experiment (GRACE) can provide high-precision time-varying gravity field and the changes of Earth's surface mass, e.g., glacier melting in Antarctica. However, one of larger errors in GRACE measurements, land-ocean leakage error, affects high accuracy retrieval of glacier mass loss along the coasts in Antarctica. The land signals will contaminate the ocean signals with significant signal attenuation, particularly the glacier-ocean leakage errors along the coasts. In this paper, land-ocean leakage errors on glacier melting in Antarctica from GRACE measurements are investigated using the forward gravity modeling. The significant effects of land-ocean leakage on glacier mass loss are found in Antarctica using time-varying GRACE gravity field with the period from January 2003 to February 2013 (about 10 years), and the forward gravity modeling will greatly reduce the land-ocean leakage errors.

IAG (Geodesy)

G03c - G03 Variations of the Gravity Field

IUGG-2050

Comparison of Antarctic basin scale mass change from GRACE/GOCE and CryoSat-2

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When data of the GRACE satellite gravity mission are combined with those of the satellite gravity gradiometer mission GOCE, it can be shown that trends in ice mass balance can be resolved at basin scale for the Amundsen Sea Sector in West Antarctica. We will extend our analysis to the complete Antarctic continent, paying special attention to unavoidable leakage effects between basins, and glacial isotactic adjustment and its uncertainty. In addition, it is known that the gravitational flattening coefficient is better determined from satellite laser ranging (SLR) than from GRACE. The GRACE C20 coefficients are therefore routinely replaced by those from SLR. We will show that an alternative SLR time series, using tracking data to more satellites, may give ice mass trend differences of 10 – 15 Gt/yr (in the order of 13% of the total signal) compared with the commonly applied SLR time series. With data of the CryoSat-2 radar altimeter mission Antarctic ice sheet elevation changes can be determined, which can be converted to mass changes. GRACE/GOCE and CryoSat-2 ice mass trends will be compared and the possible cause of differences will be discussed.

IAG (Geodesy)

G03c - G03 Variations of the Gravity Field

IUGG-3206

A global assessment of accelerations in surface mass transport

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The almost 13-year continuous operation of GRACE mission provides unprecedented global measurements of surface mass transport with high accuracy and resolution. Accurate assessments of global mass transport pattern and budget also depend critically on changes in degree-1 coefficients (geocenter motion) and in Earth's dynamic oblateness coefficient J_2. We combine GRACE measurements with time series of GPS data and JPL's ECCO ocean bottom pressure model to invert for the degree-1 coefficients and J_2. These are then compared with the SLR results. During the GRACE data period, no significant acceleration in measured geocenter motion is found. After correcting for coseismic and postseismic effects, the inverted J_2 also compares very favorably with that of SLR having barely significant acceleration during this period. These have motivated us to re-examine mass accelerations in both spherical harmonic and global geographic domains. Time series of these coefficients and GRACE measured spherical harmonic coefficients up to degree/order 60 and their calibrated full covariance matrices are used to estimate linear, annual, semiannual and acceleration components. Global mass acceleration pattern and time variation budgets for major geographical regions are derived using a priori multi-regional covariance functions up to degree/order 180 in addition to the estimated spherical harmonic accelerations or time series. A significant positive acceleration in mass balance is found for Alaska in addition to the accelerated mass losses of Greenland and West Antarctica. The fidelity of acceleration determination and uncertainty assessment including the appropriateness of a priori information is further evaluated by residual statistics and variance component estimation.

IAG (Geodesy)

G03c - G03 Variations of the Gravity Field

IUGG-4495

Advanced analysis of mass balance of the Greenland Ice Sheet from GRACE and surface mass balance modelling

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One of the primary objectives of the Gravity Recovery And Climate Experiment (GRACE) satellite mission is monitoring the state of ice sheets. A major limiting factor of GRACE data is their coarse spatial resolution, which may lead to substantial inaccuracies due to signal leakage. An efficient way to suppress it was developed by Forsberg & Reeh (2007) and Baur & Sneeuw (2011), who proposed a variant of mascon approach for that purpose. We have developed that methodology further by including the full covariance matrices of noise in GRACE level-2 solutions in order to produce statistically-optimal estimates of mass variations. Furthermore, we demonstrated the importance of keeping the exploited functional model spectrally consistent with GRACE level-2 data products. In addition, we studied the impact of various regularization matrices on the solutions. Numerical experiment showed that the proposed modifications lead to noticeable improvement of the obtained results. We applied this advanced methodology to analyze inter-annual and intra-annual variations of the mass balance of Greenland Ice Sheet (GrIS) at a regional scale using GRACE CSR RL05 data. We have compared our results with Surface Mass Balance (SMB) estimates based on the Regional Atmospheric Climate Model (RACMO2) for different GrIS regions. A good agreement of the estimates in the regions where land-terminating glaciers dominate confirms a high quality of estimates of both types. The largest differences between SMB- and GRACE-based estimates are observed at the South-East coast, particularly for Kangerdlugssuaq and Helheim Glaciers, which confirms a crucial role of ice discharge there. A further analysis allows better understanding of the factors controlling GrIS mass variations in different part of GrIS.

IAG (Geodesy)

G03c - G03 Variations of the Gravity Field

IUGG-4542

Glacier mass variations via filtered and leakage-reduced GRACE solutions evaluated by in-situ data in the Canadian Arctic

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Satellite gravimetry from GRACE is an indispensable global remote sensing tool for monitoring the Earth's mass redistribution. However, due to the orbit geometry of GRACE's twin-satellites, noise is produced, which manifests itself as long, linear features, generally oriented from north to south, known as 'stripes', implying a high degree of correlation in the gravity field coefficients. A series of different filtering methods are compared and presented in order to reduce/remove the spatial noise from the data.

When recovering ice mass changes from the total integrated-gravity signal from GRACE, the solutions are predominately affected by 'mass leakage' coming from the hydrological signal and the Global Isostatic Adjustment (GIA) uncertainty. Global hydrological models (GLDAS) and GIA models, the latter derived from finite-element spherical harmonic modelling of the ice history models ICE5G and ICE6G, were examined and subtracted from the filtered-GRACE solutions. Resultant GRACE-derived ice mass changes in Greenland and the Canadian Arctic were then evaluated against in-situ glaciological modelling.

Both seasonal and long-term mass change rates were estimated, covering the time period 01/2003-10/2014. The data used include 139 months of GFZ and CSR Release-05 GRACE time-variable gravity coefficients converted to mass changes and the time-respective simulated ice sheet mass changes based on an ice sheet model that is forced by daily reanalyzed climatology fields for this period.

Our results focus on how well the optimal filtered-GRACE data agree with regional glaciological estimates of the circum-Arctic region, and what the relation-interaction is with the ice sheet mass loss of Greenland.

IAG (Geodesy)

G03d - G03 Variations of the Gravity Field

IUGG-0466

Water storage changes and Climate variability in the Mekong River Basin

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Understanding basin-scale water storage variation and its connections to global climate change plays a key role in managing regional water resources. The Gravity Recovery and Climate Experiment (GRACE) satellite mission provides a unique opportunity to monitor global and regional terrestrial water storage (TWS) changes. In this study, we focus on the analysis of TWS change and climate variability in the Mekong River Basin. We employ the Principal Component Analysis (PCA) to extract statistically the time and space components of TWS changes derived from GRACE and hydrological models. Such extraction enables in-depth analysis of water storage changes in the study region and provides a tool for assessing the influence of climate variability caused by large-scale ocean–atmosphere interactions such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). Monthly precipitation from the Tropical Rainfall Measuring Mission (TRMM) over the Mekong basin is also analyzed by PCA. Our preliminary results indicate that both ENSO and IDO are dominant driving force affecting climate change and interannual TWS changes in the Mekong River Basin. For the study period from 2002 to 2012, there is a significant negative correlation between GRACE TWS changes and ENSO, and strong positive correlation between GRACE TWS changes and IDO. In addition, temporal and spatial patterns of GRACE TWS and TRMM precipitation changes agree well in the Mekong River Basin.

IAG (Geodesy)

G03d - G03 Variations of the Gravity Field

IUGG-1178

Gravity change during water impoundment to high water level in Three Gorges Reservoir

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In this paper, we use daily water level of the Three Gorges Reservoir and the regional topography data during pilot water impoundment to 175m water level in October of 2012 and 2014, to calculate the gravity change due to impoundment. The calculated values are compared with the measured gravity data around the Three Gorges Reservoir. The factors influencing gravity change in the reservoir area are analyzed. We find that water impoundment is the main factor causing the gravity change of the Three Gorges region. We are trying to calculate the variation of regional gravity field caused by water impoundment. The research results can provide a reference for the reservoir impoundment and the prevention of associated geological disaster in the Three Gorges Reservoir.

IAG (Geodesy)

G03d - G03 Variations of the Gravity Field

IUGG-1717

News from the local hydrological correction of the SG gravity record at Moxa

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Separation and correction of the local hydrological effect in the record of the superconducting gravimeter (SG) can enable the comparison with temporal gravity field changes at other terrestrial stations, from GRACE satellite mission, and with global hydrological models as well.

For reduction of the gravity time series of the GWR SG CD034 at the Geodynamic Observatory Moxa/Germany the improvement and prolongation of the modeling of the local hydrological effect is pursued. The local hydrology at Moxa observatory is affected by the valley of the small creek Silberleite with strong topography just above the gravimeter.

The way from the local hydrological modeling to the gravimetric 3D-model has already delivered a successful temporal correction model. The impact of the newly inserted nearest surrounding of the gravimeter including the geometry of the observatory building turn out to be of high importance. The ground water is now included, as well. The modeled seasonal hydrologic effect is about 30 - 40 nm/s² in normal years, reaching up to 70 nm/s² due to extreme snow layer. After reduction, the seasonal gravity variations around 30 - 40 nm/s² can bear comparison with global data and models over several years with improved analogy in amplitude and some details as well.

The challenge of the hydrological modeling still exists, especially in the short period range of days to weeks where the dynamic flow downhill is playing an obvious role, and for the more realistic modeling of snow melt. The gravity record is serving as boundary condition.

IAG (Geodesy)

G03d - G03 Variations of the Gravity Field

IUGG-3161

Modeling surface water variations from altimetry and remote sensing and comparison with GRACE

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Since its launch in 2002, the GRACE (Gravity Recovery And Climate Experiment) mission is recording the variations of the Earth's gravity field at unprecedented temporal (classically at 10 day to monthly samples) and spatial (a few hundreds of kilometers) resolutions, mainly due to the global circulation of surface geophysical fluids. Continental water storage variations estimated with GRACE are classically compared to global hydrology models such as GLDAS (Global Land Data Assimilation System) or MERRA (Modern Era-Retrospective Analysis) land. However most of these models do not take into account both the groundwater and the surface water (lakes and rivers) components of the hydrological cycle.

We derive surface water storage of several large rivers, characterized by various climates, using a simple routing scheme, forced by runoff outputs of GLDAS and MERRA-land hydrology models. We adjust the flow velocity, i.e. the only free parameter in our modeling by fitting the modeled equivalent water height to the observed water elevation from radar altimetry measurements. The conversion of the observed geometric heights into the modeled equivalent water heights requires the knowledge of the variations of the river widths, which can be derived from MODIS (Moderate Resolution Imaging Spectroradiometer) observations. We validate our river models by comparing the estimated discharge to independent in-situ measurements.

We finally add to the soil-moisture and snow components of the GLDAS and MERRA-land models our estimates of surface water variations and show that they are in better agreement with GRACE. We also compare these estimates to WGHM (WaterGap Hydrology Model), which includes both groundwater and surface components.

IAG (Geodesy)

G03d - G03 Variations of the Gravity Field

IUGG-3897

Is it possible to infer large scale hydrological variations using superconducting gravimeters?

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Owing to the high accuracy of superconducting gravimeters and the nature of the observed quantity, i.e. gravity on Earth, the acquired time series contain information about hydrological variations occurring far away from the actual point of observation. However, the gravity effect related to large scale variations is usually concealed by local hydrological phenomena. An effective separation of the total gravity effect, as observed by superconducting gravimeters, into a local and a large scale part might serve as a basis for the evaluation of global hydrological models. In the first part of this study, we analyse the separability of local and large scale effects using in situ hydro-meteorological parameters observed at two sites located around 160 km apart, namely Wettzell in Germany and Pecný in the Czech Republic. These observations are compared to the gravity residuals and various global hydrological models. The comparisons include statistical methods as well as physically based approaches. In the second part of this study, we investigate the implications of the gravimeter location on the detectability of large scale hydrological variations. This includes simulations for a single gravimeter as well as for a network of superconducting gravimeters. In the single gravimeter experiment, we study the potential of installing the superconducting gravimeter at a point of zero or minimum gravity effect when integrating over the local zone only. Subsequently, we evaluate the capability of an optimized network of superconducting gravimeters to observe and infer a common large scale hydrological signal.

IAG (Geodesy)

G03e - G03 Variations of the Gravity Field

IUGG-1715

Storm surge in the German Bight: Are they detectable as gravity fieldvariations at the Geodynamic Observatory in Thuringia, Germany?

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For 17 years the superconducting gravimeter SG CD-034 is operating at the Geodynamic Observatory Moxa in Thuringia, Germany. This instrument allows the detection of smallest gravity changes within the observable broad frequency band from the free modes of the Earth (from approx. three minutes) up to the Chandler Wobble (approx. 430 days). The well known gravity signals from the Earth tides reflect the excellent quality of the recorded data from our SG in Moxa.

Also the much smaller oceanic loading tides, which are dominated in Mid-Europe by the North-Atlantic and the North Sea, are significantly detectable in the SG time series. In addition to these contributions of gravity field changes, much smaller and non-periodic variations exist which can be caused by air masses or local up to global hydrological variations. The discussion about the measurability of very small signals leads to the question whether it is possible to observe and separate a unique storm surge in the German Bight also in the far away SG recording at Moxa observatory.

Of special importance are the necessary reductions of the barometric pressure effect and the local hydrological correction. The barometric pressure effect could be reduced by the application of a three-dimensional air-mass model of the surrounding atmosphere. In addition a local hydrological model was transferred into a time depending gravity model which allows a local hydrological reduction of the recorded time series. The careful correction of these influences in combination with an associated ocean load modeling leads to the conclusion, that the challenge of the separation of storm surge induced gravity effect is strongly connected to the reduction of environmental impacts.

IAG (Geodesy)

G03e - G03 Variations of the Gravity Field

IUGG-2301

Temporal variation of tidal parameters in superconducting gravimeter time series

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Analyzing independent 1 yr data sets of 10 European superconducting gravimeters (SG) reveals statistically significant temporal variations of M2 tidal parameters. Both common short-term (< 2 yr) and long-term (> 2 yr) features are identified in almost all SG time series. The averaged variations of the amplitude factor are about 0.2‰. They reflect either time variable loading processes or non-linear effects due to insufficient frequency resolution in tidal analyses. Presently, SG time series are still too short to separate tidal constituents which might produce modulation periods of 18.6 yr. The path of load vector variations equivalent to the temporal changes of tidal parameters suggests the presence of an 8.85 yr modulation while tidal analysis results do not show anomalous amplitude factors for tidal constituents having the potential to modulate M2 with this period. Whatever the variations are caused by, they indicate another upper accuracy limit for earth model validation based on gravity time series extending over a few years. The results are also useful for controlling the quality of the transfer function (scale factor, time lag) of involved SGs.

IAG (Geodesy)

G03e - G03 Variations of the Gravity Field

IUGG-2565

Gravity effects from non-tidal water mass changes in the Baltic Sea

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For a better observation of the gravitational effect of the mass transport due to glacial isostatic adjustment (GIA) in Fennoscandia, this signal needs to be separated from all other mass variations like non-tidal water mass changes, atmospheric and hydrologic effects. The separation is usually achieved by modelling the above mentioned mass changes. The unpredictable behavior of water mass changes in the Baltic Sea over longer time periods makes an entirely mathematical description not possible. Instead, observations or observation-driven models are used to calculate the direct attraction of the masses and the effect of the load deformation on gravity. The calculation of these effects is carried out by convolution of point-masses with Green's functions. For this study, the effect on gravity from non-tidal mass changes in the Baltic Sea is investigated for different gravity observation stations in the Fennoscandian GIA area. The objective is to determine the requirements for data describing the mass variations in the Baltic Sea, like water heights and water density, with respect to spatial and temporal resolution. Also information used in the transformation from the loading mass into point-masses is considered. In addition, data sources are evaluated for their suitability in the mass load calculation. For water heights, the CoastDat2 dataset is used. Provided by the Helmholz Zentrum Geesthacht, it is available in 12 km spatial and one hour temporal resolution. The World Ocean Atlas 2013 supplies the sea surface temperature and salinity, from which the water density is calculated. Here, the spatial resolution is 0.25 degree and the temporal is one month.

IAG (Geodesy)

G03e - G03 Variations of the Gravity Field

IUGG-2872

Swedish repeated absolute gravity observations in the Fennoscandian land uplift region

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In Fennoscandia evidences of glacial isostatic adjustment (GIA) are well-known. They have been observed and studied for centuries. During the last decades relative sea level observations and repeated levelling campaigns have been complemented with GNSS observations in an extensive network of permanent reference stations (BIFROST). GIA-induced gravity change has been studied in terms of repeated relative gravity campaigns since the sixties. During the last decades they have been superseded by an ambitious effort to observe the gravity change by repeated absolute gravity measurements.

We present the first results from the Swedish (Lantmäteriet's) absolute gravimeter FG5-233. It has been operational since 2006 and has performed ~80 repeated observations on 13 Swedish stations. We describe the method used and analyse the data. Values of the rate of change of gravity are derived from observations and compared with the observed uplift rate.

The relation between the gravity rate of change and vertical uplift rate contribute with information on the underlying geophysics. A trustworthy relation is also important for combining geodetic observations of both to strengthen the overall observational accuracy of the whole phenomenon. We compare the observed relation with a GIA model for a 1D spherical Maxwell earth and discuss the results.

Experience from some instrument specific (FG5) issues, of general interest for other users of this kind of instrument, e.g. offsets between different instruments and within time series from a specific instrument (FG5-233), are also highlighted and discussed.

IAG (Geodesy)

G03e - G03 Variations of the Gravity Field

IUGG-4281

Oceanographic validation of time variable gravity solutions from GRACE

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Different types of oceanographic data, in particular altimetry and ocean bottom pressure (OBP) recorders, can be used for the validation of the GRACE time series of solutions over the oceanic domain. In this presentation, we will use these data for inter-comparing and validating different time series available (ITSG/GFZ/JPL/CSR/GRGS), with a focus on the recently computed RL03-v2 of CNES/GRGS.
This monthly time series of solutions is an update of the CNES/GRGS Release 03, which corrects two problems that had been identified in the RL03-v1 time series:
- an erroneous mass signal located in two small circular rings close to the Earth's poles, leading to the recommendation not to use RL03-v1 above 82° latitudes North and South;
- a weakness in the sectorials due to an excessive down-weighting of the GRACE GPS observations.
These two problems have been understood and addressed, leading to the computation of a corrected time series of solutions, RL03-v2.The origin of the problems will be discussed and the corrective steps that have been taken will be explained.

IAG (Geodesy)

G03e - G03 Variations of the Gravity Field

IUGG-5221

A feasibility study on measuring gravitational perturbations of seismic and tsunami waves from inter-satellite ranging data of GRACE and GRACE-FO

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GRACE has detected regional-scale coseismic and postseismic gravity changes after the recent great earthquakes. The GRACE gravity data demonstrated the importance of compressibility in governing the large-scale coseismic deformation and to constrain the seismic source depth and distribution, bulk modulus, elastic lithosphere thickness, and interaction with ocean mass redistribution. The postseismic gravity measurements have suggested persistent bi-viscous relaxation constraining the range of the asthenospheric viscosity. Earthquakes also produce spontaneous gravity perturbation along with ground shakings and tsunami waves (several hours), and the Earth's free oscillations (several days). We use the normal mode summation scheme to simulate these signals. The Level-1B (L1B) data of GRACE-like missions include orbit perturbation (induced by gravity change) measured as in range-rate (relative speed) change between two co-orbiting spacecraft. Such L1B data reflect the gravity change at particular time and location of the spacecraft. We develop innovative methods of L1B data analysis to detect and analyze seismic and tsunami waves, and free oscillation. The preliminary simulation of the 2004 Sumatra-Andaman earthquake indicates sensible signals produced along the GRACE orbits. The normal modes down to 200-sec were integrated to simulate the gravity perturbation along the orbit. The computation results show range-rate perturbation of several of 0.1 micron/s with greater attenuation of higher frequency modes over time, while GRACE instrument noise is around 0.2 micron/s at 5-sec and becomes smaller at longer periods. Current and future satellite gravity missions should open groundbreaking seismological research based on a 'gravitational seismogram' from the orbits.

IAG (Geodesy)

G03f - G03 Variations of the Gravity Field

IUGG-0578

Crustal and Lithospheric structures of Himalaya, Tibet and Indian Subcontinent based on space and ground gravimetric techniques

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Bouguer gravity anomalies derived from global gravity models (e.g. Earth Gravity Model 2008) based on GRACE satellite observations and terrestrial gravity data, are used in studying the large scale geological features of the Himalaya, Tibet and Indian subcontinent. The excess mass of the Himalayan topography is compensated by thick crust and producing large negative Bouguer gravity anomalies.Thus, the Himalayan Collision Zone comprises thrust faults, subducted lithosphere, thickened crust and suture zones that are manifesting in the gravity anomalies. Constrained from various seismic studies, spectral analysis and modelling of the BGA along a N-S profile (90^{o}E) in Himalaya-Tibet region suggests maximum lithospheric thickness of ~280 km beneath the Southern Tibet (Lhasa block) subduing to 100-160 km beneath the northern Tibet. On the other hand, the minimum lithospheric thickness has been observed at Qiangtang terrain which may be due to asthenospheric upwelling.

2D density model across Indian subcontinent (along N-S profile 77^{0} E) suggests lithospheric thickness varying from ~120-140 km in the Southern Granulite Terrain (SGT) to ~175 km under Ganga basin. Whereas, the crustal thickness changes from ~ 48 km in the southern part under the SGT to ~ 35 km under the Ganga basin. We observe longer wavelength gravity high over northern part (attributed to higher mantle lithospheric density) as compared to the southern India. This study addresses the crustal and lithospheric characteristics of Himalaya, Tibetan Plateau and Indian subcontinent and discussed in conjunction with seismotectonics.

IAG (Geodesy)

G03f - G03 Variations of the Gravity Field

IUGG-1189

First Detection of Coseismic Gravity Change of a Deep-focus Earthquake by Satellite Gravimetry: The 2013 Okhotsk Sea earthquake (M8.3)

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Coseismic gravity changes originate from two factors, namely vertical deformation of the layer boundary with density contrast (i.e. surface and Moho), and density changes of rocks at depth. Satellite gravimetry with GRACE have detected such gravity changes in three M9 class megathrust events, 2004 Sumatra, 2010 Maule, and 2011 Tohoku-oki earthquake, but those for M8 class earthquakes have been ambiguous. Here we report coseismic gravity change caused by the 2013 May 24 Okhotsk Sea deep earthquake (Mw8.3), which occurred within the subducting Pacific Plate slab at depth exceeding 600 km. In the shallow angle reverse faulting, the second factor (density changes) contributes more to gravity changes than the first factor (vertical movements). In fact, at shallow rupture depth, surface uplift and subsidence are close to each other, and it is difficult to resolve them due to poor spatial resolution of satellite gravimetry. In the 2013 Okhotsk deep earthquake, however, the importance of the two factors reverses. Coseismic positive and negative density changes (second factor) occurred far beneath the surface and is almost invisible from the height of the GRACE satellites. On the other hand, the regions of surface uplift and subsidence (first factor) becomes hundreds of kilometers apart, which is enough to be resolved even by the poor resolution of GRACE. We further show that this makes GRACE and similar satellite gravity recovery systems the first efficient tool to map two-dimensional vertical ground deformations of deep earthquakes over both terrestrial and oceanic regions.

IAG (Geodesy)

G03f - G03 Variations of the Gravity Field

IUGG-1998

Long-Term Gravity Changes Caused By Crustal Movement in Tibet Region

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The uplift process of the Tibetan Plateau and its mechanism has always been the research hot spot for geoscientists. In this paper, 11 years of time-variable gravity data from the Gravity Recovery and Climate Experiment (GRACE) newest Release 05 have been used to get the secular trends of gravity anomaly in CHINA and adjacent area by least square method. A reduction of hydrological signals from the detected integral secular trends using global hydrological models (Global Land Data Assimilation System, GLDAS and Climate Prediction Center, CPC) is attempted. The glacier model provided by Paulson is used to reduce the GIA(Glacial Isostatic Adjustment) effect. In addition, the scaling factor method is used to weaken the GRACE post-process errors. It turns out that a remarkable positive signal in the inner Tibetan Plateau, which is explained by a forward modeling with 3D rectangular prism based on the hypothesis of subduction of Indian plate beneath Eurasian plate. Bangong-Nujiang suture zone is used to divide the Tibetan Plateau into southern and northern parts, then we get the gravity anomaly rate of northern part +0.27ugal, which is consistent with the GRACE result 0.35±0.13ugal.

IAG (Geodesy)

G03f - G03 Variations of the Gravity Field

IUGG-2413

"Spectral-finite element approach to post-seismic relaxation in a spherical compressible Earth: application to the 2004 Sumatra–Andaman earthquake"

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Global navigation satellite systems (GNSSs) have revealed that a mega-thrust earthquake that occurs in an island-arc trench system causes post-seismic crustal deformation. Such crustal deformation data have been interpreted by combining three mechanisms: afterslip, poroelastic rebound and viscoelastic relaxation. It is seismologically important to determine the contribution of each mechanism because it provides frictional properties between the plate boundaries and viscosity estimates in the asthenosphere which are necessary to evaluate the stress behavior during earthquake cycles. However, the observation sites of GNSS are mostly deployed over land and can detect only a small part of the large-scale deformation, which precludes a clear separation of the mechanisms. To extend the spatial coverage of the deformation area, recent studies started to use satellite gravity data that can detect long-wavelength deformations over the ocean. In this study, a spectral-finite element approach is presented to deal with the effects of compressibility for Burgers viscoelastic spherical earth model with a laterally heterogeneous viscosity distribution, which have not been considered simultaneously in previous studies. This new model is applied to the 2004 Sumatra-Andaman earthquake. It is shown that the spatial patterns of gravity change generated by the above three mechanisms clearly differ from one another. A comparison of the theoretical simulation results with the satellite gravity data obtained from the Gravity Recovery and Climate Experiment reveals that both afterslip and viscoelastic relaxation are occurring. Considering the spatial patterns in satellite gravity fields is an effective method for investigating post-seismic deformation mechanisms.

IAG (Geodesy)

G03f - G03 Variations of the Gravity Field

IUGG-3765

Results of IAG JWG 2.4: geodetic and geophysical observations and their interpretations over Tibet, Xinjiang and Siberia (TibXS)

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Tibet, Xinjiang and Siberia (TibXS) are regions of many scientific interests, among them are climate change, geodynamic evolution of the Tibetan Plateau and mountain glacier change. This joint working group is dedicated to geodetic and geophysical studies in the regions. We organize annual workshops to discuss hydrological change, geodynamic process and climate change over TibXS, based on results from spaceborne and terrestrial sensors and methods, including satellite altimetry, GRACE, GPS, SAR and other techniques. The geodetic and geophysical records in TibXS are building up and continuously refined, enabling us to see long-term phenomena of interest and to model their mechanisms. This paper will present the scientific results achieved by this working group, especially on glacier melting, lake level change, moho depth modeling, plate motion and permafrost change. Some of the results have been published in two special issues of the journal Terrestrial, Atmospheric and Oceanic Sciences (TAO).Some technical challenges, valued research subjects and potential contributions of future ground and satellite measurements in TibXS will be reported.

IAG (Geodesy)

G03f - G03 Variations of the Gravity Field

IUGG-4580

Final report of the Global Geodynamics Project (1997-2015) that established a database of high precision relative gravity measurements

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GGP began in Canada in 1987 in response to the growing number of superconducting gravimeters (SGs) that were being established worldwide. Early interest of those starting the project was to try and detect modes of oscillation in the deep interior, notably inertia-gravity waves of the liquid core and translational motions of the inner core in the period range of several hours to days. But the extremely wide frequency range (sec to years) and exceptional stability (low drift) of the SGs inevitably made them also attractive instruments for monitoring many components of the Earth's variable gravity field. Notable in this wide spectrum are effects for which the SGs are particularly suited – for example ocean-tide loading (distinguishing different models), 3-D atmospheric pressure effects, refinement of the gravity effect of polar motion, and improving the low frequency part (below 1 mHz) of the seismic normal mode spectrum. Of quite unforeseen importance was the gradual use of SG's devoted to providing invaluable data on crustal hydrology, as they are the only instrument that can continually monitor mass changes at specific locations on the Earth's surface at 1 mGal (about 1 cm water). Several studies also established that ground gravity variations due to seasonal hydrology at SG stations agree well with GRACE gravity variations and global hydrology models. Now that the database has been established and has evidently proved valuable to a large number of geoscientists, it is time for GGP to close this phase of operation. In its place a new IAG organization is being established – the International Geodynamics and Earth Tides Service (IGETS) - whose goals and structure will be reported elsewhere at this General Assembly.

IAG (Geodesy)

G03g - G03 Variations of the Gravity Field

IUGG-1087

Study of post-processing methods for future gravity satellite missions

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The treatment of noise is in general one of the most challenging issues in spaceborne gravity, both for recovery from real missions and for the design of future missions. For the GRACE mission, three of the most important noise sources are i) aliasing errors which are due to under-sampling the signals, ii) retrieval errors which are caused by the formation architecture (e.g. the North-South stripes in GRACE solutions), and iii) instrument noise. For the future gravity satellite missions, the instrument noise is expected to be drastically reduced. Moreover, the possible use of double pair missions significantly improves the sampling of the gravity field, where the formation architecture is also different from GRACE.
This research work discusses the use of some known post-processing methods such as EOF-based filters, regularization and de-striping filter for gravity recovery from the future gravity satellite missions. These methods have been employed for GRACE recovery post-processing by former studies, while the use of the methods for future missions will be soon of great interest to the geodesy community. We compare the necessity, power and results of such post-processing methods on gravity solutions of a double pair mission with the results of a single pair mission with future technology and the current GRACE mission results.

IAG (Geodesy)

G03g - G03 Variations of the Gravity Field

IUGG-1727

Ground-satellite comparisons of time variable gravity : issues and on-going projects for the null test in arid regions

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The null test concept has been introduced to validate time changes in satellite-derived gravity data like GRACE in arid regions where almost no variable hydrological signal exist because of the lack of rain. We will review some issues that might arise in any ground truth experiment using surface gravity measurements like the role played by vertical motions of the measurement point or like the impact of length scale effects in hydrology. Preliminary results concerning the Sahara region in Algeria will be shown with a comparison of changes on a time period of more than 10 years (2002-2012) as observed by absolute gravimetry at the ground and GRACE data. Because of its ability to better capture small wavelength features compared to the classical spherical harmonic approach, we use localized GRACE mascon solutions to retrieve surface mass variations. At Adrar, there seems to be a trend in the water storage change that could be of anthropogenic origin (water extraction from fossil aquifers). We will also present some prospective studies in Egypt and Saudi Arabia that could be used in ground-orbit comparisons, as well as for the validation of global hydrology models in arid regions.

IAG (Geodesy)

G03g - G03 Variations of the Gravity Field

IUGG-2063

De-aliasing of ocean tide error in future dual-pair satellite gravity missions

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Ocean tides cause notable aliasing errors for single-pair spaceborne gravimetry missions like GRACE. Due to undersampling from satellite orbit the high-frequency tidal signal will alias into the long wavelengths of the gravity signal. Moreover, errors in ocean models, used for de-aliasing in the gravity field retrieval, will directly alias into the recovered gravity field too. In case of repeat orbits, the spectrum of tidal alias periods is known and the tide errors can be corrected from the recovered gravity field in a post-processing mode. However, this correction process is limited by the fact that (1) some tidal alias periods are close to periods of signals of interest and thus difficult to separate, and (2) some aliasing periods may be longer than the observation timespan.

Several studies into future gravity missions have shown that constellations with two or more GRACE-like tandems lead to a significant reduction of aliasing error from all kinds of high-frequency signal sources. Despite the reduction tidal aliasing will remain an error source, at least up to a certain level. In view of the limitations above, we here investigate the efficiency of tidal error de-aliasing in the post-processing mode for such future dual-pair missions. To that purpose we analyse how a certain satellite mission samples each tidal constituent. Given the repeat orbit patterns and the observation timespan, we examine and model the aliasing periods and amplitudes component by component.

IAG (Geodesy)

G03g - G03 Variations of the Gravity Field

IUGG-2201

Status of the GRACE Follow-On Mission

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GRACE Follow-On, a joint US/German satellite mission to extend the critical global mass flux data records from the GRACE mission, continues to mature and advance on both sides of the Atlantic. In January 2014 the Preliminary Design Review (PDR) was conducted, and transition into phase C was accomplished in March 2014. The project Critical Design Review (CDR) happened in February 2015. The current launch date remains August 2017.

The presentation will focus on the project status after the CDR of major spacecraft systems, science payloads (microwave ranging system, GNSS receiver, and accelerometer), a demonstration payload (laser ranging interferometer), mission operations, launch services and the science data system. In addition, since we now have more mature predictions of the spacecraft and instrument expected performance, we have continued to update the expected science performance via detailed colored noise simulations.

IAG (Geodesy)

G03g - G03 Variations of the Gravity Field

IUGG-2209

What can be expected from the GRACE-FO Laser Ranging Interferometer for Earth Science applications?

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The primary objective of the Gravity Recovery and Climate Experiment Follow-on (GRACE-FO) satellite mission is to continue the GRACE time series of global monthly gravity field models. For this, evolved versions of the GRACE microwave instrument (MWI), GPS-receiver, and accelerometer will be used. A secondary objective is to demonstrate the effectiveness of a laser ranging interferometer (LRI) in improving the low-low satellite-to-satellite tracking measurement performance.

In order to investigate the expected benefit of the LRI for Earth science applications, we performed a full-scale simulation in terms of spherical harmonics over the nominal mission lifetime of five years using a realistic orbit scenario and error assumptions for orbit, instrument and background model errors.

We will present results in the spectral and spatial domain showing moderate improvements when using LRI instead of MWI observations for global quality indicators. As these global indicators are not meaningful for Earth system applications which show a clear mass variation signal in regionally defined areas such as water mass changes in hydrological basins or melting of glaciers we have also additionally investigated how simulated seasonal, sub-seasonal, secular and instantaneous (Earthquake) signals are recovered when using GRACE-FO MWI or LRI data. Related results will be presented at the conference.

Analysis of the different individual error contributions to the overall monthly gravity model error has shown that dominant errors are still due to accelerometer noise and imperfect modeling of tidal and non-tidal mass variations. Consequently, these errors have to be further reduced when using LRI observations on Next Generation Gravity Missions.

IAG (Geodesy)

G03g - G03 Variations of the Gravity Field

IUGG-2467

European Gravity Service for Improved Emergency Management - a new Horizon2020 project to improve the accessibility to gravity field products

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A proposal for a European Gravity Service for Improved Emergency Management (EGSIEM) has been submitted in response to the Earth Observation Call EO-1-2014 of the Horizon 2020 Framework Programme. EGSIEM shall demonstrate that observations of the redistribution of water and ice mass derived from the current GRACE mission, the future GRACE-FO mission, and additional data provide critical and complementary information to more traditional Earth Observation products and open the door for innovative approaches to flood and drought monitoring and forecasting. The EGSIEM project has recently started in January 2015. We present the three key objectives that EGSIEM shall address: 1) to establish a scientific combination service to deliver the best gravity products for applications in Earth and environmental science research based on the unified knowledge of the European GRACE community, 2) to establish a near real-time and regional service to reduce the latency and increase the temporal resolution of the mass redistribution products, and 3) to establish a hydrological and early warning service to develop gravity-based indicators for extreme hydrological

events and to demonstrate their value for flood and drought forecasting and monitoring services. All of these services shall be tailored to the various needs of the respective communities. Significant efforts shall be devoted to transform the service products into user-friendly and easy-to-interpret data sets and the development of visualization tools.

IAG (Geodesy)

G03h - G03 Variations of the Gravity Field

IUGG-0661

Mission objectives for a next generation gravity mission

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The monitoring of the temporal changes in the Earth's gravity field is of great scientific and societal importance. Within several days a homogeneous global coverage of gravity observations can be obtained with satellite missions. The science requirements for a Next Generation Gravity Mission (NGGM) are defined in fields of Hydrology, Cryosphere, Ocean, Solid Earth and Geodesy. For selected signals of interest the required accuracy for required spatial and temporal resolutions are formulated. In this study a straight forward approach is presented in order to derive mission objectives for a NGGM from the science requirements. This approach uses formal error propagation and homogenizes the requirements resulting in required geoid accuracies for the basic temporal resolution of one month.

Temporal aliasing of background model errors due to high-frequent tidal and non-tidal mass variations into global gravity field models will be one of the largest restrictions in future satellite temporal gravity recovery. Having a double pair low-low Satellite-to-Satellite tracking (SST) scenario on different inclined orbits reduces temporal aliasing errors significantly. The combination of two low-low SST missions based on normal equations requires an adequate weighting of the two components for optimal de-correlation. In this study it is analyzed how this can be done based on the resonance orders of the two orbits. The results of several numerical closed-loop simulations are shown including stochastic modeling of realistic future instrument noise. It is shown that this de-correlation approach is important for maximizing the benefit of a double-pair low-low SST mission for temporal gravity recovery.

IAG (Geodesy)

G03h - G03 Variations of the Gravity Field

IUGG-1494

Science and user requirements for a future gravity field mission constellation

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In an internationally coordinated initiative among the main user communities of gravity field products the science requirements for a future gravity field mission constellation (beyond GRACE-FO) have been reviewed and defined. This activity was realized as a joint initiative of IUGG, IAG Sub-Commissions 2.3 and 2.6, and the GGOS Working Group on Satellite Missions.

An international expert panel of leading scientists in hydrology, ocean, cryosphere, solid Earth and atmosphere developed science and user requirements for the main fields of application of the static and time-variable gravity field. In a user workshop that was held in September 2014, consensus among the user communities on consolidated requirements could be achieved. The consolidation of the science and user requirements became necessary, because several future gravity field studies have resulted in quite different performance numbers as a target for a future gravity mission (2025+). Based on limited number of mission scenarios which took also technical feasibility into account, a consolidated view on the science and user requirements among the international user communities was derived, research fields that could not be tackled by current gravity missions have been identified, and the added value (qualitatively and quantitatively) of these scenarios with respect to science return and societal benefit has been evaluated. The resulting document shall form the basis for further programmatic and technological

developments.

In this contribution, the main results of this initiative will be presented. An overview of the specific requirements of the individual user groups, the consensus on consolidated requirements as well as the new research fields that have been identified during this process will be discussed.

IAG (Geodesy)

G03h - G03 Variations of the Gravity Field

IUGG-1600

ESA's studies of next generation gravity mission concepts

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The presentation addresses the preparatory studies of future ESA mission concepts devoted to improve our understanding of the Earth's mass transport phenomena causing temporal variations in the gravity field, at different temporal and spatial scales, due to ice mass changes of ice sheets and glaciers, continental water cycles, ocean masses dynamics and solid-earth deformations.

The ESA initiatives started in 2003 with a study on observation techniques for solid Earth missions and continued through several studies focussing on the satellite system, technology development for propulsion and distance metrology, preferred mission concepts, the attitude and orbit control system, as well as the optimization of the satellite constellation. These activities received precious inputs from the in-flight lessons learnt from the GOCE and GRACE missions. More recently, several studies related to a new sensor concept based on cold atom interferometry were initiated, mainly focussing on technology development.

The latest results concerning the preferred satellite architectures and constellations, payload design and estimated science performance will be presented as well as remaining open issues for future concepts.

IAG (Geodesy)

G03h - G03 Variations of the Gravity Field

IUGG-1928

Accuracy required by future satellite gravity missions to resolve mass signals at glacier-scale and along oceanic fronts

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Although data from the currently available time-variable gravity mission, GRACE can be used to estimate the large scale mass balance of the Greenland and Antarctic ice sheets, as well as variations in integrated transport over large swaths of the Southern Ocean, they are insufficient to detect smaller scale signals. One of these is the very-large, but small-scale glacial mass balance for specific glacier regions. Another is variations in the front positions of the Antarctic Circumpolar Current. We demonstrate one theoretical way to separate these two signals with a future gravity mission, utilizing a least squares inversion technique. The ability to do so is highly dependent on the magnitude of errors in the recovered gravity field coefficients, and the maximum degree that the gravity field can be computed to. Using a simulated data set, we estimate what level of errors and resolution would be necessary accomplish the detection of these smaller-scale signals in a future satellite gravity mission.

IAG (Geodesy)

G03h - G03 Variations of the Gravity Field

IUGG-2722

Which electrostatic accelerometers for the next gravity missions?

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The sensor core configuration of the electrostatic accelerometers of the CHAMP, GRACE and GOCE missions has been especially designed for space applications but in order to be able to verify the performances along 2 ultra sensitive axes on ground, the 3rd axis is designed less sensitive to support the normal gravity levitation. The return of experience of these missions allows a better optimisation of the design of the accelerometer in terms of thermal stability for the near future missions. After the demonstration of performance of the interferometer laser ranging method on board GRACE follow-on, the next generation of low-low satellite to satellite tracking missions will take advantage of that to improve their performance. So the noise level of the accelerometer shall become the weakest piece in the gravity field determination. Taking advantage of the new testing possibilities offered by the catapult facility at the ZARM drop tower, ONERA's team can propose an up-dated version of its electrostatic accelerometers developed with a cubic proof-mass to be in better adequacy with the requirements of a next generation of smaller and drag compensated micro-satellites. In addition to the measurement of the surface forces exerted on the spacecraft by the atmospheric drag and by radiation pressures, the accelerometer instrument becomes a major part of the attitude and orbit control system by acting as drag free sensor and by accurately measuring the angular accelerations. After a description of the improvement of the GRACE-FO accelerometer with respect to the still in-orbit previous models and a status of its development, the presentation will describe the new cubic configuration and how its operations and performances can be verified in the Bremen drop tower.

IAG (Geodesy)

G03h - G03 Variations of the Gravity Field

IUGG-2734

Attitude determination and its impact on the current and future inter-satellite ranging missions

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One of the key subsystems of the inter-satellite ranging missions is the attitude determination and control (ADC). The very first mission that demonstrated the strengths of the inter-satellite ranging observation technique is the Gravity Recovery and Climate Experiment (GRACE), which will be succeeded by the GRACE-Follow on (GRACE-FO) mission in 2017. Even after 13 years of successful mission operation, efforts are still ongoing to improve the accuracy of the scientific data needed for the gravity field determination. One of the key elements are the systematic effects in the star camera attitude data and in the star camera calibration parameters, which significantly affect the inter-satellite pointing. Here we present the impact of the systematic errors in ADC on the GRACE scientific observations in its overall complexity. We discuss the characteristics of the star camera data; the inconsistency of the calibration parameters for star camera, phase center of the K-band ranging antenna and accelerometer alignment used in the onboard and on-ground processing; star camera attitude data combination; propagation of the attitude errors in the inter-satellite ranging observations; the error propagation into the gravity field models; and the consequence of using single star camera for onboard attitude determination on mission lifetime. We provide a unique insight into the onboard system whose profound understanding is necessary not only for improving the current GRACE results but also for the development of the GRACE-FO mission as it has a strong heritage in GRACE. Parallel to GRACE, we show the benefit of the upgraded ADC hardware on GRACE-FO which will allow improved attitude determination and control.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-415

Error analysis of the GRACE Follow-on mission based on an analytical method

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The GRACE Follow-on mission is scheduled to launch as early as 2017 in order to continue the high-resolution monthly global models of Earth's gravity field of original GRACE and demonstrate the effectiveness of a laser ranging interferometer in improving the accuracy of inter-spacecraft ranging by tenfold or more. This study performs the error analysis of the GRACE Follow-on mission based on an analytical method, which provides the direct relationship between the power spectrum density of instrument noise and the coefficients of Earth's gravity potential, and then the effects of accelerometer accuracy, the range/range-rate measurements of the proposed K-Band inter-satellite ranging (KBR) and Laser Ranging (LR) instrument aboard GRACE Follow-on, the altitude of the satellite and the operation duration on recovery are determined. This method allows us to directly evaluate the frequency characteristics of instrument on GRACE Follow-on noise from a point view of signal theory and improve our understanding of their detailed interaction, and will benefit the gravity field recovery with a more precise and better understood. Based on the simulations and analysis, a mission with the hypothesis of an orbit height of about 350 km, a mission duration of about 12 months, a LR system accuracy of about 50 $nm/s/Hz^{1/2}$, a accelerometer accuracy level of about $1 \times 10^{-10} \times (1+0.005/f)^{1/2} m/s^2/Hz^{1/2}$, and a separation of 220 km is proposed, and it permits determination of a lunar gravity field model with a high accuracy of 0.68 mGal and a geoid with an accuracy of 2.3 cm, both at a spatial resolution of 100 km.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-416

Data mining in SST monthly solutions

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Monthly variations of GRACE solutions are subjected to undesired striping. The stripes are the result of data aliasing and are, in most cases, reduced by subsequent smoothing. The smoothing process degrades the spatial resolution of the monthly variations. On the other hand, twelve years of monthly solutions from three processing centers provide a large data collection, which can be investigated by data mining algorithms. The poster describes 1. How data mining techniques like thresholding and cluster analysis can be used to discriminate between spherical harmonics coefficients, which change significantly from month to month and those that do not. 2. In terms of accuracy and stability it compares full GRACE solutions with GRACE solutions, which solve only for the significantly changing coefficients. 3. It shows that the reduced GRACE solution degrades the accuracy only within the formal error bounds, while the stability of the reduced solution improves significantly. Besides the usual de-aliasing the data mining based parameter reduction can help to reduce the striping in monthly changes of GRACE solutions.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-417

Suitability of GRACE-based geopotential models for modelling temporal variations of gravity functionals over Poland and the surrounding areas

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Since the launch of GRACE (Gravity Recovery And Climate Experiment) satellite mission in 2002, a significant progress in the knowledge regarding the temporal variations of the Earth gravity field has been achieved. The main objective of this contribution is to study the suitability of the latest release, i.e. the 5th release, GRACE-based Global Geopotential Models (GGMs) for modelling the temporal gravity field variations over the area of Poland and surrounding areas. It is aimed also to define an optimum filter for reducing the noise contained in those GGMs.

The GRACE-based GGMs provided by different computational centers have been examined. The analysis has been based on the comparison of temporal variations of terrestrial water storage (TWS) obtained from the 5th release GRACE-based GGMs with the corresponding ones derived from hydrological models. The Gaussian filter with different radii as well as DDK (de-correlating in post-processing approach) filters were investigated. The results of the comparison have been analysed and discussed.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-418

Sensitivity of the A10 absolute gravimeter to the variation of local hydrological conditions – first results

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The A10-020 gravimeter operates in the Institute of Geodesy and Cartography since October 2008. It has been widely used for various types of surveys, mostly connected to gravity control establishment and maintenance in different European countries. Starting from late 2014, regular measurements with the A10-020 gravimeter at three sites of the test network (two laboratory underground stations and on field station even to the ground) in Borowa Gora Geodetic-Geophysical Observatory are supplemented with the monitoring of local hydrological conditions via automated stations measuring precipitation, soil humidity (at two depths) and water table level variation. The purpose of this work is to assess the sensitivity of gravity determinations with the A10-020 gravimeter to gravity variations due to local hydrological conditions.

In the analysis of the results the GLDAS corrections for large scale hydrological conditions, the advanced atmospheric corrections, as well as the local tidal model (from tidal observations) will be considered. Initial local hydrological modeling will include the water cycle balance, ground porosity at the water table level, as well as various assumptions concerning the location of the measurement sites with respect to the ground level.

The results obtained are expected to show the possibility of using the A10-020 absolute gravimeter for detecting gravity variations caused by variations of hydrological conditions on local and regional scale.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-419

Status and assessments of CSR GRACE Level-2 Data Products

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The joint NASA/DLR GRACE mission has successfully operated for more than 13 years, and has provided a remarkable record of global mass flux due to a large variety of geophysical and climate processes at various spatio-temporal scales.The University of Texas Center for Space Research (CSR) hosts the mission PI, and is responsible for delivery of operational (presently denoted as Release-05 or RL05) gravity field data products. In addition, CSR generates and distributes a variety of other gravity field data products, including products generated from the use of satellite laser ranging data.This paper will provide an overview of all these data products, their relative quality, potential applications, and future plans for their development and delivery.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-420

Impact of groundtrack pattern of double pair missions on the gravity recovery quality - Lessons from the ESA SC4MGV project

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The launch of the GRACE mission brought a broad interest within the geophysical community in monitoring temporal gravity field. Due to the limited lifetime of GRACE, several studies have been conducted for the search of optimal GRACE follow-on and future satellite gravity missions. These studies mainly discuss the use of alternative formations like Pendulum, Cartwheel and LISA as well as the double inline pair missions with different orbits as a possible substitute of the current GRACE mission. The double satellite pair configuration in a so-called Bender constellation, however, is currently in the focus of research into time-variable gravity field recovery by future satellite missions, where the primary objective is to achieve higher temporal and spatial resolutions.
When looking for optimal double inline missions, one important subject is the impact of the sampling distribution or ground-track pattern of such missions on the quality of gravity recovery. The investigation of sampling distribution impact on the recovery quality may lead to better understanding of orbital parameters to be optimized. This study, in particular, investigates the influence of difference of ascending nodes of two pairs in a double pair mission. The research aims to show how the variations in ascending nodes difference change the quality of gravity solutions to the large extent.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-421

Can the satellite gravity replace the gravity survey to delineate lithospheric structure?

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The gravitational field of the Tibetan Plateau reflects the surface and internal distribution of matter change and state of motion. But the complex terrain conditions of Tibet with towering mountains and steep valleys cause gravity survey extremely difficult. Thus, there is only sparse or no terrestrial gravity points in topographic gradient zone regions. The gravity satellite is of the all weathers, high precision and a wide range of observations. However, at the Tibet with the larger terrain gradient change can the satellite gravity anomalies instead of ground gravity signal and reflects this tectonic activity?

Three gravity field surveys with roughly 5km spacing in average from Tarim and Sichuan Basins across the northern and eastern plateau are used to compared with the 2.5 'x2.5' satellite gravity data of EGM2008 model in order to answer the current question in the geophysical community that if the satellite gravity survey in space can replace the land gravity survey in a mountainous area. It suggests that on the less than 1000m above sea level basin and greater than 4500m plateau, when the deviation from the satellite altimeter and the ground GPS elevation observation is in less than 10m and 25m, the absolute difference of the Bouguer anomaly between the satellite and measurement is within 15mGal and 20mGal, respectively. However, in the big terrain changes gradient area along the edge of the plateau, the elevation measurements accumulation error cause the satellite gravity data accuracy reduced significantly, absolute error more in ± 120mGal. It is apparent that the satellite gravity data cannot take the place of measurements to explain the process of earth tectonic dynamics in the margin of Tibetan Plateau.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-422

Numerical integration of the Schwarzschild problem using Lie series for the calculation of satellite orbits

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Simulations of orbital arcs are often performed by making use of classical numerical integration techniques. Although providing highly accurate results for short to medium arc lengths, its validity degrades rapidly with time for long-term calculations. The results, in essence, only yield information on the very special case under consideration. Numerous simulations had to be performed in order to gain insight into the various correlations between force field modeling, orbital configuration, and so on. Analytical orbit integration provides deeper insight into the physical causes of the orbit evolution than any special perturbation technique. It operates directly in the spectral domain rather than in the time domain, and therefore system driving frequencies and corresponding amplitudes and phases are directly detectable. A combination of the numerical and analytical approach can be derived based on Lie series. Here, we focus on the well-known Schwarzschild problem, i.e. a major relativistic effect, and its implications especially for the long-term orbital evolution. For that purpose, an already existing Newtonian approach for the classical two-body problem is being extended to the corresponding relativistic Hamiltonian function. We present a set of expressions which enables a step-wise (in time) computation of the orbit, where the series coefficients itself result from analytical derivations instead of elaborated tables of difference quotients as in case of traditional numerical integrators. Finally, we apply the new algorithm to calculate exemplary orbits, and we also present some performance studies.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-423

Investigation of time-variable components of the gravity potential for optical clock comparisons

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Within the collaborative European project "International timescales with optical clocks (ITOC)", a coordinated programme of clock comparisons is carried out to validate the optical clocks at five different laboratories. As optical clocks are now targeting a relative accuracy of 10^{-18}, corresponding to a sensitivity of about 0.1 m^2/s^2 in terms of the geopotential or 0.01 m in height, also temporal variations of the gravity field become significant, with tides being the dominant component. This is especially important for remote clock comparisons over larger distances, when relatively short averaging times are used, since in such situations the time-variable gravity potential effects may not average out sufficiently.

The aim of this investigation is to review possible time-variable gravity field effects and their computation. In this context, emphasis is put on tidal variations as the major effect. Furthermore, ocean loading effects are investigated and assessed for each of the clock sites. In addition, also atmospheric mass movements (globally, from hourly to seasonal scales), hydro-geophysical mass changes (regional and continental scales, seasonal variations), and polar motion (pole tides) are considered. The magnitudes of all effects are estimated, and their relevance for optical clock comparisons is investigated.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-424

Improved noise model for AIUB monthly gravity field solutions

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Since December 2014 a new release AIUB-RL02 of monthly gravity field solutions from GRACE GPS and K-Band range-rate data is available at ICGEM. The strong correlation of the noise in the monthly solutions with the level of Solar flux that was visible in AIUB-RL01 could be decreased significantly by the estimation of daily accelerometer scale factors. While the resulting monthly fields compare very well with other state-of-the-art unconstrained gravity field time series, the quality of the monthly solutions still seems to be somewhat degraded during periods of high solar activity at the beginning of the mission and from 2011 onwards (corresponding to the 11 year solar cycle). While it is not yet clear, how the solar activity influences the performance of the K-Band or accelerometer observables, a tailored noise model seems to be indispensable to further improve the solutions. As a first step a time dependent weighting of the range-rate observables is introduced, thus down-weighting K-Band during spells of high solar activity. Subsequently experiments are performed with empirical covariances that were derived from the post-fit range-rate residuals of AIUB-RL02. The goal of the investigation is to make a future AIUB-RL03 fit to optimally contribute to combined gravity field products that shall be derived and distributed by the European Gravity Service for Improved Emergency Management (EGSIEM) which is currently established in the frame of a Horizon 2020 project.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-425

"Geodetic parameter time series from JASON-2 and multi-satellite SLR solutions"

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Satellite Laser Ranging (SLR) is a geodetic technique commonly used to provide very accurate satellite orbits, time series of station positions and motions and many other geophysical parameters. Laser ranging analysis for spherical satellites, which is performed within the Deutsches Geodätisches Forschungsinstitut (DGFI) using Orbit and Geodetic Parameter Estimation Software DOGS, has now been extended and upgraded to handle non-spherical satellite SLR applications. In particular, the present contribution focuses on the processing with DOGS of the non-spherical satellite JASON-2, which is currently the satellite with the highest number of SLR observations available.

First, the implementation in DOGS is described, concerning the modeling of non-gravitational perturbations on JASON-2, such as solar radiation pressure, Earth infrared radiation, Earth albedo and atmospheric drag. The box-wing satellite model is adopted as the JASON-2 spacecraft geometry, JASON-2 macro-model is implemented to account for the optical and infrared properties of the satellite surfaces and the satellite attitude is computed using quaternions and solar panel orientation angles.

Finally, results are reported and discussed, in terms of estimates of Earth Orientation Parameters (EOP), station coordinates and Earth gravity field coefficients time series, obtained both from a JASON-2-only solution and a JASON-2 solution incorporated into a SLR multi-satellite solution.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-426

Deep Crustal Structure of Warakurna Large Igneous Province from Gravity and Seismic data

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The deeper crustal characteristics of the Warakurna Large Igneous Province (WLIP) are still poorly understood due to the difficulties in interpreting geophysical characteristics in the deep lithosphere. we aim to reconcile seismic models over the Capricorn Orogen,Yilgarn-Officer-Musgrave (YOM), Gawler-Officer-Musgrave-Amadeus (GOMA) and Younami with gravity measurements. S-wave seismic velocities from receiver function models were converted to P-wave velocity and density. Geology interpreted from deep seismic reflection profiles was depth converted based on the new velocity data. Moho geometry from deep seismic reflection models was modified based on receiver function results. An initial density model was constructed based on depth converted seismic interpretation, Moho geometry and densities estimated from velocities. The initial densities were modified to get fit with Bouguer anomaly variations. To understand ambiguity in the gravity models,sensitivity testing on key features was undertaken by changing density in surrounding blocks including the mantle and upper-lower crust. High densities compared to the densities of the adjacent region were observed in the gravity models including: 1) Bandee Seismic Province (Capricorn Orogen) north of Talga Fault that locates in the mid-crust. 2) Tikelmungulda Seismic Province of the YOM that extends below the middle crust of west Musgrave province. 3) Lower crust of the GOMA in east Musgrave Province. These observations of high densities in the gravity models may be related to magmatic underplating during the WLIP event. These three regions, however, differ in their properties and character in deep seismic reflection models, so further work is needed to demonstrate the origins of these high densities in the deep-crustal provinces.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-427

Accuracy estimation for ice mass balance information derived for Greenland and Antarctica using GRACE RL05 gravity models

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In the frame of this work, GRACE RL05 gravity field models were used to determine surface mass anomaly time series for Greenland and Antarctica between April 2002 and November 2014. First and second degree polynomial functions were fitted to the time series in order to derive linear trend and acceleration of the mass variation. This way four different regions can be and has been defined based on the sign of the mass trend and mass acceleration: intensifying melt, decaying melt, intensifying accumulation and decaying accumulation.

The determination of the mass variations is not an unambiguous task, since notably different results can be obtained by using different input data or processing method. A default parametrization was defined (CSR GRACE gravity models, ICE-5G GIA model, 500 km smoothing radius) and used as a reference for other parametrizations. CSR and GFZ GRACE solutions were compared, and it was found that the differences of the trend can reach the order of magnitude of cm/yr, and that differences of the acceleration can become some mm/yr^2. Comparison of two GIA models (ICE5G and IJ05) shows a difference of more than 2 cm/yr. The largest impact on the results are obtained by the choice of the Gaussian smoothing radius, since by increasing the radius, the signal can be smoothed to a several orders of magnitude smaller one.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-428

The decomposition and interpretation of continental water storage changes using independent component analysis

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We first use the independent component analysis (ICA) method to decompose the water storage changes derived from 132 months (2003.01-2013.12) Gravity Recovery and Climate Experiment (GRACE) measurements, and then compare the results with those from NOAH and WGHM hydrological models. The comparison results show that the decomposed components from the water storage changes and hydrological models agree well, which indicates that ICA method can be used to separate the independent signals from the observed data with few a priori Information. The comparisons with other methods, such as principal component analysis (PCA), are also conducted and discussed.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-429

IAG working group 2.7 "land hydrology from gravimetry": Hydrological science requirements for a next generation gravity mission

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This presentation summarizes the activities of the IAG Joint Working Group 2.7 'Land Hydrology from Gravimetry', which was established by IAG's Subcommission 2.6 'Gravity Field and Earth System' for the years 2011-2015. The main achievement of the working group was the formulation of science requirements demanded by the hydrological user community for a next generation gravity satellite mission beyond GRACE-FO. Several future gravity mission studies have resulted in quite different performance numbers, therefore, a joint initiative of IUGG, IAG and GGOS has been working on consolidated science requirements among different thematic sub-groups concerned with hydrologic, oceanographic, glaciologic, and geophysical applications of future gravity missions. The resulting document will be used as a solid basis for further programmatic and technological development. On the poster we will present the synthesized expectations of the hydrological user community for such a mission in terms of spatial & temporal resolution, accuracy and length of time series. Furthermore, we will discuss the benefit of a limited number of pre-defined satellite mission scenarios for addressing upcoming hydrological challenges for science and society, as, e.g., climate change, regional water management, as well as the assessment of meteorological extremes that lead to large-scale flood and drought conditions.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-430

PreAnalyseExtended: An graphical analysis program for the research of geophysical time series

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Data analysis in geophysics often requires additional models for a seamless investigation of the measured time series, which are usually available from different sources and at different sample spacing. The analysis suite "PreAnalyseExtended" comprises a package of different geophysical models, such as ocean loading, earth tides (conform with the "ETERNA" code) and polar motion. For those application cases where models are not readily available, but observations from ancillary instrumentation is given instead, a number of parallel data streams can be used to provide the desired model correction. The program suite provides all necessary features for simple editing, proper data re-sampling, filtering, stability and spectral analysis. While it has been originally developed for the evaluation of the time series measurements from a large ring laser gyroscope applied for geo-science, the basic concept is very general and suitable for many other fields of geophysical data analysis. This talk outlines the basic concept and features of the PreAnalyseExtended workflow package and illustrates the versatile areas of application with some specific examples.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-431

"GRACE vs ENVISAT data at Patagonian lakes in Argentina and Chile"

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Gravity does not remain constant but changes over time depending on the masses redistribution. These changes can be associated with continental water storage temporal variations which is the main component of the global hydrological cycle.

The satellite gravity mission GRACE (Gravity Recovery And Climate Experiment) provides time-variable gravity field models that reflect the Earth's gravity field variations at a resolution of ~400 km, which are mainly due to mass transport processes.

Satellite altimetry technic has a strong potential to be used in hidrology. Besides, it is the only source of information available in many lakes located in inaccessible areas.

LEGOS -Laboratoire d'Etude en Géophysique et Océanographie Spatiale- developed a online data base (HYDROWEB: http://www.LEGOS.obs-mip.fr/soa/hydrologie/HYDROWEB) with temporal variations of water level in river, lakes and reservoirs. Information over La Plata basin, Amazons, Orinoco and Patagonia lakes in South America is available.

This work aims to analize the possibility of using GRACE data and satellite altimetry to detect variations in hydrometric levels in some Patagonia lakes. For that, EWH GRACE data were compared with water level at lakes from ENVISAT.

Nine virtual stations located at Patagonian lakes (Argentina and Chile) were selected. The corresponding data was obtained through LEGOS' HYDROWEB and CNES/GRGS site.

Correlation and regresion coefficients were determined at each station. The results show good agreement in general terms. Anyways, it is important to point out that the correlation coefficients decrease strongly southwards.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-432

Singular spectrum analysis for modelling geodetic time series

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Geodetic time series obtained via space-geodetic techniques, e.g. site displacements from continuous GPS observations and aggregated basin water storage time series from GRACE, display a seasonal behavior. Much focus has been given to separate such periodic signal from other signals buried in the geodetic time series, e.g. linear or non-linear trends. Conventionally, these seasonal signals are retrieved with constant amplitudes by the classical least squares estimation approach. Recently, singular spectrum analysis (SSA) has been successfully applied to extract the time variable seasonal signals from the GPS time series.

This study extends the application of SSA to other geodetic time series, e.g. water level time series from satellite altimetry. The possibilities of SSA to separate the non-linear trend from seasonal signals are investigated and the corresponding signal separabilities are discussed using the so-called w-correlation. In addition, we also investigate the possibilities of SSA for other geodetic applications, for instance, gap-filling and forecasting of geodetic time series. For validation, we compare SSA with other techniques like the least squares estimation.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-433

The updated ESA earth system model for future gravity mission simulation studies

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A new synthetic model of the time-variable global gravity field is now available based on realistic mass variability in atmosphere, oceans, terrestrial water storage, continental ice-sheets, and the solid Earth. The updated ESA Earth System Model is provided in Stokes coefficients up to degree and order 180 with a temporal resolution of 6 hours covering the time period 1995 - 2006, and can be readily applied as a source model in future gravity mission simulation studies. The model contains plausible variability and trends in both low-degree coefficients and the global mean eustatic sea-level. It depicts reasonable mass variability all over the globe at a wide range of frequencies including multi-year trends, year-to-year variability, and seasonal variability even at very fine spatial scales, which is important for a realistic representation of spatial aliasing and leakage. In particular on these small spatial scales between 50 and 250 km, the model contains a range of signals that have not been reliably observed yet by satellite gravimetry. In addition, the updated Earth System Model provides substantial high-frequency variability at periods down to a few hours only, thereby allowing to critically test strategies for the minimization of temporal aliasing. Data and documentation of the updated Earth System Model are accessible at doi:10.5880/GFZ.1.3.2014.001 .

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-434

Results for observations in Brazil using Microg-LaCoste gPhones

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An attempt for Earth tide models in Brazil with the support of GEORADAR Levantamentos Geofísicos S.A. and under the coordination of Laboratory Surveying and Geodesy (LTG) was derived. Two Microg-LaCoste gPhones (103 and 105) were installed successively in five gravity stations over three years. Four were in the state of São Paulo, one on the coast (Cananéia), two in intermediate location (São Paulo and Valinhos), and the other 500km away from the first (Presidente Prudente). The fifth station is in Porto Velho, Amazon region. In each point the solid Earth tides, after the corrections of atmospheric and ocean loading, pole tide, out of instrumental errors, were calculated. Tsoft package was used for removing gaps, steps, spikes and earthquake effects and ANALYZE (ETERNA package) for the determinations of tidal parameters. The amplitude factors and phases for the main tidal wave groups were detemined. The standard deviation for the residuals was less than 5 microGal. The drift of the equipments was determined by a simple polynomial fit. The next step of the project will be the analysis on the behavior of the results in Amazon region with observations in Porto Velho and Manaus.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-435

" A semi-analytical approach to gravity field analysis from pendulum formation"

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Past and current gravimetric satellite missions have contributed drastically to our knowledge of the Earth's gravity field. Nevertheless, several geoscience disciplines push for even higher requirements on accuracy, homogeneity and time- and space-resolution of the Earth's gravity field. Apart from better instruments or new observables, alternative satellite formations, e.g. the pendulum formation could improve the signal and error structure. Several approaches have been developed to optimize the orbital parameters of future gravity satellite missions. With respect to other methods, one significant advantage of the semi-analytical approach is its effective pre-mission error assessment for gravity field missions.

The semi-analytical approach builds a linear analytical relationship between the Fourier spectrum of the observables and the spherical harmonic spectrum of the gravity field. The spectral link between observables and gravity field parameters is given by the transfer coefficients, which constitutes the observation model. In connection with a stochastic model, it can be used for pre-mission error assessment of gravity field mission.

In this study, the transfer coefficients of range and range rate perturbations for the pendulum formation are derived analytically considering different orbital parameters. The transfer coefficients are further applied to assess the error patterns which are caused by different orbital parameters. In addition, orbit simulations are conducted to validate the transfer coefficients and in turn to investigate the errors. This work aims at finding the optimal ratio between along- and cross-components of ranging, while inclination, radius and distance remain similar.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-436

New insights on the 2011 Tohoku earthquake from a 4D analysis of GRACE and GPS data

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In order to better understand the processes of stress accumulation and stress release associated with the 2011 Tohoku earthquake, we estimated the mass transfers along the Japanese subduction zone using a space-time analysis of the GRACE geoid models. In a first step, we reconstruct the time variations of Earth's gravity gradients from GRACE, and we investigate how the gravity signal varies in space as a function of scale and direction using rotations of the gradients tensor filtered at different scales. We then analyze the time variations of the rotated tensor components at different spatial scales. For that, we apply a Markov chain Monte Carlo approach to estimate the time model parameters. We assess the consistency of the obtained gravity signals with GNSS measurements of deformations along the Japanese arc. We finally discuss how these results can advance the understanding of the seismic cycle in the area.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-437

Application of kalman filtering technique for correcting superconducting gravity time-series

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New approach to the processing of gravity time-series recorded by superconducting gravimeter is introduced. It supplies standard data treating procedure based on remove-restore technique. Method is using the Kalman filtering. It is a recursive data processing algorithm with high computational efficiency. Algorithm provides an estimate of current state of the process using previous parameter estimation in such a way that minimizes the mean of the squared error. Filtering enables smoothing the noisy gravity data with detection of corruptions and to predict missing values. The measured gravity signal is modelled using theoretical Earth tides, atmospheric pressure effect on gravity and pole tide effect. The state parameters of process are tidal amplitude factors, tidal phases and regression coefficients for pressure and pole tide effect assessed at any observed time. It allows identifying undesired outliers and steps in gravity data which are visible in a time variation of estimated parameters. On the other hand missing or corrupted data are replaced by filter taking into account current state of the observations. The level of data smoothness can be easily controlled by user requirements. The filtered observations without corruptions and gaps are suitable for further analysis. Additionally the preliminary tidal parameters are obtained within filtering which allow computing total tidal signal at a given site.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-438

The monitoring of terrestrial water storage changes in Tianshan Mountains measured by GRACE during 2003-2013

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Using the monthly Earth's gravity field models from 2003 to 2013, provided by the Gravity Recovery and Climate Experiment (GRACE) mission, the terrestrial water storage changes in Tianshan Mountains in China are estimated. A hybrid filtering scheme of the de-correlated filter and 300km Gaussian filter are used in the mass variation computation, while the scaling factor method in reducing GRACE post-process error. Besides, the influence of post glacial rebound is reduced. The results indicate that, the water storage from 2003 to 2013 in the whole Tianshan Mountains region present a overall decreasing trend with large fluctuations, and the rate is about -0.54 $mm \cdot yr^{-1}$. The maximum rate of decline for -5.6 $mm \cdot yr^{-1}$ appears in the middle of the Tianshan Mountains. Especially, the water storage variation in the period from 2009 to 2010 shows large increasing trend, and the rate is about 21.98$mm \cdot yr^{-1}$, which is in accord with the rain, snow and other extreme weather disasters taken place frequently in this area. Also, the computation is in good agreement with the result from GLDAS and CPC hydrological models. GRACE has played an important role in drought, flood and other extreme climate monitoring in large scale.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-439

Evaluation of land hydrology derived from filtered GRACE satellite data in North America

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GRACE monthly gravity solutions have been used to estimate changes in the redistribution of masses. The dominant time-variable signals sensed by GRACE are the result of hydrological processes on the Earth's surface. A study has been performed to model surface mass changes by extracting the hydrology signal from the integrated gravity signal of GRACE. The extraction of the hydrology signal is done by using the global and regional hydrology models GLDAS 1.0 and NLDAS 2.0. The land surface models used for GLDAS 1.0 are the Noah, CLM, Mosaic and VIC, and for NLDAS 2.0 the Noah, Mosaic and VIC.

The study focuses on equivalent water height (EWH) variability computed on 1°-grids. The same processing strategies that use harmonic analysis and filtering are applied to hydrology models to ensure maximal consistency between the GRACE and the hydrology equivalent water height (EWH) fields. The estimated total mass changes are compared with GRACE Release 05 data. De-correlation and smoothing filters are applied to suppress the 'stripping' effect caused by correlations in high degree and order Stokes coefficients. Greenland and circum-Arctic area with strong snow growth signal are also masked. The GRACE signal is contaminated with the effect of glacial isostatic adjustment (GIA) in the arctic areas of North America. GIA models, such as the latest ice history models ICE5G and ICE6G, are examined and their effect is subtracted from the GRACE signal before results are interpreted. Without applying any GIA correction, the computed EWH fields show good agreement with both the GRACE signal and seasonality. The models closest to the GRACE EWH signal are the GLDAS NOAH and VIC. In North America, the GLDAS NOAH is found to be closest to the GRACE signal.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-440

Gravity reference and gravity change in Latvia 1995-2013

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Latvia belongs to the outskirts of the Fennoscandian postglacial rebound (PGR) area, with predicted vertical rates between 0 and +2 mm/yr. In 1995 we measured three absolute gravity stations in Latvia with the JILAg-5 of the FGI. One station (at the Riga satellite laser ranging site) was repeated in 1996 with the FG5-101 of the BKG and the FG5-107 of the NGA, and in 2007 with the FG5-221 by the FGI. All stations were re-measured in 2013 with the FG5X-221 of the FGI, when also a fourth station at the Irbene Radio Astronomy Center was added.

Latvia is covered by sediments, and only the Riga station is (probably) on rock. It is about 7 m underground, with the sediments above it. Given the large contributions from local hydrology to variation in gravity, both the determination of PGR gravity trends and the maintenance of gravity reference at the microgals level is a challenging task. For isolating the local contribution at Riga, we have performed repeated relative gravity observations in a local micro-network, and collected time series of groundwater measurements. The offsets between the different absolute gravimeters can be constrained using international and bilateral comparisons. We discuss the corrections to observed gravity and the uncertainty in accessing the reference values after the measurements, and estimate the residual trends.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-441

On sensor characteristics of superconducting and spring gravity metersinvestigated by the analysis of the time series recorded by them

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In spite of the superior performance of superconducting gravity meters (SG),spring gravity meters are still used for monitoring of gravity variations. To achive a comparable quality of the time series recorded by the two basic sensor types, however, the usual inter-comparison is not sufficient. The behaviour of the sensors in function of the tidal variation itself and their response to different kinds of environmental effects have to be studied in detail, as it is outlined in the presentation. The main point of the study is the determination of the scale factor function for astatic, feed-back-less spring gravity meters, recording by capacitive position indicator (CPI) and electro-optical device. Most of the experiments were done is the Conrad Observatory where a superconducting gravity meter SG025 and an accurate tidal model based on 2000 days of observation served as reference. The results show that the momentary scale of observations has a strong correlation with the actual phase of the tidal signal and with the irregular drift of spring gravity meters. The efforts to derive reliable scale factor function by heavy mass calibration are also presented. Beyond the existing difficulties of the interpretation of data the results show how the reliability of observations taken by spring sensors can be improved.Based on this progress a discussion about the idea of 'tidal mapping' or densification of the existing but unevenly distrubuted SG stations by spring gravity meters is proposed, because the maintenance and mobility of them are cheaper and higher, respectively, compared to SG-s or iGrav SG-s. In the light of the upcoming quantum gravimetry there is no doubt about its necessity in the near future.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-442

Postseismic gravity changes after the 2011 Tohoku earthquake recorded by superconducting gravimeters

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The 2011 Tohoku Earthquake (Mw9.0) has caused large scale crustal deformations, both coseismic and postseismic, in a wide area of the Japanese islands. Surface gravity observations are also sensitive to such changes and provide independent information on the tectonic processes taking place below Japan. Postseismic gravity changes are now recorded by superconducting gravimeters at three stations in Japan, Mizusawa, Matsushiro and Kamioka. The gravimeter at the Mizusawa station, closest to the earthquake source, appears to suffer from some instrumental problem after the Tohoku event, but a long term trend of rapid temporal decrease can be identified from the gravity residual. At the Matsushiro and Kamioka stations, gravity indicates an almost linear decrease with time at similar rates of about 10 microgal per year. This was also verified by absolute gravity measurements performed at Matsushiro in July 2013 and November 2014. The latter two stations are relatively far from the earthquake source region (epicentral distances being 420 km and 490 km, respectively), and the postseismic crustal uplifts of the stations recorded by GPS are too small to account for the observed gravity decrease. The observed gravity changes are likely to reflect ongoing changes in the density of the earth material, possibly associated with afterslip or viscoelastic relaxation.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-443

Gravity variations due to geocentre displacements

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The geocentre motion is the motion of the centre of mass of the entire Earth, considered an isolated system, in a terrestrial system of reference. Up to now, geocenter motions have been derived from positioning measurements only. We propose a new approach to constrain these motions by using ground gravity measurements. We first derive a formula relating the harmonic degree-1 Lagrangian variations of the gravity, the harmonic degree-1 vertical displacements of the station and the displacements of the whole Earth's centre of mass. The relationship is independent of the nature of the Earth deformation and is valid for any source of deformation. We impose no constraint on the system of reference, except that its origin must initially coincide with the centre of mass of the spherically-symmetric Earth model. Next, we consider the geocentre motion caused by surface loading. In a system of reference whose origin is the centre of mass of the solid Earth, we obtain a specific relationship between the gravity variations at the surface, the geocentre displacement and the load Love number h'_1, which demands the Earth's structure and rheological behaviour be known. We show that an annual gravity signal of 400 nGal (100 Gal = 1 m/s^2) associated with a geocenter motion of 1 mm is above the noise level of the superconducting gravimeter (SG) in Strasbourg, France. Given that, we investigate if the present network of SGs co-located with positioning measurements can detect the annual variation of the geocenter motion.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-444

Coseismic gravity gradient change caused by the Japan Tohoku-Oki 2011 earthquake based on the GOCE observations

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Although the main scientific objectives of GOCE (Gravity field and steady-state Ocean Circulation Explorer) mission are to recover the static gravity field model with high-spatial resolution, we use the GOCE gradiometry data spanning from April 2010 to February 2012 to detect the coseismic gravity gradient change caused by the Japan Tohoku-Oki 2011 earthquake event. Two global gravity field models up to degree and order 220 before and after this event are determined based on the least-squares method with the bandpass ARMA filter applied to the gradiometry data along the orbit. Because of the low accuracy in the low frequency of the gravity field model caused by the colored noises in SGG (Satellite Gravity Gradient) data, only the medium-high frequency coefficients of the models are used to compute the coseismic changes of gravity and gravity gradient components V_{xx},V_{zz} in space domain. Considering the polar gap problem of GOCE satellite orbit, the zonal and near-zonal coefficients are excluded. The spatial Gaussian smoothing is applied to gravity and gravity gradient to suppress high frequency error of the models. The calculated gravity gradient changes based on the GOCE observations are compared with the corresponding modeled coseismic signal based upon the given fault slip model parameters. The results show that the coseismic gravity gradient signal could be recovered from the GOCE observations.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-445

Copula-based filtering for GRACE Follow-On and future satellite gravity missions

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Since 2002, the GRACE mission provides monthly snapshots of the Earth's time variable gravity field. The GRACE-Follow-On mission and future satellite gravity missions are intended to continue and improve the measurements of the original GRACE mission. Their primary objective is to obtain highly accurate global estimates for the time variable of the Earth's gravity field. However, especially the higher-degree spherical harmonic coefficients are contaminated with noise. It is thus still mandatory to apply state-of-the-art filtering-techniques to the provided spectral data in order to reveal reasonable gravity field estimates.
In this study, we analyze the potential of stochastic copula-based filtering methods for gravity field solutions from the future satellite gravity missions. Our approach exploits linear and non-linear relations between filtered and unfiltered gravity solutions by fitting a theoretical copula function into an empirical bivariate or multivariate distribution function. The fitted copula then contains the complete information about the statistical dependency between the variables. As a result, noisy data can be filtered consistently with the captured statistical structure. The dependency structure between the unfiltered and filtered spectrum is derived within a short training period. Minimizing the duration of the training period is of utmost importance to the viability of the copula-based filter approach. Based on the derived dependency structure, we then generate random data, which is expected to be statistically consistent with the filtered solutions.

IAG (Geodesy)

G03p - G03 Variations of the Gravity Field

G03p-446

Continental water storage variations inferred from 3-D GPS coordinates timeseries for the major river basins in Europe and North Amarica

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Continental water storage (CWS) is particular important for the satisfaction of human demands, including water for agricultural, industrial and domestic use. It has been widely determined by GRACE mission measurements. After serving the science community for more than twelve years, a possible gap in the GRACE gravity measurements before the launch of GRACE Follow-On mission is expected. We investigate a method for filling the gap at regional scales by using the GPS 3-D coordinate time series.

Assuming the Earth is elastic solid body, mass changes on the surface induce displacements. The amount of the displacements can be obtained by using mass-loading Green's function [Farrell, 1972]. Inverting the observed displacements yields mass variations that can be interpreted as CWS changes. The permanent network of GPS stations around the Earth (15 years of data) record the displacements induced by mass loading.

We determine weekly CWS variations from GPS 3-D coordinate time series for the major river basins in Europe and North America. The results at the basin scale are validated against GRACE and hydrological models. We demonstrate the contribution of the GPS horizontal coordinates to estimates of CWS as well as the limits of our inversion approach. With the proper inversion setting, the estimated solution is consistent with GRACE and hydrological models in a high correlation (about 0.8). No significant annual signals can be detected in the residuals of the inversion results after subtracting GRACE/ hydrological models.

IAG (Geodesy)

G04a - G04 Earth Rotation and Geodynamics

IUGG-0572

Multichannel Singular Spectrum Analysis of the Axial Atmospheric Angular Momentum

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Earth's variable rotation is mainly produced by the variability of the Atmospheric Angular Momentum (AAM). In particular, the axial AAM component, which undergoes especially strong variations, induces changes in the Earth's rotation rate. In this study we analysed maps of regional input into the effective axial AAM from 1948 through 2011 from NCEP/NCAR reanalysis. Global zonal circulation patterns related to the Length of Day (LOD) were described. We applied Multichannel Singular Spectrum Analysis (MSSA) to the mass and motion components of AAM, which allowed us to extract annual, semiannual, 4-month, quasi-biennial, 5-year, and low-frequency oscillations. Principal components (PCs) strongly related to El Nino Southern Oscillation (ENSO) were released. They can be used to study ENSO-induced changes in pressure and wind fields and their coupling to LOD. The PCs describing the trends have captured slow atmospheric circulation changes possibly related to climate variability.

IAG (Geodesy)

G04a - G04 Earth Rotation and Geodynamics

IUGG-1317

A new high-frequency Earth rotation model in the analysis of VLBI observations

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Improving the current conventional model of short period ocean tidal effects in polar motion and changes in length-of-day is a key challenge of present Earth rotation research. Accurate estimates of ocean tidal angular momentum (OTAM) that are required to this end can be inferred from a purely altimetry-based method, in which measured elevations determine the OTAM mass signal and also the horizontal velocity field through an inversion of the classical shallow water equations. Some of the subtleties of this global adjustment, which we investigate here in the context of Earth rotation, include the weighting schemes for different observation equations, the treatment of closed boundaries, as well as the choice of bathymetry and the amount of bottom friction. We perform a range of test inversions, where the optimal parameter set for diurnals and semi-diurnals is found by working with a data-assimilative global tide model for which both heights and barotropic currents are known. Having completed the fit of tidal velocities to elevations from an up-to-date altimetric model of major constituents, OTAM values are computed and supplemented by the contributions from minor tides using admittance assumptions. We assess the quality of the derived high-frequency Earth rotation model by deploying it as an a priori in the analysis of VLBI (Very Long Baseline Interferometry) observations and comparing its performance to that of the conventional model and those of empirical solutions.

IAG (Geodesy)

G04a - G04 Earth Rotation and Geodynamics

IUGG-1891

Impact of the oceanic S1 tide on Earth's rotation – answering questions related to dissipation and forcing by numerical modeling

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Oceanic mass redistributions at the principal diurnal S1 frequency elicit small but measurable variations in universal time, polar motion, and the prograde annual component of nutation. Furnishing an accurate account of these signal components for the analysis of space geodetic observations is a delicate challenge that involves the determination of reliable OAM (ocean angular momentum) estimates from free-running forward integrations of the shallow water equations. The present study employs a simple barotropic ocean model to assess the dependency of the diurnal OAM vector on several key model components such as the amount of dissipation in the deep ocean. A realistic simulation of tidal elevations and velocities across the diurnal band is achieved by parametrizing the sub-grid scale conversion of barotropic currents into small internal tides through a linear drag term. Moreover, we demonstrate that our S1 simulations critically depend on the fidelity with which the actual meteorological forcing due to diurnal air pressure variations is known. Having selected an appropriate air tide solution from a range of atmospheric reanalyses through comparison with barometric in situ data, we investigate the relevance of ocean self-attraction and loading (SAL) for OAM considerations in an additional numerical experiment. Handling the SAL term in parametrized form instead of the full integral formulation is found to have little impact except for zonal spherical harmonics that couple to variations in universal time. OAM values for our optimally-configured hydrodynamic S1 solutions are documented and discussed in the specific context of their contribution to the prograde annual signal in Earth's nutation.

IAG (Geodesy)

G04a - G04 Earth Rotation and Geodynamics

IUGG-2073

Effects of meteorological input data on the very long baseline interferometry Earth orientation parameters

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Atmosphere pressure and temperature are very important for the analysis of space geodetic techniques, e.g. very long baseline interferometry (VLBI). Atmospheric mapping functions and atmospheric pressure loading require meteorological data through the atmosphere along the line of sight or globally distributed surface data. In our paper we investigate those effects that involve in-situ surface meteorological data only: zenith hydrostatic delay and antenna thermal deformation modelling.

At the radio telescopes operated by International VLBI Service for Geodesy and Astrometry there have always been meteorological data recorded during experiments. These data are valuable because they are given in the optimal temporal resolution: the resolution of the scan length that is usually a few minutes. We have homogenized the in-situ measurements with respect to ERA-Interim Reanalysis data applying a segmentation least absolute shrinkage and selection operator approach. In addition we have calibrated the measurements using pressure and temperature from selected World Meteorological Organization stations located in the vicinity of the VLBI radio telescopes.

In this paper we apply the homogenized and absolute calibrated series of meteorological data in VLBI analysis. To assess the effects on the Earth orientation parameters, different solutions are compared that involve either the original in-situ meteorological data or the homogenized and calibrated ones. For comparison we also determine solutions based on meteorological data provided by currently available empirical atmosphere models, such as GPT2, which serve as substitutes in case of in-situ data are not available. The significance of our results is interpreted considering the Global Geodetic Observing System accuracy goals.

IAG (Geodesy)

G04a - G04 Earth Rotation and Geodynamics

IUGG-2476

Determination of atmospheric tidal effects in Earth rotation parameters by means of VLBI

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In this study, we assess the contribution of diurnal (S1) and semi-diurnal (S2) atmospheric tides to variations in Earth rotation by analyzing geodetic Very Long Baseline Interferometry (VLBI) observations. Particular emphasis is placed on the dependency of S1 and S2 estimates on varying settings in the a priori delay model. We use hourly Earth rotation parameters (ERP) of polar motion and UT1 as determined with the Vienna VLBI Software (VieVS) from 25 years of VLBI observations and we adjust diurnal and semi-diurnal amplitudes to the hourly ERP estimates after disregarding the effect of high-frequency ocean tides. Prograde and retrograde polar motion coefficients are obtained for several solutions differing in processing strategies (with/without thermal deformation, different analysis windows, selections of a priori ERP models and celestial pole offsets) and we compare the corresponding harmonics against those derived from atmospheric and non-tidal oceanic angular momentum estimates.

IAG (Geodesy)

G04a - G04 Earth Rotation and Geodynamics

IUGG-2986

Numerical issues in space-geodetic data analysis and their impact on Earth orientation parameters

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Space-geodetic observations are used to determine parameters which represent the orientation of the Earth in space. The parameters are mostly evaluated in a linearised least squares adjustment on the basis of a Gauss-Markov-Model. Then, the variance-covariance matrices of parameters and observations are generally analysed for quality and reliability investigations. It is essential to note that these matrices are not only affected by the design of the measurement process, but also by the characteristics of the functional description and, thus, also by the numerical characteristics of the solution. To describe these characteristics, the concepts of conditioning and stability of the solution can be investigated. While conditioning refers to the numerical problem, numerical stability refers to the algorithms which are used. In this context, a numerically stable algorithm does not amplify the errors of the observations. In many applications, the equation system of the least squares adjustment is ill-conditioned. As a consequence, errors of the observations are amplified during the adjustment process.

This paper focuses on the impact of numerical conditioning illustrated by an analysis of Very Long Baseline Interferometry (VLBI) observations with their limitations, like e.g., the distribution of the observing network or the presence of significant data gaps. Furthermore, VLBI is fundamental for the determination of Earth Orientation Parameters. The paper presents methods to reveal the relationship between numerical characteristics of the normal equation matrix and parameter as well as network properties. At the end, we will give recommendations to improve VLBI derived Earth Orientation Parameters which is also relevant for other space-geodetic techniques.

IAG (Geodesy)

G04b - G04 Earth Rotation and Geodynamics

IUGG-1058

Geo-center movement caused by huge earthquakes

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Geo-center variations are related to the adopted reference frame. The origins of the Earth-related frames are usually defined as one of the three centers: the center of mass of the whole Earth including the oceans and atmosphere (CM), the center of mass of the solid Earth (CE) and the center of figure of the outer surface of the solid Earth (CF) (Dong et al, 1997; Wu et al., 2012). When there are no external net forces acting on the Earth system, CM remains unchanged while the other two changed. For co-seismic deformation, however, a SNERI Earth model is being used, in which the oceans and atmosphere are not taken into account. Therefore CM is identical to CE which also remains unchanged after an earthquake occurs. Consequently, the only possible changing center after an earthquake is CF.

As our terrestrial reference frame, e.g., ITRF 2008, is defined and maintained by a set of tracking stations on the Earth's surface, hence the change of CF is of great applicable importance. Consequently, following Dong et al (1997)'s definition of geo-center, i.e., CF relative to CM, we derive a new formula to compute co-seismic geo-center movement and applied in the recent two huge earthquakes. In this paper, we discuss this issue from different approaches. We derive a new formula to compute the co-seismic geo-center and Earth's centre movements caused by the huge earthquakes, and new results are presented: the 2004 Sumatra earthquake and the 2011 Tohoku-Oki earthquake change the geo-center by 1-4 mm and about 2 mm, respectively; and displace the Earth's centre by about 0.05 mm and 0.025 mm, respectively.

IAG (Geodesy)

G04b - G04 Earth Rotation and Geodynamics

IUGG-1652

Abrupt changes in drift trend of the earth's geocenter and rotational pole in 2012-2014

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Positions of the earth's geocenter and rotational pole are constantly moved by mass redistributions on/in the earth. Such movements can be estimated via low-degree gravity field measurement by Satellite Laser Ranging (SLR). In this study, we investigate recent trends in geocenter motion and polar motion based on SLR analysis. We compute their linear changes for the following three periods: 1994-2002, 2003-2011, and 2012-2014. Here annually-averaged drift rates and directions are described as (rates, azimuth angle, elevation angle) for geocenter motion and (rates, azimuth angle) for polar motion, respectively. In 1994-2002, the obtained drift trends are (0.5mm/yr, -26°, 59°) for geocenter motion and (1.3mm/yr, -73°) for polar motion. Concerning polar motion, the good agreement with EOPs data by VLBI was confirmed. These trends are considered to be caused by Glacial Isostatic Adjustment [e.g. Wahr et al., 1993; Greff-Lefftz, 2000]. In 2003-2011, the obtained drift trends are (0.8mm/yr, 111°, -61°) for geocenter motion and (5.4mm/yr, 14°) for polar motion. These trend shifts from 1994-2002 can be well explained by large-scale ice mass depletion in polar region started in 2000s [e.g. Chen et al., 2013; Dong et al., 2014]. In 2012-2014, the obtained drift trends are (3.4mm/yr, -84°, 44°) for geocenter motion and (8.9mm/yr, -62°) for polar motion. We can see distinct departures in drift trends from 2003-2011. By analyzing other geodetic data and geophysical models, we have revealed that these trend shifts can be attributed to an abrupt stagnation of Greenland's ice loss after autumn of 2012.

IAG (Geodesy)

G04b - G04 Earth Rotation and Geodynamics

IUGG-2635

Inertial Rotation Sensing for Geodesy and Geophysics

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Inertial rotation sensing, as exploited in Sagnac interferometers, does not require an external frame of reference as opposed to the VLBI technique. Large HeNe ring lasers constitute the only technical realizations to date that have sufficient measurement resolution to be useful for geodesy and geophysics. Furthermore they represent the only measurement technique, which is directly linked to the instantaneous axis of rotation of the Earth. However there are serious demands placed on this sensor. Scale factor stability to ?f/f $\leq 10^{-10}$ and the absence of non-reciprocal coupling of the two counter-propagating laser beams are mandatory. Implementing a frequency stabilization scheme by using a pressure controlling enclosure and a piezo control stage, provides the necessary scale factor stability. Since laser beam coupling cannot be avoided by principle, we have implemented a numerical correction model, based on a few readily available measurement quantities from the ring laser cavity. Now local tilts remain as the predominant error source. We present a measurement series of more than 130 days of length, which is essentially free of drift. This talk will outline the recent achievements and explains the current status of Sagnac interferometry with respect to Earth rotation research.

IAG (Geodesy)

G04b - G04 Earth Rotation and Geodynamics

IUGG-4478

18.6-yr Tide Variations from 40-year Satellite Laser Ranging (SLR)

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40-year satellite laser ranging (SLR) has recorded the global nature of the long-wavelength mass change within the Earth system, in particular, the Earth's dynamical oblateness, characterized by the second degree gravitational zonal geopotential spherical harmonic J_2. The ocean and solid earth tide produce variations with an 18.6-yr period, but with different amplitude and phase in the time domain. Analysis of the most recent time series of 30-day SLR-based estimates of J_2 indicates that the long-term variation of J_2 appears to be the superposition of a quadratic and 18.6-yr variation. The effects of the ocean tide and anelasticity solid Earth at the 18.6 period can be detected in the 40-year time series of variations of J_2. The response of the global ocean to the lunar attraction at the 18.6-yr period deviates from equilibrium by a phase lag of ~2.5±2° and ~20% of the equilibrium amplitude (0.486 cm). A nominal anelasticity Love number, k_2, is estimated to be 0.31107±0.0011 with the IERS model of the frequency dependent Love number at 18.6-yr period from the reference frequency= 200 seconds and a = 0.155 for mantle anelasticity.

IAG (Geodesy)

G04b - G04 Earth Rotation and Geodynamics

IUGG-5422

Effects of frequency-dependent tidal deformations on the rotation of a two-layers Earth model

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We tackle the rotation of an Earth model composed of a deformable mantle and a fluid core, extending previous analytical investigations developed by Getino & Ferrándiz through Hamiltonian formalism. Specifically, we consider the complete effects of the tidal induced deformation on the rotational dynamics, which generates additional contributions, both to the kinetic and gravitational potential energies of the system.
Unlike other approaches, this method ensures the consistency of all those contributions, since they are derived from a sole Hamiltonian function. Besides, it also allows considering different rheological models for the Earth mantle and determining the resulting influences on the Earth rotation. After presenting an analytical solution of the dynamical problem, we discuss the effects of frequency-dependent deformation parameters on the nutational motion of the Earth figure axis when compared to the case of frequency-independent parameters, which is usually assumed in most of the current models. Our results show that the stringency of the accuracy requirements nowadays should entail the inclusion of these contributions.

IAG (Geodesy)

G04b - G04 Earth Rotation and Geodynamics

IUGG-5615

Investigation on the use of ring laser gyroscope data for monitoring semidiurnal and prograde diurnal signals in polar motion

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In the previous study (Tercjak et al., Proc. Journees 2014) we demonstrated that the estimation of nutation rates from the ring laser gyroscope (RLG) is possible, though under a number of restrictive assumptions which can be hardly achieved at present. Here we examine a possibility of using the RLG observations for continuous monitoring of the prograde diurnal and retrograde/prograde semidiurnal signals in polar motion, as suggested by Brzezinski (Proc. Journees 2008). We investigate the use of one RLG with the parameters of the real RLG in Wettzell, and simulate the use of several RLG's at various locations worldwide. We also consider the combination of the RLG measurements with the diurnal and semidiurnal signals in polar motion which can be demodulated from Very Long Baseline Interferometry (VLBI) observations (Böhm et al., 2012, J. Geodynamics 62, 56-68).

IAG (Geodesy)

G04c - G04 Earth Rotation and Geodynamics

IUGG-1557

Frequency dependency of the ratio between gravity variation and vertical displacement for an ellipsoidal rotating anelastic Earth

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It is well known that the Earth's mantle rheological behavior strongly depends on the frequency of the deformation. From slightly anelastic in the seismic band to viscoelastic with important dissipation at lower frequency, the deformations induced by various geophysical processes are largely variable. The nature of the rheological transition between periods of a few seconds to several thousand years is still an open question.

One of the observable Earth's parameters sensitive to this rheological change is the ratio between gravity variation and vertical surface displacement due to Earth's loading or unloading. It has been efficiently used as a way to distinguish, for instance, the present-day ice melting elastic response of the lithosphere from the long term glacial isostatic adjustment (GIA) that involves deeper mantle viscoelastic materials. In this work, we numerically compute this ratio over large frequency and viscosity ranges for an ellipsoidal rotating anelastic Earth model. We test several mantle rheologies and rheological parameters for the loading problem. So, we model the continuous variation of the ratio, from its elastic value to its viscoelastic value.

Our modeling enables us to compute other Earth's parameters, such as Love numbers whose variations with frequency and rheological parameters are studied too. In addition, we compute the gravimetric factor amplitude and phase for the Chandler wobble which is the only known eigenmode occurring at intermediate periods.

IAG (Geodesy)

G04c - G04 Earth Rotation and Geodynamics

IUGG-2054

Correlation at noise level between GPS and gravity data

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We took data from 8 globally distributed co-located GPS and Superconducting Gravimeter (SG) sites (Metsahovi, Potsdam, Onsala, Wettzell, Medicina, Pecny, Brussels and Ny-Alesund) to investigate common signals in gravity and height changes. We used GPS time series processing at the JPL using GIPSY-OASIS II software with PPP mode. The longest GPS data covered the period from 1996 until present, while SG from 1992 until present. The 1-minute SG data was resampled to 1 day using a simple moving average with time samples centred at 12:00 UTC for being consistent with the GPS Up component.. In order to make the time series consistent and comparable to each other, the solid tidal gravity effects equivalent to the tidal displacement correction that is applied on GPS data (same tidal model) was used to correct the gravity observations (based on the IERS Conventions 2003). The ocean tides were subtracted using the FES2004 model. The annual harmonics, from the 1st to the 10th, of the atmospheric tide were removed using a least squares estimation. In addition, the draconitic year both with its harmonics were removed from GPS data. The noise analysis was then done for both GPS and SG residual data. In this presentation, we focus mainly on the comparison of the noise characteristics between the GPS and SG data. In that purpose, we compare two approaches: the Power Spectral Density (PSD) and the Maximum Likelihood Estimation (MLE). Firstly, from the PSDs, we retrieve the best-fitted slopes by taking into consideration not only the whole frequency spectrum, but also the different noise features for certain frequency bands. Secondly, these results are compared to the MLE power-law estimates together with the indication of the noise amplitudes that disrupt the analysed data.

IAG (Geodesy)

G04c - G04 Earth Rotation and Geodynamics

IUGG-2744

Autocorrelation in GRACE-derived ice mass change time series and their effect on trends and accelerations

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Trends and accelerations estimated from GRACE-derived ice mass change time series have generally been based on the, often implicit, assumption that the residuals to a regression model have no serial correlation. We used the Center for Space research (CSR) Release 5 (RL05) monthly GRACE gravity fields between March 2003 and July 2012 and produced time series for locations on a regular 500 km grid across Antarctica using the Gaussian spatial averaging approach with an averaging radius of 400 km. We used power-law and autoregressive stochastic models and compared the results using the Bayesian Information Criteria (BIC) to results that assume white (uncorrelated) noise and found significant autocorrelation is present. Accounting for autocorrelation indicated that white noise uncertainties would need to be scaled upwards by a factor of up to 4 for accelerations and 6 for linear rates, depending on length of observations and location. For the subset of time series offshore we found substantially less time-correlation, and therefore lower scale factors, indicating that the correlation is related to continental mass change. Despite the more realistic uncertainties, we found significant accelerations over Dronning Maud Land (increasing mass gain) and much of West Antarctica (overall increasing mass loss). For the ice sheet as a whole we also found a marginally significant acceleration (increasing mass loss).

IAG (Geodesy)

G04c - G04 Earth Rotation and Geodynamics

IUGG-4406

The BIFROST project: 21 years of search for the true crustal deformation in Fennoscandia

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The BIFROST (Baseline Inferences for Fennoscandian Rebound Observations Sea Level and Tectonics) project was started in 1993. The first primary goal was to establish a new and useful three-dimensional (3D) measurement of the movements in the Earth’s crust based on Global Navigation Satellite System (GNSS) observations, able to constrain models of the glacial isostatic adjustment (GIA) process in Fennoscandia.

Here we present our latest GNSS-based 3D velocity field of the Fennoscandian GIA process, and compare it with the latest GIA model of Fennoscandia derived within BIFROST. The solution to be presented is the result of a re-processing of data from 1997 to 2014 including more than 200 stations in northern Europe. It was computed using state-of-the-art strategy with the most recent versions of both GAMIT and GIPSY/OASIS software. We evaluate computed station velocities and discuss agreements and differences to previous presented GNSS solutions and especially the recent developments in GIA models.

Of special interests in activities like BIFROST are issues regarding reference frames, which are especially important while searching for true vertical velocities, as well as long-term stability in the observation system including new generation of satellites and changes in the ground segment. These issues will also be discussed in the presentation. Observed gravity change derived from repeated absolute gravity campaigns have the potential to additionally constrain models of GIA, and possibly also the stability in the geodetic reference frame. We will therefore also compare the GNSS results with some recent results of rate of gravity change.

IAG (Geodesy)

G04c - G04 Earth Rotation and Geodynamics

IUGG-4411

Present day contribution of ice-sheets and glaciers to the sea-level in view of GIA model uncertainties

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A recently developed global mascon method takes CSR level-2 data from GRACE between February 2003 and June 2013 as input. The method assumes that the data is corrected for degree 1 geocenter loading and degree 2 loading for which SLR predictions are used. A main correction that affects the present day sea-level contribution comes from adopted glacial isostatic adjustment (GIA) model. An ensemble of published GIA models developed with various ice histories and rheological Earth model parameters provides for Greenland a mass loss of −278 +/- 19 Gt/yr. Whereas the mass balances for the GrIS appears to be less sensitive to GIA modeling uncertainties, this is not the case with the mass balance of Antarctica. New ice history models for Antarctica were recently improved, and an updated historic ice height dataset and GPS time series have been used to generate new GIA models. We investigated the effect of two updated GIA models for Antarctica and found −92 +/- 26 Gt/yr, which is half of what is obtained with ICE-5G based GIA models, where the largest GIA model differences occur on East Antarctica. In addition we looked at the performance of finite element GIA models that allow lateral heterogeneities, these models estimate a variation between -146 and -178 Gt/yr when they are based on the ICE-5G ice model and between -39 to -55 Gt/yr when based on the Whitehouse 2012a ice model. The mass balance of land glaciers and ice caps currently stands at −162 +/-10 Gt/yr. With the new GIA models for Antarctica we assess the mass contribution to the mean sea level at approximately half of the global sea level rise signal obtained from tide gauges and satellite altimetry.

IAG (Geodesy)

G04c - G04 Earth Rotation and Geodynamics

IUGG-5198

Vertical crustal motions from tide gauge observations and satellite altimetry in southern Italy

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The Italian peninsula with its islands is tectonically active to the effect that the entire territory is exposed to high natural hazard due to earthquakes and volcanoes. The tectonic activity leads to vertical motions that affect the coastlines. Tide gauges measure the relative motion between the coastline and the sea surface. A measured increase in sea level is therefore the sum of sea level rise and crustal subsidence. If the goal of the observations is measuring the vertical crustal motions, the sea level rate must be subtracted. Satellite altimetry gives an independent measurement of the sea surface rise. Due to interannual variability of sea level change, the time series of tide gauges and satellite altimetry must be at least 10 years long and contemporaneous. The observations of the satellite missions ERS, Topex/Poseidon and Jason and the tide gauges of the Italian tide gauge network meet this criterion (Fenoglio Marc et al., 2012). For southern Italy the tide gauges are analyzed statistically among each other to obtain the relative sea level rise variations along the coast (Braitenberg et al., 2010). The correlation coefficient between tide gauges is very high, over 0.9, between tide gauges and altimeter lower, but still relatively high up to 0.7. Statistically significant vertical movements have been found in southern Calabria and eastern Sicily. The results are validated with geomorphologic results, vertical rates from GPS, and from repeated leveling (Spampinato et al., 2013).

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IAG (Geodesy)

G04d - G04 Earth Rotation and Geodynamics

IUGG-1498

Detailed analysis of diurnal tides and associated space nutation in the search for the Free Inner Core Nutation resonance

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We propose a comparison of the tidal analysis results obtained from the continuous records of time-varying surface gravity obtained by a worldwide network of Superconducting Gravimeters (SGs) with the analysis results of space nutation observed by the international Very Long Baseline Interferometry (VLBI) network. The length of the surface gravity time series enables now to look for additional diurnal tides that were previously not analyzed. In parallel, we now possess 35 years of VLBI data permitting to look for additional nutation terms. We focus our analysis on the diurnal prograde frequency band in the search for a possible resonance effect linked to the Free Inner Core Nutation (FICN). This Earth's normal mode has never been clearly observed. Its direct deformation effect at the Earth's surface is theoretically predicted to be too small to be detected. However, the tidal forcing at a frequency close to its eigenfrequency could enhance some tidal or nutation amplitude resulting in the characterization of this mode through its resonance effect.

IAG (Geodesy)

G04d - G04 Earth Rotation and Geodynamics

IUGG-2332

Anelasticity of the asthenosphere inferred from GPS observations of ocean tide loading displacements in western Europe

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GPS-observed vertical ocean tide loading displacements for the main tidal harmonic M_2 in Cornwall, southwest England and in Brittany, northwest France, show discrepancies of 2-3 mm with respect to predicted values based on the isotropic preliminary reference Earth model PREM. However, in central Europe the agreement is better than 0.5 mm. By comparison of numerical ocean tide models and validation with tide gauge observations, we establish that the uncertainties in the former are too small to cause this disagreement. Furthermore, we find that different local models of the crust and different global elastic reference models derived from seismological observations can only reduce the observed discrepancies to 1-2 mm, which still exceeds the GPS observational uncertainty of 0.2-0.4 mm (Penna et al., this meeting). Previously, there has been insufficient evidence to determine how to modify the elastic properties of the Earth as given by seismic models during the transformation from seismic to tidal frequencies so as to account for possible anelasticity in the asthenosphere, and so this effect has been ignored. If we include it, the discrepancies reduce further to 0.2-0.4 mm, which is of the same order as the sum of the remaining errors due to uncertainties in the ocean tide models and in the GPS observations themselves. Our research provides evidence of a reduction of around 8-10% of the shear modulus in the asthenosphere from seismic to tidal frequencies, in western Europe. Consequently, we find that the asthenosphere absorption band frequencies can be represented by a constant quality factor Q.

IAG (Geodesy)

G04d - G04 Earth Rotation and Geodynamics

IUGG-3604

Free Core Nutation parameters from hydrostatic long-base tiltmeter records

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The Free Core Nutation (FCN) can be observed by the resonance effects on the forced nutations of the Earth's figure axis detectable in VLBI observations, or in the diurnal tidal waves, retrieved from whatever geophysical recording sensor (e.g. gravimeters, tiltmeters, strainmeters, etc). FCN parameters (period, quality factor and resonance strength) have a clue role in constraining some deep Earth's properties (e.g. dynamic ellipticity of the core, dissipation through electro-magnetic coupling at the core-mantle boundary, etc.).

The resonance associated with the FCN has been widely studied in superconducting gravity records, but few experiments have been done with tiltmeters. In this study we use records collected with a pair of about 100 m long hydrostatic silica tiltmeters, orthogonally installed in a dismissed silver mine at Sainte Croix aux Mines (Alsace-Eastern France).

Main difficulties in retrieving FCN parameters from tidal analysis arise from the weak amplitude of PSI1 tidal wave (the closest in frequency to the FCN), as well as from the inaccuracy of the available ocean loading correction. Moreover because of the closeness in frequency of the single constituents of the diurnal tidal band, long (> 1 year) records are needed for resolving K1, PSI1 and PHI1 waves. Hence we analyze a ten-year dataset of tilt records, which has preliminarily required a critical review and a relevant editing for making records suitable for tidal analysis and subsequent inversion of the tidal parameters. A detailed analysis is even carried out on the possible instrumental and physical sources limiting the signal-to-noise ratio in tiltmeter records.

A linearized least-squares Marquardt method as well as a Bayesian inversion are used for the retrieval of the FCN parameters.

IAG (Geodesy)

G04d - G04 Earth Rotation and Geodynamics

IUGG-3702

Improved determination of postglacial rebound and sea-level change using geodetic constraints on models of glacial isostatic adjustment

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Based on the repeated levellings, tide gauge records (combined with satellite altimetry) and GNSS measurements the rates for sea level and geoid changes as well as land motions are estimated in Estonia. Due to the ongoing postglacial rebound (PGR) process in the study area, the observed rates can be used to verify the predictions from glacial isostatic adjustment (GIA) models.

The test computations with different ice and viscoelastic Earth's models in the GIA modelling process are made to find the optimum fit between observed and predicted rates. Before the comparison, these rates need to be transformed to a common reference frame. Simple 2-parameter transformation (taking account sea level and geoid changes) is tested for the comparison of predicted uplift rates (in GIA-related frame) with observed apparent and absolute uplift rates (relative to sea level and Earth's center of mass, respectively). For the rates of horizontal motion the comparison through the 7-parameter transformation is experimented.

To evaluate the significance of the differences between the observed and predicted rates, uncertainties of both components need to be estimated. However, the estimation of uncertainty is complicated for the predicted quantities from GIA modelling. To evaluate the accuracy of observed uplift rates from the geodetic measurements and predictions from GIA models, the empirical land uplift models are included into the comparison. Despite some systematic differences, good agreement between the observed and predicted uplift rates is found. Similar conclusion can be made for the rates of horizontal motion.

IAG (Geodesy)

G04d - G04 Earth Rotation and Geodynamics

IUGG-4592

Effective mantle viscosity and heat flux: Addressing uncertainty in glacial isostatic adjustment and ice sheet models for Antarctica

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With the data collected in seismology and geodesy from the International Polar Year 2007-2008 Polar Earth Observing Network (POLENET) the outlook for resolving many of the long-standing issues concerning the amplitude and spatial distribution of present-day time-varying geoid and vertical crustal motions related to glacial isostatic adjustment (GIA) have improved greatly (e.g., King et al., 2012; Shepherd et al., 2012; Groh et al., 2012). There is wide acknowledgement of the high probability of strong contrast in solid earth structure (e.g., A et al. 2013) and its potential role in generating non-uniqueness in ice load – earth response combinations to explain both the secular component of time-varying gravity observed from space, and vertical motion of GPS stations. POLENET has provided both the geodesy and the seismology communities with data for taking many giant steps in formulating new ideas and promoting a general understanding of tectonics, rheology and late-Quaternary ice sheet evolution. Here we try to demonstrate the interconnection of the two community efforts toward bounding viable models for geothermal heat flux and demonstrate its profound impact on prognostic sea-level rise experiments using sophisticated numerical simulation of the Antarctic ice sheet in a climatically warming environment several hundred years into the future.

IAG (Geodesy)

G04d - G04 Earth Rotation and Geodynamics

IUGG-5016

Separating glacial cycle impacts upon Earth rotation from that due to global warming

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The Late Quaternary glacial cycle continues to exert impact upon Earth's rotational state, an impact that may be accurately estimated on the basis of the most recent model of the global process of glacial isostatic adjustment, the ICE-6G_C (VM5a) of Peltier, Argus and Drummond (JGR-Solid Earth, 2015). Similarly, modern earth orientation data sets can be employed to constrain the rates of change of the primary rotational observables, the most important of which consist of the observed speed and direction of true polar wander and the non-tidal contribution to the rate of change of the length of day. In addition to these primary constraints there is also strong rotational influence on the degree 2 and order 1 Stokes coefficients in the spherical harmonic expansion of geoid height time dependence. By separating the impact of ice-age influence on these parameters from the modern strengths of variation in each we may isolate the impact due to modern global warming of the lower atmosphere. Since the global warming effect is associated primarily with the rates of melting of both the great polar ice sheets and of small ice sheets and glaciers and since the contributions due to the Greenland and Antarctic ice sheets as well as from ice loss occurring from the high altitude ice catchments in Alaska and the Yukon territory of Canada, the small ice sheets and glaciers contribution is constrained by the remaining residual. I will report a series of analyses devoted to inferring the primary locations of the small ice sheets and glaciers contribution on the basis of this residual. Although this inverse problem cannot be solved uniquely, an exploration of plausible solutions provides considerably insight as to where the dominant sources may reside.

IAG (Geodesy)

G04e - G04 Earth Rotation and Geodynamics

IUGG-0481

Coseismic slip distribution of the 2011 Tohoku (Mw 9.0) earthquake inverted from GRACE

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GRAC gravity data have been used so far to invert the seismic source parameters of megathrust earthquakes assuming a uniform slip over the fault or a point-like seismic source. Herein, we extend further the inversion of GRACE gravity data to heterogeneous slip distributions over a constant-strike fault I and a realistically varying strike fault II models for the 2011 Tohoku earthquake. The total seismic moments of our slip models, 4.4 and 5.1×10^{22} N m, are smaller than those from other studies relying on GRACE data and their centroids are located at greater depths, 24 and 22 km, for fault I and II. The slip pattern on fault I is moved southward with respect to that obtained from GPS and we discuss how this is related to an anti-clockwise rotation of about 10° of the gravity pattern synthetized using GPS with respect to that observed by GRACE. Our results show that this inconsistency between inversions from GPS and GRACE data is due to the usage of a constant-strike angle along the Japan Trench in the fault I model: the varying strike in the fault II model carries in fact into coincidence the slip and gravity patterns from GRACE and GPS. The strike variation along the trench of the subducting plate plays thus a major role on the shape of the gravity pattern and on the epicenter location from GRACE data inversion. The slip distribution for the fault II has a maximum slip of 23 m and a large scale rupture due to the GRACE spatial resolution of 300 km, which is however consistent with that from inland GPS data whose geographical distribution over Japan is herein shown to require a more compact rupture once compared with that from a simple, planar constant-strike fault.

IAG (Geodesy)

G04e - G04 Earth Rotation and Geodynamics

IUGG-1560

Tidal spectroscopy from a long record of superconducting gravimeters in Strasbourg

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Long term gravity records are of great interest when performing spectral analysis. The long series enable to separate contributions of near-frequency waves (the frequency resolution is the inverse of the data length) to detect very weak amplitude signals and also to detect low frequency signals (the lowest frequency in the spectrum is also the inverse of the data length).
There is a long tradition of recording solid Earth tides at Strasbourg. Since 1987, two models (T005 and C026) of superconducting gravimeters (SGs) have been recording consecutively at J9 Observatory, resulting, after merging, in the longest available series ever recorded by SGs at the same site. We use this series to perform high spectral resolution in the various tidal bands. We compare the spectral analyses of the observed and theoretically predicted signals at Strasbourg using the Hartmann and Wenzel (1995) tidal potential development in the various frequency ranges, from the quarter-diurnal to the 18.6-year tidal band. The length of the data series allows us to retrieve small amplitude waves in the major tidal groups (e.g. tides generated by the third-degree potential), to separate waves close in frequency and to detect very low frequency signals that have never been observed in gravity data of shorter duration. In addition to the length of the series, we show that the quality of the data and the temporal stability of the noise are also very important. From the comparison of the independent series from each gravimeter, we infer how the signal to noise ratio (SNR) of each gravimeter impacts the SNR of the entire series.

IAG (Geodesy)

G04e - G04 Earth Rotation and Geodynamics

IUGG-1563

Hybrid gravimetry as a tool to monitor sub- surface mass changes

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Time-lapse gravimetry is known to be a powerful tool to monitor mass redistributions near the Earth's surface (water, oil, gas, ice, magma) and hence is of interest in various fields (volcanology, hydrology, glaciology, geothermics, C02 sequestration). Hybrid gravimetry relies on the combined use of different types of instruments i.e. relative spring gravimeters (RG) and superconducting gravimeters (SG), as well as ballistic absolute gravimeters (AG) in a specific study.

Ideally there is a need for a continuous monitoring of a base station (reference) with a relative SG. AG measurements have to be done regularly at this base station to check the instrumental drift and the time stability of the calibration of the SG. Finally repeated micro-gravimetric measurements with a RG on a network around the base station bring additional insight on the space and time variable gravity field in the investigated zone.

We show here that hybrid gravimetry is able to provide new constraints on various processes occurring underground or at the Earth's surface. We will focus on several applications in Earth's sciences: underground water storage changes in hydrology, ice melting rates in glaciology, and magma motion in volcanology. We will also show the importance of hybrid gravimetry in the monitoring of deeper geothermal reservoirs.

IAG (Geodesy)

G04e - G04 Earth Rotation and Geodynamics

IUGG-2483

A Non-tidal Atmospheric Loading Model: Its Quality and Impacts on Results from SLR

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Based on European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim data we evaluate long-term displacements of global station coordinates in a non-tidal atmospheric loading model based on Farrel's theory. We apply these displacements to Satellite Laser Ranging (SLR) data processing over a recent six years period of the LAGEOS, AJISAI, STARLETTE, and STELLA geodetic satellites. We discuss the results and assess the accuracy of the model in comparison to other publicly available models. For this we look into time series of station coordinate solutions at selected sites on Earth. We also quantify the impact of non-tidal atmospheric loading on the resulting large scale figure of the Earth by evaluating the impact on the low degree spherical harmonics solutions with particular focus on the degree two terms.

IAG (Geodesy)

G04e - G04 Earth Rotation and Geodynamics

IUGG-4525

High precision gravimetry applied to the improvement of lunar laser ranging at Apache Point Observatory, New Mexico, USA

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A 3.5 m optical dish at Apache Point Observatory is currently one of the leading instruments for measuring the instantaneous Earth-Moon distance, a project known as APOLLO, especially important at the lunar synodic and orbital periods of 29.53 and 27.55 days respectively. Such measurements are at the forefront of the improvement in assessing theories of gravitation, testing quantities such as preferred reference frames, geodetic precession, the time variation of G, and the strong equivalence principle. As part of an effort to improve the distance accuracy, APOLLO added a superconducting gravity (SG) to its site in 2009 to permit more accurate modeling of the tidal response of the Earth and other deformations that arise at local regional crustal scales to influence the telescope coordinates. Regular AG measurements at the site are also made for calibration and drift purposes. To date we have provided high quality tidal parameters for the site, and cross-analyzing the gravity perturbations with GPS measurements from a nearby solar observatory, SUNSPOT. Of some importance in getting a reliable estimate of mass changes and deformation has been to construct a hydrological model that has significantly reduced the SG residuals at timescales of days – months. The current status of the measurements and possibilities for continued improvement will be presented.

IAG (Geodesy)

G04e - G04 Earth Rotation and Geodynamics

IUGG-4570

Complexity of source fault of inland earthquakes revealed by SAR interferometry

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Since the Landers earthquakes of 1992, SAR interferometry (InSAR) has been utilized to detect coseismic deformations and estimate configuration of source fault and slip distribution. In Japan, studies of conseismic deformation and fault model have been conducted using mainly L-band SAR sensors since the Kobe earthquake of 1995. Especially, ALOS/PALSAR observed coseismic deformations of earthquakes all over the world since 2006 and had successful results. Among of all, the complexity of source fault is the most important. In this report, I review some of important results and discuss their significance in earth and disaster sciences.

We revealed slip on parallel faults, heterogeneous slip distribution and variation of configuration of faults along strike for the Wenchuan earthquake of 2008. Anti-correlation of coseismic deformation to the topography was detected during the Haiti earthquake in 2010. We concluded that the source fault is not a vertical left lateral sinistral fault, the Enriquillo fault, but a buried one in the crust. In the same year, more than 5 small segments ruptured during the Darfield, NZ, earthquake. Obliquely crossing faults ruptured during the Iwaki earthquake of 2011. There are earthquakes with a simple plane fault, but they are minority during the 5 year operation of ALOS/PALSAR.

The above results contradict the characteristic earthquake model on which the long-term forecasts in Japan is based. Therefore it is important to model these complicated behavior of earthquake rupture and incorporate it to long-term forecasts.

IAG (Geodesy)

G04f - G04 Earth Rotation and Geodynamics

IUGG-1620

Impact of interannual mass loading deformation on secular surface velocities

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Geodetic velocities derived from data as short as 3 years are often assumed to be representative of linear deformation over past decades to millennia.
Here, we assess the impact of mass loading deformation at the interannual period on secular surface velocities.
We use two decades of vertical surface deformation predictions due to variations of atmospheric (from ERA Interim), oceanic (from ECCO) and continental water (from ERA Interim) mass loading on a 2° global grid. We found that the interannual deformation is clearly time-correlated at most of the locations and, generally, is adequately described by a power-law process of spectral index varying between -0.2 to -1.5.
Depending on the power-law parameters, the predicted non-linear deformation due to mass loading variations leads to vertical velocity biases up to 0.7 mm/yr (at 95 %) when estimated from 5 years of continuous observations. The maximum velocity bias can reach up to 1 mm/yr in regions around the southern Tropical band.
Non-linear deformation at interannual timescales from surface mass changes has a significant impact in geophysical applications requiring the maximum accuracy and precision of geodetic secular velocities when they are extrapolated beyond the last two decades.

IAG (Geodesy)

G04f - G04 Earth Rotation and Geodynamics

IUGG-1902

Short-term slow slip events in southwest Japan, observed by GNSS

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Southwest Japan is known as a well-studied area for slow slip events (SSEs). Previous studies suggested that SSEs on the plate interface of the subducting Philippine Sea plate along the Nankai Trough. Short-term SSEs with duration of days to weeks were found at a downdip edge of the past megathrust earthquakes. However, no systematic search for short-term SSEs has been conducted all over southwest Japan.

We developed to detect short-term SSEs using GNSS (Global Navigation Satellite System) data. We analyzed the data of ~800 GEONET GNSS stations along the Nankai Trough and the Ryukyu Trench, southwest Japan. Offsets detected in GNSS time series using Akaike's Information Criterion helped automatically identify SSE candidates with motion direction opposite to that of the relative plate motion. By non-linear inversion of the detected displacement, we estimated rectangular fault models on the plate interface. We found more than 360 possible SSEs with Mw ≥ 5.6 for 17 years.

The detected short-term SSEs were found to have a variety of characteristic recurrence intervals, magnitudes, durations and coincidental seismic activities. The detected SSEs concentrate in a depth range of 25-40 km and form the ETS (Episodic Tremor and Slip) zone along the Nankai Trough. The detected SSEs extends from the ETS zone toward southwest, and then fades away around the subducted Kyushu-Palau Ridge. Although shallow (depth ≤ 20 km) short-term SSEs have never been detected along the Nankai Trough, such SSEs often occur on the shallow plate interface along the Ryukyu Trench. This may be related to the incomplete interplate locking. Our results suggest that the distribution of short-term SSEs, as well as that of large earthquakes, is affected by the topography of the subducting plate.

IAG (Geodesy)

G04f - G04 Earth Rotation and Geodynamics

IUGG-2568

Post-seismic crustal deformations after the 2010 earthquakes in Latin America

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Crustal deformations up to 4 meters were caused by the Maule 2010 earthquake in Chile, and significant station displacements were observed in distances up to more than 1000 km from the epicentre. The station velocities in the regions adjacent to the epicentre changed dramatically after the seism; while they were oriented eastward with approximately 2 cm/year before the event, they are now directed westward with about 1 cm/year. The 2010 Baja California earthquake in Mexico produced displacements in the decimetre level also followed by anomalous velocity changes. The main problem in geodetic applications is that there is no reliable reference system to be used in the region. For applications in geodynamics we have to redefine the tectonic structure in South America. The area south of 35° S … 40° S was considered as to be a stable part of the South American plate. Now it is evident that there is a large and extended crustal deformation zone. The paper presents a new multi-year velocity model computed from the Geocentric Reference System of the Americas (SIRGAS) including only the four years after the seismic events (mid-2010 … mid-2014). These velocities are used to derive a continuous deformation model of the entire Latin American region from Mexico to Tierra de Fuego. The model is compared with the same velocity model for SIRGAS (VEMOS2009) before the earthquakes.

IAG (Geodesy)

G04f - G04 Earth Rotation and Geodynamics

IUGG-3284

Analysis of detailed crustal strains due to the dense GNSS array in the Tokai region, central Japan

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The Tokai region, central Japan, is an area of scientific interest where the Philippine Sea plate subducts beneath the Japanese Islands and is expected to generate a large interplate earthquake in the near future. Moreover, the area experienced a long-term slow slip event during 2000-2005. The Japanese University Consortium for GPS Research (JUNCO) established a dense GNSS array in the region and started observation in around 2004 for monitoring the crustal deformation. The array is an augmentation of the GEONET, the nationwide GNSS array. The JUNCO network consists of more than 50 GNSS sites and the combined network of JUNCO plus GEONET is denser with 5-10km baseline lengths, compared with the 20km spacing of GEONET. The obtained data has been used to estimate the strain change in the area. For this purpose, consecutive 3yr data are used for, first, estimating velocity vectors at each GNSS sites, and then the Least Square Prediction technique is applied to estimate dilatational and maximum shear strains. The time period of data analysis is shifted yearly, so that strains of eight time periods of strains (2004-2006),....,(2011-2013) are obtained. The results show strong disturbances from nearby large earthquakes. In particular, 2009 Suguga Bay earthquake (Mw6.3) affected the area with significantly complicated strain pattern, suggesting importance of dense GNSS array introduced in this study. Moreover, we examined how our dense array improves the resolution in estimating areal distribution of plate coupling and slow slip events using the GNSS dense array. We conducted simple checker board tests for this purpose and found that our dense array significantly improve the resolution, though more extensive research may be needed.

IAG (Geodesy)

G04f - G04 Earth Rotation and Geodynamics

IUGG-4118

New Geodetic constraints into the Active tectonics of Eastern Indonesia

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We use new GPS observations in East Indonesia for the period between 1994 and 2014 to identify active structures accommodating convergence between the Australian and Pacific plates. During the observation period, this region has been highly seismically active, requiring careful analysis to separate secular interseismic deformation from coseismic offsets and postsesimic transients present in the GPS deformation time-series. We show the importance of taking into consideration the post seismic deformation in GPS time series analysis for defining a stable Sunda block, which has undergone considerable post-seismic deformation as a result of the sequence of great earthquakes along the Sunda trench since 2004. We use the estimated GPS velocities to constrain an elastic Block model to investigate strain rate in major faults. Our results suggest that there is a simple transition from subduction at the Java Trench off east Java, to a partitioned convergence along both the Timor Trough and the Flores Thrust. Our results show a significant strain variation from West to East in the transition zone between the Sunda and Banda Arcs with rates decreasing from 68 mm/yr to 12mm/yr in Timor Trough. Significant strain is detected in the E-W back-thrust along Flores and Alor Thrust discerning a major active tectonic structure (21 - 30 mm/yr) and indicating a partitioning of the convergence. Our preferred model suggest a newly identified Sumba Block as a transition zone extending from Lombok to Timor Island in the East rotating anti-clockwise and producing a significant strain along the Semau fault with slip rates between ~11 and 15 mm/yr. Our model suggest a declining convergence from the West to the East, to a complex system of faults, leading to strain accumulation in multiple segments

IAG (Geodesy)

G04f - G04 Earth Rotation and Geodynamics

IUGG-5056

Characterizing the crustal deformation on nw South America (Colombia) using gnss observations

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Tectonic and volcanic activity in northwestern South America is directly related to the interaction of the South America, Nazca, Cocos and Caribbean plates, and smaller North Andean, Maracaibo, Choco and Panama blocks. These interactions have resulted in a very diverse geography in which a relatively high percentage of the population lives under the threat of active tectonic faults capable of producing large magnitude earthquakes and tsunamis, which can inflict great damage in terms of loss of life and destruction of infrastructure. Additionally, the many active volcanoes of South America pose a similar threat with their potential for devastating explosive eruptions (e.g., the 1985 eruption of Nevado del Ruiz, Colombia).

This work presents and discusses a new horizontal velocity field for northwestern South America (Colombia) derived from CORS GNSS observations of the GeoRed network. The GeoRed network is a dedicated GNSS network for geodynamic studies installed by the Colombian Geological Survey that currently consists of 65 stations. It is particularly dense over the North Andean block. GeoRed network includes stations over three of the major plates (South America, Nazca, and Caribbean), permitting for improved estimates of the angular velocities of these major plates, necessary to constrain the relative velocities of all tectonic units. For the estimate of the angular velocities of the major plates, we also use data from other networks. The estimated angular velocities of the major plates are computed with respect to the latest global reference frame, ITRF2008. We compare our estimated model with other estimations based also on geodetic and geophysical and geological data to show the consistency of the predicted motions.

IAG (Geodesy)

G04g - G04 Earth Rotation and Geodynamics

IUGG-0763

Seismic gaps and seismic potential on the East Anatolian Fault System using an Improved GPS velocity field

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The East Anatolian Fault System (EAFS) is the second major fault system in Turkey, following The North Anatolian Fault System (NAFS). Unlike the NAFS, which produced 11 large earthquakes in the last ~75 years, the EAFS is relatively quiet during the same period of time. While historical records show that EAFS has the potential to produce large earthquakes, the fault slip rates on the EAFS were not studied in detail, and were not quantified sufficiently. This is possibly due to the relatively low seismicity and slow slip-rates of the EAFS with respect to the NAFS. However, the determination of the slip rates of EAFS is equally important to understand the kinematics of the Anatolian plate.
In this study, we collected and analyzed new survey-type GPS data, and homogeneously combined published velocities from other studies to form the most complete GPS data set covering the EAFS. In particular, continuous GPS observations were utilized for the first time to study the northern part of the EAFS. The results of the analysis give well-constrained slip rates of the northwestern segments of EAFS, which is further connected to the Dead Sea Fault System (DSFS) in the south. The results show that the slip rate along EAFS is not constant, and gradually decreases from 13.1±1.6 mm/yr near Karliova to 4.1±1.2 mm/yr near its connection to the Dead Sea Fault System (DSFS). The contraction rates along EAFS are below 5 mm/yr, except for the northernmost part near Karliova, where it reaches a maximum value of 11.7±1.8 mm/yr. The results also show that two well-known seismic gaps across EAFS, Palu-Sincik and Çelikhan-Türkoglu segments, have slip deficits of 1.82 m and 5.16 m and have the potentials to produce earthquakes with magnitudes of M_w7.5 and M_w7.7, respectively.

IAG (Geodesy)

G04g - G04 Earth Rotation and Geodynamics

IUGG-0771

Lithospheric structures and crustal flow of Eastern Himalaya region from GPS and satellite geodesy

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The crustal deformation in the Eastern Himalaya region is characterized by clockwise rotation of crustal material, evidenced by recent geophysical and geodetic observations (e.g. magnetotelluric study delineating channels of high electrical conductivity, GPS), adhering to the notion that the Eastern Himalaya lithosphere behaving like a continuous pervading viscous medium. This phenomenan interpreted to be an integrated effects of extrusion tectonics as a consequence of northward and eastward movement of the lower crust of the Indian plate blocked by its surroundings possessing high viscosity. The gravitational collapse of the Tibetan plateau also seems playing an important role in controlling the extrusion/crust flow. Given that the direction and magnitude of the GPS derived strain rate are sensitive to crustal dynamics at the surface where as gravitational potential energy (GPE) derived deviatoric stresses give an overall picture of stresses integrated over the full thickness of the lithosphere, the differences in the two stress patterns around the Eastern Himalaya Syntaxis (EHS) could be a pointer of the depth sensitive dynamics. The space borne gravimetric data from GRACE, GOCE and EGM models also found to be extremely useful in delineating these large scale structures pertinent to crust and lithosphere. Despite all the above studies, mapping the geometry of lower crustal channel and the lateral variation of crustal rheology remain disputing. This study addresses lithospheric structures and crustal flow of Eastern Himalaya region from GPS and space gravimetry constrained by other geophysical models, facilitating to examine the complex seismotectonic scenario and its geodynamic implications.

IAG (Geodesy)

G04g - G04 Earth Rotation and Geodynamics

IUGG-1905

A GNSS-derived velocity field around the Arabian Plate

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GNSS stations of Eastern Africa, South-East-Europe and Asia up to India between 2006 and 2014 are combined to a network for a densification of the IGS network. The solutions are partially already reprocessed according to repro2 guidelines and will continue the next years to create consistent network results between 1994 and 2014. The main focus lies on a velocity field around the Arabian Plate which includes boundary zones of the Anatolian, Arabian, Eurasian, Nubian and Somali Plate.

IAG (Geodesy)

G04g - G04 Earth Rotation and Geodynamics

IUGG-2407

"Detection of strain accumulation regions on Tibetan Plateau based on continuous GNSS measurements"

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Tibetan Plateau has been created by the continental-continental plate collision between Indian and Eurasian and with widespread crustal deformation and earthquakes caused. Today, Indian plate continuously moves to north at about 50mm/yr respecting Eurasian plate fixed according to the observations of continuous GPS stations. In this paper, by using observations of 136 continuous GPS stations on and adjacent to the Tibetan plateau during 1999 to 2014, a set of radiated GPS baselines at each station are processed and time series of their length changing are used to analyze the local strain accumulation rates. Through spatiotemporal analysis, the strain accumulation regions are detected and compared with earthquake activities.

IAG (Geodesy)

G04g - G04 Earth Rotation and Geodynamics

IUGG-2651

Using GNSS measurements to solve the debate over tectonic behavior of western segment of the Makran Subduction Zone (MSZ)

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Based on National GNSS CORS of Iran, deformation of the western Part of Makran Subduction Zone (MSZ) is studied. The MSZ with 1000km length located within Iran and Pakistan and is resulted from convergence of Eurasia and Arabian tectonic plates. The derive of the study has been the apparent aseismicity on the western part of Makran as compared to its eastern part and the risk great tsunamigenic earthquakes, and to answer its related debates as follows:

1. *The entire Western segment is deforming aseismically.*
2. *The subduction process is no longer active in this segment.*
3. *The western part is locked and as such is capable of generating plate boundary earthquakes.*

According to the analysis of the CORS observations the subduction process is active and has convergence with the rate of 2 cm/yr in its western part and the rate is increasing toward east. Furthermore we found that MSZ is not locked and is silently deforming, i.e., with silent earthquakes. Moreover repeated precise leveling within Iran, which runs perpendicular to MSZ shows 9.5 mm uplift within 14 years.

IAG (Geodesy)

G04g - G04 Earth Rotation and Geodynamics

IUGG-4139

Geodetic and seismological analysis of the January 26, 2014 Cephalonia Island earthquake sequence.

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On January 26, 2014 a strong earthquake of magnitude Mw=5.8 occurred on Cephalonia Island followed by a similar magnitude earthquake Mw=5.7 one week later on February 3, 2014. Extensive structural damages, landslides and many damages on the island's main roads, harbour and airport caused mainly on the western and central part of the island. The first event located 2km eastern of Lixouri town and was followed five hours later by a strong aftershock of magnitude Mw=5.3. The second strong earthquake located in the north part of Paliki eninsula (North-East Cephalonia).
Geodetic data of six permanent GNSS stations were available and analysed in this study both in pro and post seismic terms, using 30sec and 1Hz data where available. The time series analysis shows the effect of each event at nearby stations.
Seismological data are used to determine the focal mechanisms of the earthquake sequence and an attempt to investigate the homogeneity of the mechanisms and the stress field of the area is presented in the study.
Geodetic analysis and seismological results are used to understand the mechanism of the events.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-126

On the nonlinear and Solar-forced nature of the Chandler wobble in the Earth's pole motion

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About 250 years ago L. Euler has derived a system of three quadratic-nonlinear differential equations to depict the rotation of the Earth as a rigid body. Neglecting a small distinction between the equatorial inertia moments, he reduced this system to much simpler linear one, and concluded that the Earth's pole must experience a harmonic oscillation of the 304-day period. Astronomers could not find this oscillation, but instead, C.C Chandler has found two powerful wobbles with the 12- and ~14-month periods in reality. Adhering to the Euler's linearization, astronomers can not explain the nature of the later wobble up to now. I indicate that the neglecting by the above small distinction ("a small parameter" of the Euler's primary nonlinear equations) is not admissible because the effect of this parameter is singular. Analysing the primary equations by an asymptotic technique, I demonstrate that the Chandler wobble tones are formed from combinational harmonics of the Euler's 304-day oscillation, long-term Luni-Solar tides as well as the 22-year cycle of the Solar magnetic activity. Correlating simultaneous variations of the wobble and a solar activity index, I corroborate that the Chandler wobble is really affected by the Sun.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-127

Prediction of the Chandler Wobble and Climate Variability

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Similarities have been found between the Earth rotation and climate characteristics, such as temperature and sea level changes. Chandler wobble amplitude has been decreasing in 2010s as in 1930s. It is very similar to what was observed for the temperature changes, attributed to Atlantic Multidecadal Oscillation (AMO) and El Nino activity (ENSO). If these processed are interrelated, it could be used for their prediction. We try to predict the complex envelope of the Chandler wobble. The equation for the complex envelope propagation through the Euler-Liouville equation was derived. The excitation of the Chandler wobble reconstructed by Panteleev's filter was analyzed. Similarities with the climate change characteristics are discussed.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-128

Automated near-real time analysis of VLBI Intensive sessions

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VLBI is the only space geodetic technique that gives direct access to the Earth's phase of rotation, i.e. universal time UT1. Beside multi-baseline sessions, the IVS also organises daily Intensive sessions in order to provide low-latency estimates of UT1. The turn-around time of these sessions heavily depends on the availability of analysis personnel who should process the data immediately after the correlation has been finalized. Since this prerequisite is hard to fulfil, today the turn-around time of Intensives sessions varies between hours to days.

In order to improve the latency, efforts have been made to realize fully unattended operation and robust estimation of UT1 (Hobiger et al., 2010). This concept has been applied to dedicated ultra-rapid UT1 sessions that further improve the latency of UT1 (Haas et al., 2010).

In our presentation we will discuss algorithms and processing strategies for such an automated near-real time analysis of VLBI data. Moreover, we will demonstrate how these approaches can be applied to the IVS Intensive series that are an ideal test-bed for continuous operations, as anticipated for the next generation VLBI systems. The results will be compared to interactively post-processed UT1 results as well as the IERS C04 series with the goal to assess the accuracy of our automated strategy. In addition, we will address how future VLBI networks can be processed automatically in order to provide near real-time information about important Earth system parameters in the framework of GGOS.

References

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IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-129

Inverting earthquake slip model with simulated GPS data

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Large tectonic earthquakes lead to significant deformations from the satellites. The seismic source parameters of a uniform slip model over the fault or a point-like seismic source can be inverted by GPS, GRACE, InSAR data and so on. Herein, we compare the spatial density of data and the distance of the data from the earthquake source to estimate their effect on the inverted fault model and magnitude. We simulate a few sets of data to invert the parameters of finite-fault or point model and compare them with the result from the GPS data of 2011 Tohoku-Oki earthquake (Mw 9.0). To avoid producing unreasonable solutions, Akaike Bayesian Information Criterion (ABIC) method was used to invert fault slip model. The result tells us that there exists some useless data which can be got rid of in our inversion. By comparing the inverted magnitude results of far field and near field, the result from near field is more closed to the model magnitude than that from far field. In the practical application, combination of both the data from both near field and far field can get better slip model.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-130

Determining slip rates of main fault zones driving Turkey's neotectonics and forming intraplate block deformation models by geodetic methods

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Although many regional and local studies were performed in the past, the slip rates of the active faults in Turkey have not been determined. To determine the slip rates, which are the main input to produce seismotectonic maps, geodetic measurements are the most common methods. In this project, the block modelling, which is the most common method to produce slip rates, will be done. GPS station velocities required for block modeling will be compiled from the published studies and the raw data will be provided then velocity field will be combined. To form a homogeneous velocity field, different stochastic models will be used and the optimal velocity field will be achieved. In literature, GPS site velocities, which are computed for different purposes and published, are combined globally and this combined velocity field are used in the analysis of strain accumulation. It is also aimed to develop optimal stochastic models to combine the velocity data.

In this project; real time, survey mode and published GPS observations will be combined. Furthermore, micro blocks and main fault zones from Turkey Active Fault Map will be determined and homogeneous velocity field will be used to infer slip rates of these active faults.

In this presentation, the current status of the project will be presented.

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IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-131

Numerical solution of rotational normal modes of triaxial two-layered non-elastic Earth model

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The nature of Earth rotation is uniquely determined by Earth model, including the layer structures, geophysical parameters such as principal inertia moments of different layers and the compliances. This study focuses on providing numerical solution of the rotational normal modes of a triaxial two-layered anelastic Earth model without external action. We provide a relatively complete parameter set which is applied in this study. We first formulate the rotation equation of the triaxial two-layered anelastic Earth model and then provide numerical solution of that equation. We obtain eight solutions, of which only four solutions may exist in reality. Further, based on the present choice of the conventional reference systems, only two of these four solutions correspond to the real existing prograde Chandler wobble (CW) and the retrograde free core nutation (FCN). Our calculations show that the periods of CW and FCN are respectively 430.46 solar days with its quality factor as 84.9 and 430.22 solar days with its quality factor as 23932. *This study is supported by National 973 Project China (grant No. 2013CB733305) and NSFC (grant Nos. 41174011, 41210006, 41429401).*

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-132

Estimating the Q of the Chandler wobble in the absence of excitation

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The quality factor Q of the Chandler wobble is a function of various dissipation processes acting in the Earth. Better estimates of the Q of the Chandler wobble can therefore be used to better understand these processes. Because of them, and in the absence of any excitation process, the amplitude of the Chandler wobble will freely decay with a time constant proportional to its Q. If a period of time can be found during which the Chandler wobble is not being excited but is instead freely decaying, then estimating the time constant associated with this free decay yields an estimate of the Q of the Chandler wobble. Observations of the Chandler wobble indicate that it was apparently freely decaying during the early 1960s. The Q associated with this apparent free decay is 32.5, somewhat lower than estimates of the Chandler wobble's Q that have been obtained recently by modeling its excitation by atmospheric and oceanic processes. This may indicate that the Chandler wobble was, in fact, not in free decay during the early 1960s or, alternatively, that recent estimates of its Q based on modeling its excitation are biased high.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-133

Muti-GNSS Processing for Earth Rotation Parameter Determination using MGEX and iGMAS data

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Earth rotation parameters (ERPs) are important basic data for satellite precise orbit determination (POD), high-precision space navigation and positioning. In this paper, the solution of ERPs including polar motion (PM), polar motion rate (PMR) and length of day (LOD) are presented using MGEX and iGMAS Muti-GNSS data. The ERP accuracies from different GNSS includeing BDS, GPS and GLONASS are analyzed and compared using MGEX and iGMAS data. The contribution of iGMAS data on ERP solution is given relative to MGEX data. In order to balance BDS, GPS and GLONASS contribution on ERP determination, the variance component estimation (VCE) is used to get reasonable weight of Muti-GNSS data. Inter-System Bias (ISB) and Inter-Frequency Bias (IFB) are estimated and their stabilities are analyzed when combing MGEX and iGMAS data for ERP determination. One month data of MGEX and iGMAS network from 01/12/2014 to 30/12/2014 is used for computation and comparison on Muti-GNSS ERP solution . The results show that the accuracy of ERP determination from MGEX data can be improved to some extent when including iGMAS data since the latter plays a key supplement of station distribution in China. The optimal relative weight are obtained and the ERP solution is enhanced when VCE involved in the Muti-GNSS processing. In the case of same station number and distribution, BDS do contribute to ERP solution especially for the components of PMR and LOD using MGEX and iGMAS data. The results also show that the ISB and IFB from Muti-GNSS processing are very stable and wave in dm-level.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-134

Nutation coefficients and Earth rotation parameters determined from LLR data

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Lunar Laser Ranging (LLR) provides measurements of the Earth-Moon distance for more than 45 years. Under optimal conditions, the newest observatories reach accuracies at the millimeter level. The accuracy of the LLR model/analysis at our institute has been improved correspondingly to bene?t from the high observational accuracy. With the updated analysis software, parameters of the Earth orientation are determined. On the one hand, nutation coefficients for ?ve periods (18.6 and 9.3 years as well as 365.3, 182.6 and 13.6 days) are estimated applying different modeling approaches for the ITRS-GCRS transformation. A comparison with the offcial nutation model MHB2000 shows signi?cant differences especially for the long-periodic coeffcients. On the other hand, Earth rotation parameters like polar motion and Earth rotation phase for different con?gurations with respect to the datum de?nition (varying time spans, station-re?ector combinations) are ?tted. Here, we obtained promising results especially if the highly accurate APOLLO data are included. Earth rotation phase ΔUT can be estimated with an accuracy up to 5 μs.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-135

Amplitude and phase of the gravimetric factor at the Chandler frequency determined from GGP superconducting gravimeters

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The gravimetric factor is a commonly used parameter in the study of polar motion and its effect on the Earth's gravity field. Assuming that the discrepancy between observed and theoretical gravity perturbations is due to anelasticity, it may provide some insights about the Earth's mantle rheology at intermediate periods (435 days).

Using superconducting gravimeter (SG) data from the Global Geodynamics Project (GGP) and Earth orientation parameters provided by the International Earth Rotation and Reference Systems Service (IERS), we estimate the gravimetric factor amplitude and phase lag at the Chandler wobble period. The influence of the processing (namely offsets removal) and the various corrections (atmospheric and hydrological loadings) are carefully considered because of their strong impact on the resulting amplitude and, especially, phase.

After the validation of the method with individual SG time series at different stations, we then extend it to jointly process the gravity data from a set of SG stations and estimate a global gravimetric factor. To do so, we first apply a spatial data weighting taking into account the latitude and longitude dependency, which is a degree-2, order-1, surface spherical harmonics, of the gravity perturbation related to polar motion, then we stack the resulting signal to improve the signal-to-noise ratio. The stacking method enables us to get rid of local effects that considerably affect the individual estimates of the gravimetric factor at the Chandler period. The convergence with time of these values is used as a realistic way of estimating the uncertainty of our results. We finally compare our new results with previous estimates using SG data. Some concluding remarks are made in terms of constraints on Earth's rheological parameters.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-136

SPINA Region (South of Iberian Peninsula, North of Africa) GNSS geodynamic model

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As it is well known, GNSS data analysis is a powerful tool to study geodynamic processes. However, observational methodologies and data analysis results should be adapted to determine local or even regional effects. It is particularly important in tectonic plate boundary areas when looking for subduction zone limits. When using Continuous GNSS (CGNSS) observing receiver networks, a set of precise topocentric coordinates (e,n,u) for each place, will be available. Furthermore time series formed by the daily positions will produce the sites temporal variations. If those time series are long enough, horizontal components (e,n) use to show linear behaviors if there are no other geodynamic effect affecting the tectonic plates movement. Anyway the height component (u) uses to show periodical but not linear effects. But often time series are disturbed by different processes, as local subsidence, periodic dilatation-compression effects, GNSS signal interferences, etc. This paper shows a detailed topocentric coordinates time series study for sites belonging to what we call the SPINA network, which stands for South of the Iberian Peninsula, North of Africa Region. To avoid the above mentioned local effects, a priori quality control is carefully performed. Solutions are obtained from network approach with the Bernese software as well as the Precise Point Positioning approach using the Jet Propulsion Laboratory GIPSY-OASIS software. Results will be compared and combined. Then, a designed methodology, using filter processes, harmonic adjustments and wavelets will be applied. As final product we expect to get horizontal and vertical displacement model to describe the regional geodynamic main characteristics, as well as its strain and stress.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-137

Validation of tidal displacements estimated using kinematic GPS

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GPS estimates of tidal displacement have been used over the last decade or so to quality-control ocean tide models and to infer the elastic properties of the Earth. However, the accuracy assessment of these GPS tidal displacement estimates has often been carried out by comparison with geophysical models, which themselves are imperfect and whose quality is also desired to be assessed. Here, we validate kinematic GPS estimates of tidal displacement by assessing the accuracy with which the technique can recover synthetic, controlled periodic ground displacements. We use periods close to those of the major semi-diurnal and diurnal tidal constituents and amplitudes ranging from 0 to 6 mm, commensurate with expected errors in ocean tide loading and solid Earth tide displacements caused by uncertainties in ocean tide and Earth models. By analysing in precise point positioning mode up to 7 years of GPS data from over 20 sites distributed across western Europe, we demonstrate an attainable plan and height accuracy of typically 0.2 mm, depending on the time series noise. This requires careful tuning of the zenith tropospheric delay and coordinate process noise values, the incorporation of simultaneously-estimated tropospheric delay parameters rather than a priori fixed values, and a GPS time series around 4 years long with at least 70% data availability. The method is largely insensitive to centimetre-level offsets due to equipment changes or daybreak effects.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-138

Ocean tide loading inference in Deception and Livingston Islands (Antarctica) from ground displacements, tide gauges and global models.

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Near real-time surveillance of volcanic activity based on ground displacements detected in GNSS position time series require sub-daily solutions. In Deception volcano (South Shetland Islands - Antarctic Peninsula), during austral summers, positions are computed every 30 minutes, in which residual semi-diurnal and diurnal periodicities are identified. Such position periodicities are partially related to Sun and Moon gravitational attractions or to atmospheric and oceanic mass loads. Only a few constituents need to be imported into fairly unsophisticated formulas in order to describe tidal motion, which is considered in GNSS processing. Given the existence of 2 tide gauges with nearby GNSS benchmarks, in Deception and in Livingston Islands, the lithospheric elastic response to ocean tide loading was inferred in GNSS computed ground displacements and compared to tide gauges data and ocean tide loading models. A height solutions tidal analysis was performed and minor diurnal ocean tide loading constituents overcorrection was recognized in compared models, particularly on O1 or Q1. Superposition with some other external factor was not discarded, although no influence of the constellation orbital related effects is expected. Although S2 may suffer from such influences, higher yearly variability was found on this constituent both in tide gauges data and in GNSS height solutions. Ocean tide loading effects vary irregularly, depending on local elastic properties of the upper mantle and crust. Therefore, differential response between Livingston Island in the South Shetland block and Deception Island in the Bransfield basin, related to crustal thickness, was investigated.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-139

Research on Earth rotation parameters estimation from GNSS and SLR

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Earth Rotation Parameters (ERPs) include polar motion(PM) and length-of-day (LOD) parameters. The ERPs connect the International Celestial Reference Frame (ICRF) and the International Terrestrial Reference Frame (ITRF). Furthermore, the ERPs can be applied to aircraft precise positioning and navigating. And because it contains abundant geodynamic information, the accurate ERPs estimated with modern space technology still have important astronomical geodynamic meaning. In this paper, the data of global uniformly distributed 80 IGS stations with about 70 sites tracking GPS+GLONASS simultaneously are used to estimate ERPs. The Root Mean Square(RMS) of the PM and LOD estimated from daily GPS ,GLONASS and GPS+GLONASS observations ,which are respectively compared with IERS C04 solutions shows the precision of estimated parameters. In addition, the ERPs are also estimated with the SLR data of LAGEOS-1 during the same period. The method of normal equation stacking is adopted to combine GPS ,GLONASS and SLR to get the combining ERP solutions. The RMS of the combining ERP solutions compared with IERS C04 solutions is used to evaluate the accuracy of the combining ERP solutions. At last, the advantages and disadvantages of combining the different global navigation satellite system(GPS and GLONASS) and the different space technology (GNSS and SLR)are analyzed.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-140

Geophysical excitation of Earth orientation

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Atmospheric and oceanic excitation functions together with schematic excitations at the epochs of geomagnetic jerks (rapid changes of the second time derivative of Earth's geomagnetic field) are used to derive their impact on all five Earth's orientation parameters. Two components of position of spin axis within the Earth (polar motion), two components of position of spin axis in space (precession-nutation) and proper rotation measured as length-of-day are studied using the numerical integration of broad-band Liouville equations. We focus on the atmospheric excitation functions derived by the European Centre for Medium-Range Weather Forecasts (ECMWF) and oceanic excitation function based on the Ocean Model for Circulation and Tides (OMCT) and driven by the atmospheric model of ECMWF provided in GFZ Potsdam. The combined results of numerical integration of the geophysical excitations are then compared with the observed Earth orientation parameters.

IAG (Geodesy)

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Hydrological excitation functions determined from GRACE, SLR and GNSS data

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The comparison of the Hydrological Angular Momentum (HAM) with hydrological signal in observed geodetic excitation functions is a common method of assessing the influence of land hydrology on polar motion excitation function.

This hydrological signal is estimated as differences between observed geodetic excitation functions (Geodetic Angular Momentum, GAM) and a sum of Atmospheric Angular Momentum (AAM) and Oceanic Angular Momentum (OAM).

HAM can be estimated either from global models of land hydrosphere or from harmonics coefficients C_{nm}, S_{nm} of the Earth's gravity field.

We compare several sets of degree-2, order-1 harmonics of the Earth's gravity field, derived from the Gravity Recovery and Climate Experiment (GRACE), Satellite Laser Ranging (SLR) and Global Navigation Satellite Systems (GNSS) data. We use the degree-2 coefficients to estimate gravimetric polar motion excitation functions χ_1 and χ_2. Additionally, the global models of land hydrology such as Global Land Data Assimilation Systems (GLDAS), which contain information about water mass redistributions in the global hydrosphere, are used to estimate hydrological polar motion excitation functions χ_1 and χ_2.

The aim of this study is to determine the optimum model of the hydrological angular momentum (HAM) by finding the best agreement between the values derived from geodetic observations and different combination of the hydrological excitation functions.

Our algorithm is based on a fit of hydrological excitation functions to geodetic residuals using the least-square method.

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G04p-142

Multilayer stress from gravity and its tectonic implications in urban active fault zone: A case study in Shenzhen, South China

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It is significant to identify urban active faults for human life and social sustainable development. The ordinary methods to detect active faults, such as geological survey, artificial seismic exploration, and electromagnetic exploration, are not convenient to be carried out in urban area with dense buildings. It is also difficult to supply information about vertical extension of the deeper faults by these methods. Gravity, reflecting the mass distribution of the Earth's interior, provides an alternative way to detect faults,which is more efficient and convenient for urban active fault detection than the aforementioned techniques. Based on the multi-scale decomposition of gravity anomalies, a novel method to invert multilayer horizontal tectonic stresses is proposed. The inverted multilayer stress fields are further used to infer the distribution and stability of the main faults. In order to validate our method, the multilayer stress fields in the Shenzhen fault zone are calculated as a case study. The calculated stress fields show that their distribution is controlled significantly by the strike of the main faults and can be used to derive depths of the faults. The main faults in Shenzhen may range from 4 km to 20 km in the depth. Each layer of the crust is nearly equipressure since the horizontal tectonic stress has small amplitude. It indicates that the main faults in Shenzhen are relatively stable and have no serious impact on planning and construction of the city.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-143

On modeling environmental loading induced displacements in the local area

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Displacements of the Earth's crust due to the environmental loading can be modelled in terms of the global Green function approach. This approach can be applied at scales varying from global, regional to local. In the case when you might want to compute surface displacements due to environmental loading in the near field, for example, a 2 degree by 2 degree area, other approaches, e.g. the half-space Green function approach (see Farrell 1972) and the Becker and Bevis (2004) approach, can also be utilized for estimating the displacements.

This study aims at comparing and evaluating the differences of these approaches using a local high spatial and temporal resolution load dataset observed during a severe flood episode in 2011 along the lower Mississippi river. In addition, the observed displacements from GPS are used to validate the computed displacements from both the load dataset and the hydrological models. The advantages and disadvantages of these approaches for modeling displacements due to near field surface loads are presented. Moreover, using such a high spatial and temporal resolution load data, we also investigate the effects of site-dependent loading Love numbers in the global Green function approach.

IAG (Geodesy)

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G04p-144

Advective diffusion of volcanic plume captured by dense GNSS network in Sakurajima volcano

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We assess the ability of GPS data to detect volcanic plumes at Minami-dake of Sakurajima Volcano. In this study, we describe the July 24, 2012 activity at Minami-dake of Sakurajima Volcano. We analyzed the data from more than 20 continuous GPS stations, which located on the volcano flanks, and neighboring region. We used GIPSY-OASIS II version 6.3 software. We extracted the post-fit phase residual in the ionosphere-free linear combination for each pair of GPS satellites and ground stations for the detection of eruption column. The wet zenith tropospheric delays and its gradient at all the GPS sites were estimated at all processing epochs (30 seconds). Firstly, we analyze the all of the GPS data in July 23, 2012 for the reference. Obtained post-fit phase residual of the reference days showed the noise-level for the path delay effects caused by the volcanic plume. This reference post-fit phase residual contained many noise sources such as multipath effects. The noise level of the post-fit phase residual strongly depends on the each GPS satellite and ground station pair. Finally, we analyzed the data of the July 24, 2012. The post-fit phase residual clearly shows large disturbance just after the eruption. For example, the phase residual between SVN34 satellite and GEONET 0720, which located in the east coast of Sakurajima, suddenly increased just after the eruption. The obtained residual amount reached 80mm. It is clearly larger than the noise level measured on the reference days. Furthermore, other GPS satellite and ground station pairs also clearly showed significant amounts of disturbance. These results suggest that the eruption column moved to the westward by the wind after the eruptive event.

IAG (Geodesy)

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G04p-145

Elliptical polarisation of the polar motion excitation

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Polar motion is excited by equatorial angular momentum exchange between the solid Earth and its environment, mostly its fluid layers. In order to model polar motion, the equatorial excitation is generally decomposed into circular prograde and retrograde terms in frequency domain. But the current analysis considers these terms as independent. We aim at showing that counter-clockwise (prograde) and clockwise (retrograde) excitations are correlated. Complex Fourier Transform permits to determine retrograde and prograde circular terms of the observed excitation and of its atmospheric, oceanic and hydrological counterparts. Statistic distribution of their complex ratio is investigated, and we reconstruct the corresponding time series. Complex linear correlation between retrograde and complex conjugate prograde part is observed both in the geodetic excitation and the matter term of the hydro-atmospheric excitation. On the other hand retrograde to the prograde terms have amplitude ratio, which the probabilistic gamma distribution is centred around 1.5, and their phase difference obeys a normal law centred around 2 x 80°. This traduces an elliptical polarisation towards ~80° East, mostly resulting from the matter terms of the hydro-atmospheric excitation. Whatsoever the frequency band above 0.1 cpd, the hydro-atmospheric matter term tends to be maximal in the geographic areas surrounding the great meridian circle of longitude ~80° East.

IAG (Geodesy)

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G04p-146

Testing a new Free Core Nutation empirical model

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The Free Core Nutation (FCN) is a free mode of Earth rotation caused by the different material characteristics of the Earth core and the mantle. This causes the rotational axes of those layers to slightly diverge from each other, resulting in a wobble of the Earth rotation axis comparable to nutations. FCN is a free mode of Earth rotation, i.e. it shows variable excitation or damping and is thus not predictable with theoretical models. In Very Long Baseline Interferometry (VLBI) estimates of the celestial pole offsets, however, FCN shows up as a retrograde motion of the Earth figure axis with a period of about 430 days and an average amplitude of about 100 microarcseconds.

The scientific community demands the empirical FCN models with increasingly high accuracy to improve the knowledge about the geophysical excitation mechanisms that cause the amplitude, period, and phase variations. In this research we develop a new FCN empirical model with high temporal resolution based on the VLBI data analysis performed with the GeoForschungszentrum (GFZ) version of the Vienna VLBI software (VieVS). A comparison with other recently determined empirical FCN models: Krásna et al (2014) and Lambert & Dehant (2007) is included by means of the weight root mean square of the residuals during the entire period of VLBI data. Moreover, we assess the sensitivity of our empirical FCN model with respect to different a priori Earth Orientation Parameter series: IERS 08 C04 and USNO finals.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-147

Routine analysis of GNSS stations in South Aegean: Processing scheme, results and dissemination of products and data.

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Dionysos Satellite Observatory and Higher Geodesy Laboratory of the National Technical University of Athens, have developed an automated processing scheme to accommodate the daily analysis of all available continuous GNSS stations in Greece. For the moment, a total of approximately 150 regional stations are processed, divided in 4 subnetworks.
We focus our interest on the tectonically active region of South Aegean under the ongoing research program "South Aegean Geodynamic And Tsunami Monitoring Platform" (SEISMO), where a dense network of GNSS stations is installed, with data spanning several years. The results of the analysis, yield a high quality velocity field, which could provide significant insight on the tectonics of the region.
In addition, the laboratory's processing routine will be presented, which is based on Bernese GNSS Software v5.2 developed by AIUB, the models and tools used to analyze position time-series and the ongoing effort to establish a near real time monitoring platform for the area. All data and results are hosted on a dedicated website and made available for any interested party. To this end, the laboratory makes use of the Geodetic Seamless Archive Center (GSAC) software package, developed by UNAVCO.

IAG (Geodesy)

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G04p-148

"Changes in strain rate with a decadal scale recorded by vault-housed extensometers at Miyazaki, Japan"

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Disaster Prevention Research Institute, Kyoto University, Japan, has conducted continuous observation of ground strain using vault-housed extensometers at several sites in Japan since 1970s. At Miyazaki site (MYZ), one of our observation tunnel, we have observed prominent changes in strain rate. Extensometers in MYZ are set in three directions, referred to as E1, E2 and E3, respectively. Strain in one direction, E3, shows a marked changes in its rate. Before 1994, strain in E1 had been almost constant; but around 1994, it turns to . After around 2002, the strain rate becomes almost constant, again. Similar trend of strain has been observed in E1 with small amplitude, and has not been recorded in E2. Temporal variation in number of earthquakes in the vicinity of MYZ site shows similar shape to the strain rate. The observed changes in strain rate seem to be related to occurrence of a major earthquake. Near the subduction zone near MYZ, M7 class earthquakes have repeatedly occurred. The latest events are M6.7 and M6.9 earthquakes in 1996. The change in strain rate seems to proceed occurrences of these two earthquakes. If the observed changes in strain rate are actually linked to major earthquakes, possibilities are that changes in strain triggers major earthquakes.

IAG (Geodesy)

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G04p-149

Beyond nanoradians? High sensitivity tilt measurements in the Conrad observatory, Austria

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Geodetic and Geophysical Institute (GGI), Sopron, Hungary started tilt recording at the Conrad observatory (COBS), Austria using an interferometric water level tilt meter (iWT) in August 2014 to monitor earth tides, loading effects and crustal dynamics in cooperation with Central Institute for Meteorology and Geodynamics. The 5.5m long prototype iWT was built and tested in early 2014 at the Finnish Geodetic Institute (FGI) which has been merged to National Land Survey, Finland. The principle of the instrument follows the Michelson and Gale (MG) famous experiment performed 100 years ago at Yerkes observatory, Wisconsin, USA. The MG interferometer was modified according to the innovations by FGI during the last 50 years. A 50.4 m long modern MG type tilt recording system has been operational at the Lohja2 geodynamic station in Finland since 2008. GGI installed also a Lippmann-type 2D tilt sensor (LTS) near to iWT at COBS in the Oct. 1. 2014. LTS has very short base (~10cm) and different tilt sensing (pendulum) principle. Both instruments show high, nanoradian resolution and broad band spectral response, although the iWT seems to have a better resolution by at least one order of magnitude. Thus both are suitable for recording of tilts of equipotential and solid surfaces caused by planetary, global, regional and local sources. A preliminary evaluation of tilt data induced by earth tide, ocean and atmospheric loading effects is presented. The analysis of the two time series reduced by the above effects indicate a definite interrelation between their long term tendencies. This supports the idea of applying both of these tilt sensors for tectonic investigations.

IAG (Geodesy)

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G04p-150

Report of activities of the IAU/IAG Joint Working Group on Theory of Earth Rotation

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Earth rotation is considered as one of the three pillars of Geodesy. In April 2013 the International Association of Geodesy (IAG) and the International Astronomical Union (IAU) set up a Joint Working Group on Theory of the Earth Rotation (JWG ThER) to promote the development of improved theories of Earth rotation meeting the needs of accuracy of the near future as recommended by, e.g. GGOS, the Global Geodetic Observing System of the IAG. That JWG is chaired by the first two authors and comprises three Sub-Working Groups (SWG) addressing (1) Precession/Nutation, (2) Polar Motion and UT1 and (3) Numerical Solutions and Validation, which are chaired by the last three authors, respectively. Those SWG should work in parallel, for the sake of efficiency, but keeping consistency as an overall issue. This presentation intends to report about the activities carried out by the JWG during this term of operation and the future work plans.

IAG (Geodesy)

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G04p-151

The Earth's free core nutation: Formulation of dynamics and estimation of eigenperiod from Very-Long-Baseline Interferometry data

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The free-core nutation (FCN) is a rotational normal mode of the Earth's outer core. We derive the equations of motion for FCN w.r.t. both the inertia space $\boldsymbol{F_0}$ *and the uniformly rotating "terrestrial" frame*$\boldsymbol{F_\Omega}$*, and show that the two sets of equations are invariant in form under the reference frame transformation, as required by physics. The frequency-domain formulation describes the FCN resonance (to nearby tidal signals), which has been exploited to estimate the complex eigenfrequency of FCN, or its natural period P and quality factor Q. On the other hand, the time-domain formulation in terms of temporal convolution describes the response of resonant FCN under a (continual) excitation. The convolution well explains the dynamic behaviors of FCN in the observed VLBI data (in* $\boldsymbol{F_0}$*), for example the undulation of the FCN amplitude and the apparent fluctuations in the period and phase over time as well as the temporal coincidence of an abrupt phase jump with the nero-zero amplitude around ~1997, in analogy to the observed behavior of the Chandler wobble (in* $\boldsymbol{F_\Omega}$*). The convolution formulation is further exploited to yield optimal estimates for FCN's P and Q, following the approach of Furuya and Chao [1995] via the process of deconvolution using 1992-2014 VLBI data. While this method is found to be insensitive to Q owing to the short span of the data, we obtain the estimate of P = 440 sidereal days (sd) with 1-sigma uncertainty of ± 4.5 sd according to a Monte Carlo simulation. This is closer to the theoretical value of ~460 sd predicted by Earth models under hydrostatic equilibrium than the prior estimates by the resonance method. In addition, the deconvolution process yields the excitation function generated by the excitation source(s).*

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-152

Improving the reconstructions of post-glacial coastline changes in the eastern Baltic Sea by using glacial isostatic adjustment models

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The shore displacement reconstructions indicate significant marine transgression and regression events in the eastern Baltic Sea region. These events reflect the processes like the melting of large continental ice sheets and postglacial rebound which can be predicted by using glacial isostatic adjustment (GIA) models. This study aims to improve the reconstructions of relative sea-level change for several coastal sites in Estonia with the help of GIA modeling.

The computer simulation of the GIA process with different ice sheet and viscoelastic Earth's models are used to theoretically predict postglacial land uplift and sea-level changes for the sites in western and northeastern Estonia where detailed chronology and shoreline changes have recently been reconstructed from geological as well as archaeological data. These reconstructions help to verify GIA modeling results, but also more accurate palaeoshoreline positions, tilting histories and morphogenesis for the Baltic Ice Lake, Ancylus Lake and Litorina Sea stages can be expected by combining the geological data with theoretical GIA-based predictions. It is the purpose of this study to present preliminary results and to analyse the impact of issues like different reference frames, uncertainty estimations of reconstructed and predicted quantities etc on the computation process and results.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-153

Testing influence of the adopted strategy of VLBI observations analysis on estimation of the Earth Orientation Parameters

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Very Long Baseline Interferometry (VLBI) is the only space geodetic technique which is capable to measure all the Earth Orientation Parameters (EOP), thus the role of VLBI in determination of the universal time UT1, nutation and polar motion is invaluable. Although geodetic VLBI has been providing observations for more than 30 years, the procedure of observation analysis is still not unified. Even though many authors suggest different approaches, there are no clear guidelines how to deal with the stations or baselines having significantly bigger post-fit residuals than the other ones. In our work we apply the VieVS software for testing different approaches to the weighting procedure of stations or baselines: common weighting of observations using squared formal errors; excluding or down-weighting of stations or baselines, in term of EOP determination, and then compare these solutions. Additionally some statistical indicators have been considered in term of finding the criterion of excluding or down-weighting the poor quality stations or baselines. For each approach a full set of EOP has been determined and then compared to each other and to the IVS combined solution. Additionally we analyse the network reliability and its changes due to chosen strategy in order to establish the best approach.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-154

Spectral analysis of the Chandler wobble: comparison of the discrete Fourier analysis and the maximum entropy method

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The methods of spectral and cross-spectral analysis are applied to solve the following two problems concerning the free Chandler wobble (CW): 1) to estimate the CW resonance parameters, the period T and the quality factor Q, and 2) to perform the excitation balance of the observed free wobble by comparison of the observed excitation to the contributions from the available geophysical excitation series. It appears, however, that the results derived by various algorithms of spectral analysis yield significantly different results, even when based on the same input data sets; see e.g (Brzezinski, 2012, IAG Symposia Vol.136, pp.499-505) for discussion. In this work we compare two algorithms which are frequently applied for spectral analysis of the polar motion data, the classical discrete Fourier analysis and the maximum entropy method corresponding to the autoregressive modeling of the input time series. We start from general description of both methods and of their application in the Chandler wobble excitation studies. Then we perform comparison by applying the algorithms for analysis of the polar motion series and the related excitation data sets.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-155

Performance of a Kalman filter in VLBI data analysis: test case CONT14

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In this work we investigate the performance of a Kalman filter within very long baseline interferometry (VLBI) data analysis. Our test case is the continuous VLBI campaign CONT14, observed from May 6th until May 20th 2014. We compare daily and hourly Earth orientation parameter (EOP) estimated by using the least squares method (LSM) with the results provided by various specifications of the Kalman filter. For external validation, hourly GNSS data are used.

Our filter offers two main processing modes, one for near real-time processing, where the filter is run only forwards, and one for post-processing, where the data is filtered twice, forward and backward, followed by a smoothing algorithm. The latter is more precise than the first, since all the information contained in the data is used to improve the prediction. The drawback is the longer processing time, making it inapplicable for near real-time applications. Additionally, the filter includes a forecast tool, where EOP are predicted on the basis of angular momentum functions (AMF) of the atmosphere and the oceans. This tool not only forecasts EOP but also helps bridging gaps in the VLBI data and thus stabilizes the results. We assess the performance of the filter settings concerning internal precision (i.e., relative to each other and to the LSM solution), external accuracy (e.g., GNSS), and near real-time applicability (processing speed, memory consumption, and availability of the necessary external data like AMF).

The performance of an adaptive Kalman filter will be tested as well because various authors suggest its use especially for EOP determination. So far our tests have not shown significant impact on the results.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

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Inferring anelastic Earth properties from tidal loading measurements: a modern perspective

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Constraining the elastic and anelastic properties of the Earth from tidal loading measurements has been a long-standing objective of Earth-tide research. However, systematic noise in Earth-based tidal observations, together with past ocean-tide models of limited precision, have hindered progress towards adding more constraints on Earth properties than those already inferred from seismological models. A growing set of satellite-based measurements of tidal displacements, improved local and global ocean-tide models, detailed seismological models of Earth's heterogeneities, and rock physics data on anelasticity, together offer new, unexplored ways for characterising Earth properties at tidal frequencies, especially anelastic ones. The ensemble of such data, however, is overwhelming; thus, an attempt at assessing their relevancy is called for. This is done here by focusing on the dissipation of tidal energy as fluid-saturated, fractured rock formations respond to ocean-tide loading at semi-diurnal frequencies. The likely source of dissipation here is the periodic viscous flow of liquid-films bounded to the walls of rough-surface fractures; that is, a squeeze-flow, micro-mechanical absorption mechanism. Linear viscoelasticity is used to quantify dissipation by a mesoscopic loss factor Q^{-1} (with phase lag), scaled-up from losses at the nanoscopic scale of a characteristic absorption cell within differentially-stressed fracture confinements. The modeling parameters of this mechanism are largely based on field-scale measurements. Q^{-1} values versus frequency for areas where ocean tides are resonant show significant dissipation, often peaking round the principal semi-diurnal tidal constituent M_2 that are sensitive to absorption-cell geometry, pore-fluid viscosity and temperature.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-157

High-frequency nutation models revisited

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The deployment of the next generation of VLBI stations, referred to as VGOS (VLBI Global Observing System) is bringing closer the obtaining of series of EOP (Earth orientation parameters) with higher temporal resolution. Recent analyses of continuous VLBI campaigns data (e.g. Nilsson et al. 2014), especially CONT11, allowed the determination of the whole set of EOP at a diurnal rate with noticeable gaining in precision, as well as the estimation of some EOP with hourly resolution. While the simulations indicate that the coming VGOS network could make possible the determination of more accurate EOP series with daily and sub-daily resolutions, the studies reveal also that available high-frequency EOP models need to be improved to reduce the impact of the error sources in data analysis.

In this research we are mainly concerned with high-frequency variations of astronomical origin, which are studied following the methods of the precession-nutation theories. Those contributions are due to the harmonic components of the tidal potential different from the main zonal term of degree 2 and are partially included in the IERS Conventions 2010 as polar motion, besides effects of other origins, like oceanic or atmospheric. The few solutions derived more than a decade ago were not in complete agreement and the origin of differences was not clear, although not relevant at the level of accuracy required at that time. Therefore, we revisit the issue and present a solution for a non-rigid Earth model derived by computer algebra, which allows the treatment of the problem with less simplifying assumptions than the conventional approaches.

IAG (Geodesy)

G04p - G04 Earth Rotation and Geodynamics

G04p-158

A Matlab application for the estimation of Euler pole parameters (EP)

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Euler theorem, presented in public in 1776, states that the motion of a rigid body on a spherical surface can be described as a rotation around an axis that passes through the center of the earth. This theorem is used widely for the study of regional and global tectonics. A MATLAB application has been developed for the estimation of Euler pole parameters, given the velocity field of the region. The user can also solve for the inverse problem, i.e. calculate the velocity field according to a specific pole. The application can be used for any amount of data from all around the world. The application is accompanied by a visualization tool enabling the inspection of results. It also includes a variety of functions, that enable outlier identification and marking and is versatile enough to enable various tests within the same project.

IAG (Geodesy)

G05a - G05 GNSS++: Emerging Technologies and Applications

IUGG-0239

Multi-sensor point cloud generation with small unmanned aerial vehicles

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The goal of the study presented here is to exploit sensing and navigation technologies for sUAS platforms with a variety of sensor configurations, including optical cameras, GPS receivers, laser scanners and IMU, to create accurate 3D DEMs and DTMs. The vast majority of sUAS currently on the market use single-frequency GPS receivers and a MEMS IMU for waypoint-based flight navigation and platform stabilization. While this sensor configuration is sufficient for flight control, the platform georeferencing accuracy is below the requirements of mapping applications, in particular for active sensors, such as LiDAR. The analysis presented in this paper compares the performance of three different positioning approaches used for sUAS image sensor georeferencing: dual-frequency GPS data; single frequency, pseudorange data, and indirect image georeferencing, based on aerial triangulation. The latter solution is of high interest, as it is closely connected to terrain/image-based navigation, which is important to sUAS, when flying in urban canyons or indoors. In addition, we compared the performance of various point cloud generation methods, including both active and passive imaging sensors. Using an octocopter sUAS platform, three sensor configurations were flown for test data collection over the same area. First, a Nikon D800 camera was installed on sUAS, followed by a GoPro camera, and then the last sensor was a Velodyne HD-32. In addition, a dense network of ground control points was established to support the QA/QC processes. The paper provides a cross performance evaluation of the different sensor types and methods used for point cloud generation.

IAG (Geodesy)

G05a - G05 GNSS++: Emerging Technologies and Applications

IUGG-0240

Sensing aircraft attitude and velocity by LiDAR

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Active imaging sensors, such as LiDAR, allow collecting mass 3D data from objects, usually presented as a point cloud. Then, using surface models, created from point clouds, more sophisticated and accurate object extraction results can be derived. In most applications, LiDAR is used to collect geospatial data of the static environment. In this study, the focus, however, is on acquiring data of moving objects (namely aircraft) and estimate the motion parameters of the object, including the nine navigation parameters, three position, three attitude and three velocity components.

Monitoring aircraft motion parameters, including position, orientation, etc., during taxiing, taking off, and landing provides essential information for runway and traffic design and planning, and thus the airport safety can be improved. In addition, this information helps us better understand pilot's driving patterns on runways and taxiways (e.g., center line deviation), and can be used in aircraft and airport planning, pilot education and airport monitoring systems. This study presents a comparison of different laser scanners, in terms of accuracy, range, reliability and capability to reconstruct aircraft body parameters based on point cloud data. With support from FAA, various tests with parking and moving aircrafts have been conducted at the The Ohio State University's Don Scott Airport. Initial results on reconstructing 3D models from 2D profiles and point clouds as well as estimating the aircraft position and orientation are reported in this study.

IAG (Geodesy)

G05a - G05 GNSS++: Emerging Technologies and Applications

IUGG-1525

Geodetic Stereo SAR - 4-D coordinate retrieval of persistent scatterers from TerraSAR-X radar observations

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The combination of geodetic principles for correcting radio signals with spaceborne Synthetic Aperture Radar (SAR) has led to a new type of accurate radar observations. This approach is comparable to satellite altimetry or Global Navigation Satellite Systems (GNSS), where errors in the signal time-of-flight due to the Earth's atmosphere and geodynamic effects (solid Earth tides, ocean loading, …) are removed by external models or complementary observations. In the case of the high-resolution radar satellites TerraSAR-X and TanDEM-X, we have demonstrated the feasibility of such geodetic SAR observations by retrieving radar corner reflectors not only in the 2-D radar geometry (range, azimuth) but also in absolute 3-D with an accuracy of 1-2 centimeters (1 sigma level). Moreover, additional secular velocity determination has become attainable if the radar data has sufficient temporal coverage.

The concept of geodetic stereo SAR shall now be applied to opportunistic persistent scatterers (PS). High-resolution TerraSAR-X data covering several years have been acquired for the city of Munich and our goal is to use geodetic stereo SAR to retrieve both the global coordinates of PS as well as their common velocity vector linked to plate tectonics. Based on a test scenario at campus Technische Universität München (TUM), we will provide insight into our methods and compare the results with reference data derived from an accurate building model and permanent GNSS observations.

IAG (Geodesy)

G05a - G05 GNSS++: Emerging Technologies and Applications

IUGG-2300

Single-epoch BDS/GPS Attitude Determination with Length Constrained LAMBDA Method

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Global Positioning System (GPS) based attitude determination has been widely used in a variety of applications on land, at sea, in air and space because of its advantages (inherently drift-free, lower in cost, etc). The advent of modernized and new global navigation satellite systems (GNSS) has enhanced the availability of satellite based attitude determination solutions. Specifically, it increases redundancy and yields operational back-up or independence in case of failure or unavailability of one system. Among existing GNSS, the Chinese BeiDou Navigation Satellite System (BDS) is being developed. In this paper, an efficient GNSS attitude determination algorithm using single-epoch observations and known baseline length constraint is put forward, and then a comprehensive performance analysis relating to BDS/GPS attitude determination is performed. The analysis bases on standalone or combined GNSS attitude determination with single/double/triple frequency data. To carry out these, a set of real GNSS data involving static, car, ship and airborne experimental scenarios were collected using receivers from different manufacturers. Experimental results show that 1) standalone BDS or GPS single-frequency instantaneous attitude determination does not get very high success rate, availability and not meet the needs of practical application in most cases; but combined BDS/GPS attitude determination does; 2) for single- and dual-frequency cases, owing to the advantage of BDS regional coverage, BDS shows a comparable(even slightly better) performance with GPS; 3) triple-frequency attitude determination is slightly better than that of the dual-frequency, while they both outperform the single-frequency case.

IAG (Geodesy)

G05a - G05 GNSS++: Emerging Technologies and Applications

IUGG-3594

Robust spatial approximation of laserscanner point clouds by means of free-form surface approaches

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In several geodetic applications deformations and deflections to a target-state are derived from point clouds, captured by laserscanner. In order to determine deformations or deflections, the spatial object has to be modelled. The modelling can be performed point-wise, line-wise or surface-wise. In this research work, we introduce a general model to approximate spatial objects by means of free-form-surfaces, such as Beziér- or B-Spline surfaces.

The modelling of laserscanner point clouds by means of free-form surfaces will be performed in several ways. On the one hand, the free-form surfaces can be estimated by solving a Gauss-Markov model with equidistant, deterministic control points. On the other hand, the free-form surfaces can be obtained using a Gauss-Helmert model with non-equidistant, stochastic control points. Unfortunately, the laserscanner measurements may contain data gaps and possibly include defects. In order to overcome the problems of outlier and data gaps, a robust estimation approach, e. g. an Expectation-Maximization-Algorithm, will be introduced.

As a relevant example, the above mentioned approach will be applied in field of rail track inspection. Kinematic laserscanning is used to measure the deflection of the rail construction within a rapid and efficient surveying approach. The measurements are carried out by two continuous georeferenced 2D-Laser scanners which move along the rail track. The objectives in this case are to cope with the data gaps and to identify the rail defects. In addition, useful information for the segmentation of the laser scanner profile will be obtained, because it is prior not known to which part of the rail track the profile measurements of each laserscanner belong.

IAG (Geodesy)

G05a - G05 GNSS++: Emerging Technologies and Applications

IUGG-3703

Noise modelling for geo-referencing of a TLS-based multi-sensor system using low-cost GNSS

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Stationary terrestrial laser scanning (TLS) provides a 3D point cloud in a local sensor-defined coordinate system. In general, the transformation parameters of local 3D point clouds to a global coordinate system are obtained by pre-surveyed control points with known geodetic datum. To improve this procedure, a direct geo-referencing method of a multi-sensor system with geodetic GNSS equipment has been developed at the Geodetic Institute Hannover. For this purpose, 3D position sensors (here: GNSS equipment) are mounted on top of the laser scanner which rotates about its vertical axis. The analysis of the trajectories of the 3D GNSS-points and the estimation of the transformation parameters are based on a recursive filter approach in form of an extended Kalman Filter (EKF). To provide optimal results with the EKF algorithm, the system noise should be normally distributed with known variance covariance matrix and no correlations over time (usually known as white noise). Unfortunately, this assumption of the noise process is not sufficient in our evaluation approach due to the stochastically time-correlated state vector. For this reason, different approaches (e. g. Gauss-Markov process modelled by means of shaping filter) for modelling the system and the measurement process are introduced and discussed. The main benefit will be the optimization of the stochastic model and its influence on the resulting trajectory. In addition, the performance of the filter model will be investigated by means of a global sensitivity analysis approach in order to identify the main influencing factors. Finally, this contribution will discuss the use of low-cost sensors, its implementation, and its stochastic characteristics as an alternative equipment to deliver the transformation parameters.

IAG (Geodesy)

G05b - G05 GNSS++: Emerging Technologies and Applications

IUGG-0725

Weighted mean temperature model for Turkey using GNSS observables

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Ground-based GNSS receivers are an attractive source of total zenith delay (ZTD) and precipitable water vapor (PWV) data for weather prediction since they are portable, economic and provide measurements that are not affected by weather conditions. The tropospheric zenith delay which consists of the wet and dry components, and eliminated by using a priori model and mapping functions. Previous studies have demonstrated successfully estimation of PWV from ZTD which is computed from GNSS observations within 1-2 mm of accuracy at 15-minute temporal resolution. To bridge between ZTD and PWV, Bevis have developed a linear regression model to determine the weighted mean temperature (T_m) depending on the surface temperature (T_s). In previous studies, a regional Tm model based on a radiosonde analysis algorithm (Deniz and Mekik, 2013) has been developed for Turkey which computes the surface temperature and the weighted mean temperature using the radiosonde profiles from eight radiosonde stations. In this study, a regional model using the weighted mean temperature equation have been used for the determination of precipitable water vapor, and applied to the GNSS derived wet tropospheric zenith delays. Hereafter, the precipitable water vapor estimated from GNSS observations and the precipitable water vapor obtained from the radiosonde station are compared. The average values of the differences between the radiosonde and the model for Istanbul and Ankara stations are obtained as 2.1±1.6 mm, 1.9±1.5 mm, respectively. *This study is funded by funded by the Scientific and Technological Research Council of Turkey (TUBITAK).*

IAG (Geodesy)

G05b - G05 GNSS++: Emerging Technologies and Applications

IUGG-0787

Real-time retrieval of precipitable water vapor from GPS and BeiDou observations

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The rapid development of the Chinese BeiDou Navigation Satellite System (BDS) brings a promising prospect for the real-time retrieval of zenith tropospheric delays (ZTD) and precipitable water vapor (PWV), which is of great benefit for supporting the time-critical meteorological applications such as nowcasting or severe weather event monitoring. In this study, we develop a real-time ZTD/PWV processing based on GPS (Global Positioning System) and BDS observations. GPS and BDS observations of a half-year period for 40 globally distributed stations from the IGS (International GNSS Service) MGEX (Multi-GNSS Experiment) and BETN (BeiDou Experiment Tracking Network) are processed. The performance of ZTD and PWV derived from BDS observations based on real-time precise point positioning (PPP) technique is carefully investigated. The contribution of combining BDS and GPS for ZTD/PWV retrieving is evaluated as well. The results show that the real-time BDS-only ZTD series agree well with the GPS-only ZTD series, with the RMS values of about 11-16 mm (about 2-3 mm in PWV). Furthermore, the real-time ZTD derived from the GPS-only, the BDS-only and the GPS/BDS combined solutions are compared with that derived from the Very Long Baseline Interferometry (VLBI) as an independent technique for validation. The comparisons show that the BDS can contribute to real-time meteorological applications, slightly less accurate than GPS. More accurate and reliable water vapor estimates, about 1.3-1.8 mm in PWV, can be obtained if the BDS observations are combined with the GPS observations in the real-time PPP data processing. The comparisons with PWV derived from radiosondes further confirm the performance of BDS-derived real-time PWV and the benefit of adding BDS to standard GPS processing.

IAG (Geodesy)

G05b - G05 GNSS++: Emerging Technologies and Applications

IUGG-1046

Influences of Interoperability of Coordinate Reference Systems among Navigation Satellite Systems

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The compatibility and interoperability of GNSS (Global Navigation Satellite System) multi-constellation can reduce the computation burden of users and reduce the production costs of GNSS receiver manufacturers. There are some issues on the interoperability of GPS, GLONASS, BeiDou and Galileo navigation satellite systems. The paper emphasizes particularly on the influence analysis of the interoperability in coordinate reference systems between the four navigation satellite systems. Firstly, the differences of the constants of ellipsoids adopted by the four navigation satellite systems are listed and compared. Then, the influences of the small difference of the earth's gravitational constant and the earth's rotation rate value on the positions of navigation satellites are analyzed in theory and computed by actual data when using broadcast ephemeris. Both theory and computation indicate that the small difference value of the earth's gravitational constant between the different navigation satellite systems can make satellite position several meter errors. And the small difference value of the earth's rotation rate constant between the different navigation satellite systems can generate errors more than ten meters. The ellipsoid differences between GPS and BDS, however, only result in maximum discrepancy 0.1mm and 0.1mm for latitude and height, respectively, but no effect on normal gravity value. The ellipsoid differences between GPS (or BDS) and Galileo result in maximum discrepancies about 0.15mgal for normal gravity, 0.3cm for latitude and 0.5m for height, respectively, while the ellipsoid differences of GPS (or BDS) and GLONASS will result in 0.3mgal, 3.0cm and 1.0m for normal gravity value, latitude and height, respectively.

IAG (Geodesy)

G05b - G05 GNSS++: Emerging Technologies and Applications

IUGG-1932

GNSS tomography: technique resolving vertical structure of severe weather

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The GNSS tomography is a method to reconstruct 3D data based on Slant Delay integrated measurements. As the method was researched by many scientists around the world its advantages (high horizontal resolution, sensitivity to troposphere changes, capturing dynamics of the weather) and limitations are well known (sensitivity to biases in observations, instability of solution, complicated mathematical derivation).

The next step in GNSS tomography research is inevitably linked with its applications in the weather studies, one of the concept is that it can be used to investigate severe weather. In mid-latitudes these are usually linked with multi or super cell storms. Whereas the storms forming mechanism is well known, the forecasting in terms of location and severity is not so well investigated. One of the major reason is that we don’t have a measurements that will provide 3D structure of the troposphere priori, during and after the event. The GNSS tomography can fill that gap.

Within this study we will investigate several storms outbreaks in Poland using GNSS tomography models developed in Belgium (BIRA) and Poland (TOMO2) to make sure we can apply this innovative tool to address issues of weather nowcasting and forecasting. As a result recommendations for further development of tomography models will be formed.

IAG (Geodesy)

G05b - G05 GNSS++: Emerging Technologies and Applications

IUGG-3117

Quality assessment and screening of GPS ZTD estimates

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An efficient detection of outliers and a good knowledge of the accuracy of GPS ZTD estimates are important for optimal use of these data in meteorology and climatology. The accuracy of GPS ZTD estimates depends on many factors such as the reliability of the equipment, the number of observations, the magnitude of noise and interferences in the measurements, the quality of the troposphere model used for the data processing. As these factors may change over time, an adaptive screening and quality control is required.

Here we propose a method to detect and eliminate ZTD estimates that are less accurate and/or may be classified as outliers. The method depends on parameters available at the end of the data processing such as the number of fixed ambiguities, the position and ZTD estimates and their formal errors. It is therefore totally independent of external data. This method is first applied to the HyMeX post-processed GPS dataset produced with GIPSY-OASIS II 6.2 software. It is evaluated against a method with uses an atmospheric model analysis as a reference. The method is intended to be generalized to GPS solutions produced with other GPS software and especially to IGS and EUREF products. The methods can also be applied to other space geodetic techniques like DORIS and VLBI.

IAG (Geodesy)

G05b - G05 GNSS++: Emerging Technologies and Applications

IUGG-4413

Evaluation of multi-GNSS real-time atmospheric parameters using microwave radiometer and numerical weather model

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Keywords: *Multi-GNSS; tropospheric delay; integrated water vapor; BeiDou, Galileo, GLONASS and GPS; microwave radiometer; numerical weather model; real-time precise point positioning*

The multi-constellation GNSSs (e.g. BeiDou, Galileo, GLONASS, GPS) bring great opportunities and challenges for real-time retrieval of atmospheric parameters for supporting numerical weather prediction (NWP) nowcasting or severe weather event monitoring. In this study, the observations from different GNSSs are combined together for atmospheric parameter estimation based on the real-time PPP technique. We process the multi-GNSS observations of a 180 days period from about 100 globally distributed stations in both single-GNSS and multi-GNSS modes. The atmospheric parameters including zenith total delay (ZTD), slant total delay (STD) and integrated water vapor (IWV) derived from multi-GNSS stations are carefully analyzed and compared with those from collocated water vapor radiometer and numerical weather model (ECWMF) to independently evaluate the performance of individual GNSS and also demonstrate the benefits of multi-constellation GNSS for real-time atmospheric monitoring. The statistical results show that an accuracy of several millimeters with high reliability is achievable for the multi-GNSS based real-time ZTD estimates, about 1~1.5 mm for IWV. The multi-GNSS real-time ZTD, STD and IWV products would be beneficial for atmospheric sounding systems, especially for nowcasting of extreme weather due to its higher accuracy, stronger reliability and better distribution.

IAG (Geodesy)

G05c - G05 GNSS++: Emerging Technologies and Applications

IUGG-0561

Radio occultation excess phases to derive bending angle and refractivity over Poland

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Since 2015 Wroclaw University of Environmental and Life Sciences (WUELS) routinely collects and processes GPS Radio Occultation (GPS RO) level1b data of FORMOSAT-3/COSMIC mission using products provided by COSMIC Data Analysis and Archival Center (CDAAC). From over 1,500 daily occultations available worldwide, we find these occurred over the area of Poland to derive atmospheric profiles of bending angle and refractivity. In this study, we present results for processing of satellite signal excess phases on both, L1 and L2 frequencies obtained from atmPhs real time product. As the phase-locked loop (PLL) method cannot provide precise retrievals in the troposphere, open-loop (OL) tracking is applied to enhance results of calculated bending angles. Conversion to refractivity can be then carried out by Abel inversion. Reference values of calculated parameters are obtained from atmPrf product provided by CDAAC as both, bending angle and refractivity are unusual in meteorological observing system, thus making the quality assessment of radio occultation retrievals difficult when using in-situ measures. However, refractivity is additionally evaluated using radiosonde reports by comparing radio occultation profiles in the immediate vicinity of three Polish stations.

IAG (Geodesy)

G05c - G05 GNSS++: Emerging Technologies and Applications

IUGG-1072

Tropospheric profiles of total refractivity from the collocation software COMEDIE

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The refractivity of the troposphere is measured in GNSS (Global Navigation Satellite Systems) meteorology by zenith total delay (ZTD) and troposphere gradients in north and east directions. The collocation method can be applied to reconstruct the troposphere conditions based on GNSS and meteorological observations in an interpolation model.

In this study we reconstructed the total refractivity profiles over a western part of Switzerland using the least-squares collocation software COMEDIE (Collocation of Meteorological Data for Interpretation and Estimation of Tropospheric Pathdelays). Different datasets were included into collocation algorithms: total refractivity calculated from meteorological parameters at ground-based SwissMetNet sites as well as GNSS derived ZTD and horizontal gradients of ZTD from Automated GNSS Network for Switzerland (AGNES). The refractivity fields were compared to the values on the reference radiosonde station in Payerne. We are also investigating the application of collocation algorithms to improve modeling of refractivity field in Poland and Australia.

We presumed that introducing the horizontal gradients will improve the interpolation, but for the vertical interpolation case study in Switzerland at Payerne the refractivity field from the dataset with gradients was worse by about 0.5 ppm than the interpolation without gradients. Currently, we are actively researching the reason for results degradation (gradient noise, orography of Switzerland, parameterization problems).

IAG (Geodesy)

G05c - G05 GNSS++: Emerging Technologies and Applications

IUGG-2626

Long-range GNSS reflectometry aboard the International Space Station: simulating the potential coverage and refraction bias for ocean altimetry

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An ocean altimetry experiment using Earth reflected GNSS signals has been proposed to the European Space Agency (ESA). It is part of the GNSS Reflectometry Radio Occultation Scatterometry (GEROS) mission that is planned aboard the International Space Station (ISS). The presented study focuses on ocean coverage and refraction biases (troposphere and ionosphere) that have to be investigated beforehand for such a spaceborne reflectometry experiment. Special effort is put to observations with long ranges (distance between surface reflection point and receiver). This long range feature of GNSS reflections increase the ocean coverage at the expense of a potentially increased refraction bias. The first part concentrates on the ocean coverage disregarding considerable visibility limitations that arise for an ISS based setup. The idealized surface coverage is simulated in the interest region of the Argulhas current (15°W to 55°E and 5°S to 58°S). An assimilation of simulated GNSS-R observations in a sea surface height model shows a mitigation of the model's initial rms error by 15-30% depending on the assimilation period. The second part uses case studies to characterise the tropospheric and ionospheric bias. Variations of the tropospheric height bias (between 0.2 and 10.3m) are range-dependent (with respective ranges of 510km and 1280km). Variations of the ionospheric height bias (-1.4 and -38.0m) are less affected by range. In this case the local sun incidence has greatest effect. It is concluded from the study that the expected increase of observation coverage improves existing sea surface height models. However, variations of tropospheric and ionospheric bias require an adapted correction considering the strong range effect of the tropospheric bias.

IAG (Geodesy)

G05c - G05 GNSS++: Emerging Technologies and Applications

IUGG-3047

GEROS-ISS: Innovative Ocean Remote Sensing using GNSS Reflectometry onboard the International Space Station

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In response to an ESA announcement of opportunity the GEROS-ISS (GEROS hereafter) proposal was submitted in 2011 and accepted by to proceed to Phase A. GEROS-ISS is an innovative ISS experiment primarily focused on exploiting reflected signals of opportunity from Global Navigation Satellite Systems (GNSS) at L-band to measure key parameters of ocean surfaces.

The primary mission objectives of GEROS are: (1) to measure the altimetric sea surface height of the ocean using reflected GNSS signals to allow methodology demonstration, establishment of error budget and resolutions and comparison/synergy with results of satellite based nadir-pointing altimeters and (2) to retrieve scalar ocean surface mean square slope (MSS), which is related to sea roughness, wind speed and direction, with a GNSS spaceborne receiver to allow methodology testing, establishment of error budget and resolutions. Secondary objectives include the generation of the 2D MSS or directional MSS retrieval and the associated proof-of-concept scientific data product.

The definition of the GEROS mission and system requirements was completed end of 2013. Two industrial phase A studies were started end of 2014, complemented by the scientific study GARCA (GNSS-R – Assessment of Requirements and Consolidation of Retrieval Algorithms) to develop an End2End Simulator for the preparation of the GEROS-Mission and to perform Observing-System Simulation Experiments (OSSE) to assess the oceanographic significance of the expected GEROS-ISS measurements and to demonstrate the usefulness of the GEROS-ISS concept.

The presentation will give an overview and current status of the GEROS-ISS experiment and the related ESA-supported activities.

IAG (Geodesy)

G05c - G05 GNSS++: Emerging Technologies and Applications

IUGG-4571

The effect of ionosphere on GNSS radio occultation signal

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GNSS based radio occultaion has been a powerful technique to remotely sense the Earth's atmosphere and ionosphere. Since GPS/MET mission, lost of LEO satellites have been launched equipped with GPS radio occultation payload, such as CHAMP, GRACE, COSMIC, Metop-A/B, TerraSAR-x/TanDEM-x, SAC-C/D, C/NOFS, COMPSAT-5, etc. Of these missions, COSMIC is the first constellation dedicated for radio occultation. In this presentation, we will first generally describe how the radio occultation data are processed in the ionosphere and atmosphere. Then we are going to show how the ionosphere influence the atmospheric data processing, in terms of large- and small-scale ionospheric residual. In addition, we are also going to show how radio occultation signal be used to detect the ionospheric irregularities.

IAG (Geodesy)

G05c - G05 GNSS++: Emerging Technologies and Applications

IUGG-5689

Simulated GNSS signal propagation paths during a severe troposphere weather event

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The impact of transverse and downrange refractive gradients on Global Navigation Satellite Systems (GNSS) signal paths in the ionosphere and troposphere during a tropospheric storm event are investigated. The tropospheric refractive gradients from the storm event over Melbourne, Australia on 6th March, 2010 are used to determine the impact that this and similar storms have on GNSS signal paths. The traditional GNSS atmospheric retrieval methods typically assume spherical stratification of the refractivity in the atmosphere and do not take into consideration the transverse refractivity gradients acting on GNSS signals.

A three dimensional numerical ray tracing technique based on geometrical optics is used together with models of the ionosphere, lower atmosphere and magnetic field to simulate signal propagation from GNSS. The ray tracing technique involves tracing finite flux, or ray tubes and has accurate homing-in capabilities. In recent years GNSS has been increasingly used to remotely sense the Earth's atmosphere and ionosphere using two approaches. This includes ground-based GNSS atmospheric sounding provided by a network of Continuously Operating Reference Stations (CORS) and space-based GNSS Radio Occultation (RO) using GNSS receivers on-board Low Earth Orbit (LEO) satellites. For both GNSS CORS and RO techniques 2-D signal paths are assumed and the signal path bending via transverse refractive gradients are ignored. The magnetic field effects on the signal paths are also ignored. The transverse and downrange displacements as well as the phase delay of the signal caused by the refractive gradients in the ionosphere and a severe tropospheric storm event will be presented.

IAG (Geodesy)

G05d - G05 GNSS++: Emerging Technologies and Applications

IUGG-1410

Analysis of GNSS time series obtained from Turkish National Permanent GNSS Stations Network-Active System using Hilbert-Huang Transform

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In this study, time series of position estimates are generated from the data collected at Turkish National Permanent GNSS Stations Network-Active (TNPGN-Active) stations with high-precision GNSS analysis methods. Produced time series are analyzed applying Hilbert Huang Transform (HHT), whereby in this context associated problems of this transformation are also investigated. While daily GNSS data from TNPGN-Active (a Real Time Kinematic (RTK) network) provide an indispensable tool for investigating tectonic and seismic activities, the accuracy of the coordinate correction parameters sent to the end users on the field is significant when it is considered that the new cadastral applications are started to be based upon these coordinates. Thus, detailed analysis of the coordinate time-series of TNPGN-Active stations and the removal of the unwanted signals affecting the coordinate and velocity estimates are of primary importance. GNSS time series show non-linear and/or non-stationary behaviours due to the underlying physical processes. Adaptive nature of HHT makes it possible to address each time series seperately and sheds light upon the individual characteristics of the time series. With Empirical Mode Decomposition (EMD) method, original time-series are transformed into amplitude/frequency modulated Intrinsic Mode Functions (IMFs). Together with the Hilbert Spectrum, a more detailed representation of the physical processes is supplied. Some critical aspects and weaknesses in HHT, such as interpolation technique between extrema, end effects, stopping criteria for sifting process, mode mixing, and some coproducts of EMD, such as detrending and denoising are also evaluated and their results reflected in the analysis.

IAG (Geodesy)

G05d - G05 GNSS++: Emerging Technologies and Applications

IUGG-1576

Towards reliable and precise BeiDou positioning with stochastic modelling

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The China's BeiDou system is the first global satellite navigation system to broadcast the triple frequency signals for full constellation. In recent years, the BeiDou system received very fast development and the GPS-like PNT (positioning, navigation and timing) technologies have been basically realized. However, all these BeiDou applications are currently based on the empirical stochastic model that describes the observation precisions and correlations. In principle, an arbitrarily positive-definite stochastic model can be used to compute the unbiased least squares estimate, but one achieves the optimal estimate only if the correct stochastic model is applied. This paper aims to synthetically study the stochastic modelling of BeiDou observations using variance component estimation. The between-receiver single-difference geometry-free model is applied to remove effects of systematic errors, such as satellite orbit and atmospheric biases, without introducing any mathematic correlations. For structuring the stochastic model, we set up the satellite-dependent precisions for each satellite so as to analyze the satellite-type-specific (GEO/IGSO/MEO) observation precisions; we set up the cross-correlations for phase and code between arbitrary two frequencies to capture any potential correlations between frequency-dependent observations; and the time-correlations for each type of frequency-dependent observations. The result indicates that the stochastic model varies with the different type of receivers and observation situations, and the estimated stochastic model can moderately capture the varied observation scenarios, improving the positioning precision and reliability.

IAG (Geodesy)

G05d - G05 GNSS++: Emerging Technologies and Applications

IUGG-1607

Correcting NetworkRTK for non-linear tectonic deformation in New Zealand

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The use of modern network RTK systems have significantly increased the accuracy requirements of the base stations incorporated in the network Coordinates input in the software are usually in the ITRF system at the reference epoch (2005 for ITRF2008) however computations must be done at the epoch of observation requiring that coordinates are projected forward in time. This transformation is critical because inaccuracies in reference station coordinates result in biases in user coordinates.

Over most of the world deformation can be modelled as a constant velocity. However, some subduction zones are affected by slow slip events and regions which have recently undergone large earthquakes will be subject to post seismic deformation. Both of these effects may produce significant deviations from linear trends. The Australian-Pacific tectonic plate boundary New Zealand is currently undergoing both post-seismic relaxation and slow slip events and thus is a natural laboratory to study their effects on NetworkRTK systems. For example, the Dusky Sound 2009 event for which the post-seismic signal extends over 500 km that affecting over 50% of the South Island. Slow slip events (which are common in the northern half of the country) can have amplitudes of several centimetres and periods between a few days to a year or more. This is a problem because most NetworkRTK systems use simple predictive models (e.g. position and velocity only) and do not have any ability to account for non-linear deformation.

In this paper we discuss techniques to correct network RTK systems for New Zealand deformation events.

IAG (Geodesy)

G05d - G05 GNSS++: Emerging Technologies and Applications

IUGG-1926

A Single Antenna Yaw angle Determination Method Based on Ground-based Carrier Phase Wind-Up Effect

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Since GPS signals have aright-hand circular polarization, a change in the measured phase is occurreddue to rotation of the receiving antenna. This phenomenon is calledground-based carrier phase wind-up (GPWU). When the spin axis is aligned withthe antenna boresight, the produced GPWU is independent of satellite and iscompletely correlated with the receiver clock error. Since the GPWU iseliminated in double-difference observations and is inseparable from receiverclock error in conventional single-difference and non-difference observations, little isknown about the characteristics, effect and potential usage of the observed GPWU.

A singleantenna yaw angle determination method (SAYD) based on GPWU effect is proposed inthis study. Inside multi-antenna synchronized GNSS receiver, multiple antennasshare a common clock. Using this type of receiver, single-differencecarrier phase observations are able to eliminate both the satellite andreceiver clock errors simultaneously. Making use of this advantage, we derived GPWUeffect from single-difference carrier phase observations and applied it todetermine yaw angle successfully for the first time. The unique feature of thismethod is that the accuracy of the estimated yaw angle is independent of thebaseline length. Therefore this method is of greater advantage in the ultra-short baseline applicationsover the current GNSS yaw angle determination method based on two antennas.

IAG (Geodesy)

G05d - G05 GNSS++: Emerging Technologies and Applications

IUGG-1970

Deterministic and stochastic modeling of low-cost clocks in pseudo-range kinematic positioning

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Modeling high-precision receiver clocks (e.g., hydrogen masers), instead of an epoch-wise estimation, has been proved to be beneficial in kinematic applications. Especially the vertical coordinate component is improved (Wang and Rothacher, 2013).

In this contribution, we show the improvement of the height component in a kinematic pseudo-range precise point positioning (PPP) obtained by modeling low-cost receiver clocks. The impact of different deterministic models and of relative clock constraints between subsequent and nearby epochs is investigated. A range of different clock types connected to stations from the International GNSS Service (IGS) network as well as phase clock data of crystal oscillators and rubidium clocks from Spectratime are used for the experiments. Simulated and real observations are analyzed applying diverse measurement noise and processing scenarios. Dual-frequency data allowing the ionosphere-free linear combination as well as single-frequency L1 data is used with different sampling rates up to 1 Hz.

Moreover, real experiments are planned using a low-cost rubidium clock connected to a receiver. We will discuss the first results from these experiments.

References:
Wang K., Rothacher M. (2013): Stochastic modeling of high-stability ground clocks in GPS analysis, Journal of Geodesy 87(5): 427-437, doi: 10.1007/s00190-013-0616-5.

IAG (Geodesy)

G05d - G05 GNSS++: Emerging Technologies and Applications

IUGG-2917

Developing a high precision GNSS receiver using low cost OEM products, 3D printing and smartphone based software.

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In this paper a description of a developed GNSS receiver kit is presented in terms of high precision real time and post processing positioning and appropriate interface guidelines for adaptive user experience in the field. The main concern was the hardware and software integration that will improve the ease of use reducing the cost at the same time. The main hardware part, in the core of the receiver, is a third party manufacturer GNSS OEM processing engine and communication board. This mainboard can be connected either with an internal or an external GNSS antenna. For data transmitting purposes, the receiver uses a long range high speed Wi-Fi antenna. A high capacity Li-Ion polymer rechargeable battery, with a sophisticated power management and usb charging system, is used. All the above GNSS and modem electronics are accommodated in an elegant, rugged, light and hermetically sealed plastic enclosure created with special 3D printing technology. The receiver is controlled by an individual smartphone and tablet developed software that exploits the advantages of new technology smartphones instead of the old handheld PDA's. Examples are the high performance processing and graphics chips, the super-fast internet communication technologies (4G LTE) for RTK applications and GIS mapping information access, the cloud computing for data exchange between multiple devices, the touch screen technology avoiding stylus usage and the ease of software updates. Finally the presented GNSS kit highlights the hardware and software components in developing a low cost experimental GNSS receiver for research and more.

IAG (Geodesy)

G05e - G05 GNSS++: Emerging Technologies and Applications

IUGG-2142

LEO orbit and attitude determination using low-cost multi-GNSS receivers on a nanosatellite

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The Swiss CubeSat project CubETH has the scientific goals to perform precise orbit determination and attitude determination of a nanosatellite (10x10x10cm) using low-cost, single-frequency, multi-GNSS receivers.
We present the main concepts and challenges of the scientific tasks as well as the methods of external validation. Orbit and attitude determination will be performed in a post-processing and a real-time mode. For real-time, orbit accuracies of around 2m, for post-processing - based on a combination of L1 phase and code observations - accuracies on a sub-meter level are expected. As the GNSS receivers used are able to track GPS, GLONASS and BeiDou (and are ready for Galileo), combinations and comparisons of the respective measurements and results will be performed. Validation will be done by SLR. Based on differential phase measurements between the four receivers/antennas on the zenith face of the cube, its attitude will be determined with an accuracy of 5-15 degrees – limited by the very short baselines of 5-8 cm between the antennas. However, it shall present an innovative new approach and a proof of concept of real-time attitude determination based on single-frequency GNSS data on a CubeSat.
As the GNSS receivers selected – low-cost, single-frequency COTS receivers for embedded solutions, providing navigation solutions as well as raw code and phase measurements, characterized by good performance and very small size, weight and power consumption – are not space-qualified, numerous tests have been performed in order to evaluate their behaviour and usability in the intended space environment. We present promising results of radiation and thermal vacuum tests as well as of the receiver performance in GNSS simulator tests simulating GPS signals in LEO orbits.

IAG (Geodesy)

G05e - G05 GNSS++: Emerging Technologies and Applications

IUGG-2696

IGS real-time service – an open service for positioning, navigation and timing

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The International GNSS Service (IGS) is one of the most important services of the International Association of Geodesy (IAG). It provides GNSS products, such as precise satellite orbits in a global terrestrial reference frame, Earth orientation parameters, stations coordinates and atmospheric parameter for post processing purposes all at the highest level of accuracy. With its Real-Time Service (RTS) the IGS extends its capabilities to support applications which need real time access to such products.

We introduce the IGS RTS and give an overview of its infrastructure. As is true for the entire IGS service, the IGS RTS observations and products are provided on a best effort basis and use open data and product formats.

The definition of GNSS open data formats such as for real-time observation data, ephemeris data and the different components of the GNSS error budget is the responsibility the sub-commission 104 of the Radio Technical Commission for Maritime Services (RTCM-SC104).

We describe the IGS-RTS products and present an evaluation of their quality. We also present the status of State Space Representation (SSR) standardization within RTCM-SC104. The SSR format uses the principle of state space corrections to describe the error budget of the GNSS observations and supports applications such as Precise Point Positioning (PPP). Finally, we give an outlook on the progress towards high precision multi-GNSS applications based on IGS RTS products.

IAG (Geodesy)

G05e - G05 GNSS++: Emerging Technologies and Applications

IUGG-4547

Assessment of the CODE MGEX Clock Products

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In the frame of the Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS), the Center for Orbit Determination in Europe (CODE) is contributing with a fully integrated 5-system (GPS, GLONASS, Galileo, BeiDou, QZSS) GNSS orbit and clock solution, based on data starting from January 2014. Several solutions are produced based on different orbital arc lengths and different solar radiation pressure (SRP) models. These solutions were assessed using satellite laser ranging (SLR) data, clock metrics and running precise point positioning (PPP) tests.

In this paper we propose an in-depth analysis of the clock performance from all systems. In order to get full insight on the clocks' quality, weekly and monthly time series are analysed over the whole year 2014 for the about 70 satellites available within the five GNSS considered. The impact of the orbital arc length (1, 3 or 5 day(s)) and of the SRP model on the clock estimates will be quantified and checked against SLR residuals. Based on the results of the analysis, tests on satellite clock modelling shall be undertaken, comparing two solutions: one following the classical approach, where satellite clocks are represented as independent epoch-wise parameters, and a second one in which the most stable satellite clocks are modelled using either deterministic or stochastic models.

IAG (Geodesy)

G05e - G05 GNSS++: Emerging Technologies and Applications

IUGG-4934

Noise model of the Galileo "mm-Clock" - geometrical mapping of the orbit perturbations using a clock on board Galileo satellites

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Galileo is the first GNSS equipped with a highly stable onboard clock. This paper provides a comprehensive analysis of the performance of the Passive H-Maser (PHM) used as a primary clock onboard Galileo. The noise contribution of the Galileo PHM shows a standard deviation of only 15.5 mm (52 ps), after removing a linear model (time drift) from the epoch-wise clock parameters (over 24 h). Our analysis is based on noise simulation of the Galileo PHM clock performance as measured during on-ground tests, their comparison with the estimated clock parameters from the MGEX Campaign of IGS and an independent validation with SLR. For the clock modelling, we consider all the relevant noise processes, including white phase noise, white frequency noise, flicker frequency noise and frequency drift. We considered effects such as the periodic relativistic contribution of the J2 gravity field coefficient as well as the relativistic effects due to the gravity field of the Moon and the Sun. Environmental effects, such as variations in temperature and magnetic field, were integrated along the orbit without indicating a significant impact. We show that due to the very high altitude, there is an equivalence between the radial orbit error and the estimated clock parameter. Hence, estimated GNSS satellite clock parameters completely absorb variations of the radial errors along the orbit and can be used as 'continuous SLR' to geometrically map radial orbit perturbations continuously along the orbit. In sequel, we focus on the strong Sun elevation effect in the Galileo clock and SLR data vs. relative Sun argument of latitude. Although several groups have been trying to remove this effect with enhanced SRP modeling, we show that this effect can be analytically modeled for both, GPS and Galileo.

IAG (Geodesy)

G05e - G05 GNSS++: Emerging Technologies and Applications

IUGG-5360

BeiDou Satellites maneuvers detection for precise Orbit determination

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BeiDou Navigation Satellite System is composed of three types of orbits: Geostationary Earth orbit (GEO), Inclined Geo-Synchronous Orbit (IGSO) and Medium Earth Orbit (MEO). These satellites are frequently maneuvered due to orbit perturbations, i.e. the solar radiation. Especially for GEO satellites, which are reported to have station keeping maneuvers in the east–west direction every 25 to 35 days, and north-south every two years. For precise orbit determination (POD), maneuver epochs, velocity changes, and trust forces need to be estimated precisely. Under normal circumstances, satellite Keplerian elements are changing periodically with different frequencies. With broadcast and precise ephemeris of BeiDou satellites, Keplerian elements are derived every epoch and the maneuver periods are detected where orbit elements differences of two consecutive epochs are significant. Furthermore, with observations from ground monitoring stations, POD processes are carried out separately before and after the approximately detected maneuver epoch, from which two sets of satellite positions, velocities and Keplerian elements are derived. These two arcs should interact with each other in principle, due to orbit errors and maneuver lasting time, the maneuver epoch is determined at the point where the two arcs are the closest. Moreover, according to the changes of Keplerian elements during maneuver periods, trust forces are figured out based on the Gaussian Perturbed Equation of Satellite Motion. The results show that GEO satellites have much frequent and complex orbital maneuvers compared to IGSO and MEO satellites due to their special positions. BeiDou satellites maneuver periods, velocity changes and accelerations derived in this paper are sure to be of great help for satellite POD.

IAG (Geodesy)

G05f - G05 GNSS++: Emerging Technologies and Applications

IUGG-3470

Multi-GNSS, multi-frequency PPP-RTK analysis for mixed-receiver network and user scenarios

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***Introduction**: PPP-RTK is integer ambiguity resolution enabled precise point positioning (PPP). With PPP-RTK, the PPP network-derived satellite orbits and clock corrections are extended by also providing information about the non-integer satellite-dependent terms in the network ambiguities. Once applied at the user side, this information recovers the integerness of the user ambiguities, thus enabling single-receiver ambiguity resolution. Due to linear dependencies between these non-integer terms and the network ambiguities, the stated information cannot be properly extracted, unless a careful application of S-system theory is made.*
***Motivation and objectives**: With the advent of multi-GNSS satellites transmitting modernized multi-frequency signals, network measurements of mixed-receiver types experience instrumental biases that are generally different for different constellations. The way these biases interact with the satellite phase biases and how they can be correctly formulated in both the network and the user measurement setup are the topics of this contribution.*
***Approach and results**: In this contribution, we apply S-system theory to form full-rank undifferenced observation equations of both the network and the single-receiver user tracking multi-GNSS, multi-frequency satellites. The estimable functions of the corresponding non-integer terms, recovering the integer user's ambiguities, are then identified and compared to their single-GNSS dual-frequency counterparts. It is shown, next to the estimable satellite phase biases, that additional estimable functions are needed to realize multi-GNSS, multi-frequency single-receiver ambiguity resolution. The link between the estimable parameters of the multi-GNSS user and those of the single-GNSS user is finally established.*

IAG (Geodesy)

G05f - G05 GNSS++: Emerging Technologies and Applications

IUGG-4655

Variometric approach for real-time GNSS navigation: first demonstration of Kin-VADASE capabilities

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The use of GNSS for navigation purposes is continuously increasing. High performances (accuracy at the cm level) can be achieved with established techniques such as Network Real Time Kinematic and Precise Point Positioning, but their application is still not exploited in many fields mainly due to the high cost.

This work presents a new methodology in GNSS kinematic positioning, based on the Variometric Approach. The Variometric Approach for Displacements Analysis Standalone Engine (VADASE) was originally thought to estimate real-time waveforms induced by earthquake (GNSS-Seismology). It is subject of international patent and was awarded the DLR Special Topic Prize and the Audience Award at the European Satellite Navigation Competition 2010.

Here, for the first time, we present VADASE extension to the kinematic field: the so-called Kin-VADASE. It processes in real-time observations of a single GNSS receiver on board of moving vehicles, to estimate its kinematic parameters (using broadcast ephemeris). The model validation was performed with simulated signals; the assessment of achievable accuracy was addressed with real-data. All the Kin-VADASE processing were carried out using double (L3 iono-free combination) and single frequency observations, to investigate the potentialities of the software with geodetic and low-cost receivers.

Considering real data experiments, the accuracy in trajectory length estimations is 0.050 m/Km and 0.075 m/Km for L3 and L1 processing, over a trajectory of 38006.69 m with an average speed of 15 Km/h (experiment duration of about 4 hours).
This accuracy, achievable in real time by a standalone GNSS receiver, paves the way to the application of the kinematic extension of the Variometric Approach to many fields.

IAG (Geodesy)

G05f - G05 GNSS++: Emerging Technologies and Applications

IUGG-5338

A new method for estimation of relative Inter-frequency Bias in GLONASS receivers: A Particle Filter Approach

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The inter-frequency bias in GLONASS receivers complicates accurate positioning when receivers from different manufactures are employed. This bias varies to different channels, but it has been proved to have a linear relationship with carrier wave frequency. Once the difference of the inter-frequency bias values on two adjacent frequencies for two receivers is estimated, the relative inter-frequency bias between receivers could be corrected in baseline data process. But the inter-frequency biases blend with the ambiguities, and the relationship between integer ambiguity resolution and inter-frequency bias is difficult to be analytically modelled. So the normal estimation methods such as Kalman filter fail to give a solution directly.

However, particle filter method simulates the distribution of the unknown parameter by large quantities of specific values in calculation. When these values are used to represent the inter-frequency bias, relative larger ratio values could be derived by those specific values which are closer to the real inter-frequency bias. This provides a chance to estimate the inter-frequency bias directly. Therefore, in this paper, the linear relationship is further proved by experiments, and then an approach based on particle filter for estimating the relative inter-frequency bias is proposed. This approach works without prior bias values, known baseline or GPS assistance. The experiments in this paper show that this approach is very effective and precise.

IAG (Geodesy)

G05f - G05 GNSS++: Emerging Technologies and Applications

IUGG-5431

Real-time precise point positioning with extended precise orbit/clock products

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The availability of precise real-time orbit and clock products from IGS and other sources is pushing for the application of Precise Point Positioning (PPP) in real-time. For IGS real-time orbit and clock products, they are generated using either prediction-based or estimation-based strategies. The former leads to the IGS Ultra-rapid (IGU) products while the latter to the IGS Real-Time Service (RTS) products. The real-time orbit products can satisfy real-time requirement but there are still limitations for the real-time clock products. For RTS, for instance, the PPP users need to maintain continuous wireless connections to receive high-frequency correction data. Data service charge is also a concern to users.

In this paper, the concept of extended precise orbit and clock products will be introduced. It focuses on satellite orbit and clock prediction to make it an appealing alternate to current real-time products due to reduced communication requirement. Since the stabilities of different types of satellite clocks are different, their stability characteristics are analyzed and the factors that represent satellite clock stabilities are assessed. An improved satellite clock prediction model will be developed. Numerical results will be provided to demonstrate the performance of the extended orbit and clock products.

The extended precise orbit and clock products can be useful to real-time PPP users and can help create new applications such as precise positioning using low-cost handheld and mobile devices where low data transmission and low cost to access the precise orbit and clock corrections are essential.

IAG (Geodesy)

G05f - G05 GNSS++: Emerging Technologies and Applications

IUGG-5507

Enhancing precise point positioning with ionospheric stochastic modelling

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The ionosphere plays an important role in satellite based positioning, either in standard positioning service or in precise applications. One popular way adopted in precise positioning is to form an ionosphere-free combination using measurements from two frequencies which can remove about 99% of ionospheric errors. However, it takes up to several tens of minutes in order to obtain solutions with better than 10 cm accuracy. Even though ambiguity resolution can be achieved in PPP, a similar convergence time is still needed to fix the ambiguities. This prevents PPP from being widely used in real-time applications. Recent researches show that strengthening the PPP model with precise external ionosphere information can accelerate this convergence. This additional information is used as pseudo-observables to strength the positioning model. Like any other observables, a proper stochastic model for ionosphere is also needed to exploit the benefit of external ionosphere information, but few studies have been conducted to address this problem. In this work, the effectiveness of the new stochastic model will be evaluated with large real datasets. And its potential improvement to PPP will also be investigated.

IAG (Geodesy)

G05g - G05 GNSS++: Emerging Technologies and Applications

IUGG-0562

Differential Wi-Fi – A new approach for Wi-Fi Positioning using lateration

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For positioning using Wi-Fi either location fingerprinting or lateration is commonly employed. Fingerprinting is very labour consuming as a database with RSSI (received signal strength indicator) scans from all visible access points (APs) measured on a large number of known reference points has to be established. Lateration requires the use of theoretical path loss models to convert the RSSI measurements into ranges to all visible APs. The idea of the novel approach is based on the well-known DGNSS operation principle. For differential Wi-Fi (DWi-Fi) positioning corrections can be deduced if reference stations are deployed at certain AP locations. They measure the RSSI to all other visible APs similar as it is done on the mobile user's side. The RSSI and the deduced range or coordinate corrections are obtained from a comparison with the known ranges between the AP reference stations. In addition, in a reference AP network area correction parameters can be calculated similar as it is done in RTK-GNSS positioning in a CORS network. They are then applied to the current RSSI scans from the mobile user. The major advantage of DWi-Fi is that the RSSI to range conversion is based on the area correction parameters and not only on standard theoretical path loss models. Thus the positioning performance is significantly improved compared to conventional approaches. In this contribution the concept is discussed in detail and analyzed using simulations and field experiments. It is shown that the positioning accuracy is increased by a factor up to 3 to 4 using this new DWi-Fi approach.

IAG (Geodesy)

G05g - G05 GNSS++: Emerging Technologies and Applications

IUGG-3497

GNSS accuracy and integrity issues in transport and mobility services

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Today, Intelligent Transportation Systems (ITS) and Personal Mobility (PM) applications are the most promising markets for GNSS. However, the high influence of operational and environmental conditions on GNSS performance in the road sector has led to various standardization initiatives that despite their substantial contribution many scientific issues are still open and a unified certification process is missing. SaPPART (Satellite Positioning Performance Assessment for Road Transport, TU1302) is a COST Action the aim of which is to develop a common framework for the definition, assessment and certification of GNSS service levels for ITS and PM applications through a pan-European research oriented network that brings together scientists from the Geodesy, Geomatic Engineering and Transportation sectors.

The scope of this article is twofold. Firstly, to introduce the SaPPART Action, its objectives, range of activities and achievements as a whole. Secondly, to discuss the main issues and challenges related to GNSS positioning accuracy and integrity in the road environment and in relation to ITS and PM needs. In this line, it reviews summary results and perspectives from a number of Short Term Scientific Missions (STSM) undertaken between participating research teams in the SaPPART COST Action. Particularly, it outlines the findings from a number of independent experimental testing and simulation studies that aim at generating and assessing vehicle trajectories based on their position, velocity, time (PVT) error estimates and models respectively and in relation to a reference trajectory.

IAG (Geodesy)

G05g - G05 GNSS++: Emerging Technologies and Applications

IUGG-4748

The Effects of the April 1st, 2014 GLONASS Outage on GNSS Receivers

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The use of multi-constellation GNSS receivers has been assumed as a way to increase system integrity both by increased coverage during normal operations and failover redundancy in the event of a constellation failure. On 1 April 2014 the entire GLONASS constellation was disrupted as illegal ephemeris uploaded to each satellite took effect simultaneously. The outage continued for more than 10 hours.

While ephemeris were incorrect, pseudoranges were correctly broadcast on both L1 and L2 carrier phases; in the best case, GNSS receivers could be expected to continue to track all signals including GLONASS and in the worst case to continue to track GPS and other constellations.

We use data recorded by GLONASS enabled global sites for the days during, preceding and following the outage to evaluate the impact of on tracking and positioning performance. We observe that for some receiver types the onboard receiver autonomous integrity monitoring (RAIM) failed to ignore the incorrect messages, resulting in degraded GLONASS and GPS tracking and in some cases complete tracking failures and significant data loss. In addition, many of the receivers with clock steering enabled showed outliers in their receiver clock bias estimates that also coincided with the outage. Our results show how different brands, configurations, and distributions of receivers were affected to varying extents, but no common factors are apparent.

This event shows that current receiver technology was not yet ready for all failure scenarios and that tracking multiple constellations hindered rather than helped during this outage. Network operators should reevaluate their system configuration and GNSS upgrade strategies while receiver manufacturers work to ensure that systems behave properly in the future.

IAG (Geodesy)

G05g - G05 GNSS++: Emerging Technologies and Applications

IUGG-5700

New methodologies for real-time GNSS and MEMS accelerometer data combination in structural and ground monitoring

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The aim of this work is to develop a methodology to integrate data provided by GNSS receivers (geodetic and low-cost) and MEMS-accelerometers for structural, ground and infrastructures monitoring purposes.

The GNSS technology is already established in such a field and, over the past decade, several research have shown the reliability and sensitivity of low-cost triaxial accelerometers for use in seismological applications.

Hence, several tests were performed on MEMS sensors (LIS3LV02DQ and LIS331DLH MEMS accelerometers produced by STMicroelectronics) and GNSS receivers (a dual frequency Leica Viva and a single frequency low-cost receiver uBlox 6) using a one direction vibrating table with different oscillation frequencies, from high (in the range 1.5 – 3 Hz) to low (< 1Hz) and different amplitudes (2 cm, 3 cm and 4 cm). The aims of such trials are manifold and can be summarized as follows:

- exploit the sensors performance in retrieving oscillatory motions

- address the problem of different reference systems of data acquired by the different sensors (body reference frame for accelerations acquired with MEMS accelerometers and global reference frame for GNSS receivers observation) through a new methodology based on the Principal Component Analysis

- deal with the problem of asynchrony due to the presence of different time reference systems (the GPS time and the MEMS time for GPS observation and MEMS acceleration, respectively)

Finally, a strategy for GNSS receivers and MEMS accelerometers observation integration in real-time, based on the use of VADASE software for the GNSS data processing and the subsequent combination of GNSS-derived and MEMS-derived velocities is proposed.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-447

A Geometry-based Ambiguity Validation (GBAV) Method

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To ensure reliable ambiguity resolution in Global Navigation Satellite System (GNSS) data processing, integer ambiguity validation is an indispensable and critical step. A good ambiguity validation method should have at least three properties: the probability of fixing to wrong ambiguity combinations (mis-fixing) is controlled, the observation period required for ambiguity resolution is minimized, and the computation burden for the process is acceptable for its implementation. In this paper, a new Geometry Based Ambiguity Validation (GBAV) method is proposed which will ensure different ambiguity combinations are both geometrically separable and mis-fixing rate controlled. The theoretical analysis indicates that different strategies can be used to improve spatial separability, such as to reduce size of measurement errors, to use multiple frequency band GNSS data, and to extend observe period for satellite geometry changes. In addition, to improve mis-fixing condition, we need to increase data update rate for more observations and to apply fault detection and exclusion algorithms to remove large measurement errors. Two data sets with 24 hour GPS observation data are used to compare the performance of the proposed GBAV method with the popular R-ratio method. The results show that ambiguity can be fixed faster and more reliably with the GBAV method than that with the R-ratio test method. Moreover, there are 0.1%-0.2% cases for the two test data sets where mis-fixing happens with the R-ratio test method, while there are no mis-fixing cases with the proposed GBAV method.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-448

Diurnal oscillations in local GNSS monitoring

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Intraday periodicities in GNSS baseline components of local deformation control networks are revealed. It occurs in both results of Earth's surface and artificial construction monitoring. Diurnal and semi-diurnal oscillations take place presumably in all horizontal and vertical baseline components. Estimations of periods of the oscillations show that it is closer to ionosphere than to earth's tidal periodicities. The hidden periodicity analysis of F2 layer critical frequency of ionosphere shows the close periods and phases of the oscillations to the baseline vector components. Review of a behaviour of different natural and artificial processes from tides to daily regulation of hydropower plant regime demonstrates that the accuracy improving using digital filtration procedures is a troublesome. The special techniques of systematic error corrections are required for the accuracy improvement in the order of mm.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-449

Characteristic analysis of BeiDou satellite clocks in orbit

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The geodetic performance of Global Navigation Satellite System is intimately related to the characteristics of the on-board satellite clocks. In order to analyze the characteristic of the BeiDou satellite clocks, clock products of Wuhan University sampling at 5-min are used. Focusing on the sub-daily regime, two nanoseconds root mean square error of one day fitting are obtained. Under the frame of general relativity, linear variation of semimajor axis for GEO and IGSO satellite would give rise to a quadratic drift of clock, and its magnitude is at the 10^{-16}*/day level, much smaller than the frequency drift of BDS satellite clocks at the* 10^{-13}~10^{-14}*/day level. Just like GPS satellite clocks, several harmonics are found in BeiDou satellite clock by spectrum analysis. To clarify the origin of harmonics in the BDS satellite clock, correlation analysis between the period and amplitude of harmonics and the property of satellite orbit are performed. It is found that period of the harmonics of clock is not exactly equal to the orbit period, and ratio of orbit period and clock period is almost equal to that of the sidereal day and the solar day. We therefore deduce that harmonics in the BDS satellite clock are due to periodic temperature variations caused by the sun illumination. Results show that BeiDou satellite clock obey white frequency noise processes over the time intervals from 300s to several thousand seconds. For the time intervals larger than 10,000 seconds, all of the BeiDou satellite clock display more complex non-power-law behavior due to the above clock periodic variations. After corrections of the harmonics, Allan deviations at the time interval from about 3 hours to one day can be reduced.*

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-450

Multi-GNSS Precise Point Positioning : Biases modeling and Unified Model

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Currently the IGS does not define conventional models for the inter- and inner- system biases (ISB or IFB) for the multi-GNSS data analysis, which results in apparent clock difference for GLONASS satellites between analysis centers. The clock differences have impacts on the multi-GNSS PPP. In the first part of this paper, we evaluate the GPS/GLONASS ISBs/IFBs and their impacts on multi-GNSS PPP using data of 74 IGS stations over 3 years. Precise ISB/IFB models are also derived and evaluated for each station.

Traditional multi-GNSS PPP treats ISB/IFB as explicit parameters, which are estimated epoch-wisely or session-wisely. Based on the scaled sensitivity matrix (SSM) method, we theoretically prove that the ISB parameter is not correlated with coordinate parameters and can be assimilated into clock and ambiguity parameters. Thus, removing ISB from multi-GNSS PPP model does not affect coordinate estimation. Based on this analysis, we develop a simplified and unified model for multi-GNSS PPP, where ISB parameter does not need to be estimated and observations from different GNSS systems are treated in a unified way.

To verify the new model, we process 1 year GPS/GLONASS data of 53 IGS worldwide stations and 1 month GPS/BDS data of 15 IGS MGEX stations. Two types of GPS/GLONASS and GPS/BDS combined PPP solutions implementing the traditional and new models are performed. RMSs of coordinate differences between the two types of solutions are few μm for daily static PPP and less than 0.02 mm for GPS/GLONASS kinematic PPP in the North, East and Up components, respectively. Considering the millimeter-level precision of current GNSS PPP solutions, these statistics demonstrate equivalent performance of the two solution types.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-453

Taiwan/TriG Radio Occultation Process System (TROPS):Brief Introduction

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Global Positioning System (GPS) Radio Occultation (RO) technique has been used to investigate the Earth's atmosphere since 1990s. In 2006, Taiwan has launched six low Earth orbit (LEO) satellites as a RO constellation mission, named FORMOSAT-3/COSMIC (F-3/C). F-3/C mission can release 1500-2500 data sets per day for both neutral atmosphere and ionosphere. With the advent of Global Navigation Satellite System (GNSS) in ten years and FORMOSAT-7/COSMIC-2 (F-7/C-2) mission, which will launch 12 LEO satellites in 2016 and 2018, the amount of RO data set will increase to about 8000 set per day. In order to retrieve the RO data of F-3/C and F-7/C-2 under real time, Taiwan/TriG Radio Occultation Process System (TROPS) is developing by NSPO, GPSARC, and TACC. TROPS is a process system including the retrieval procedure and user interface. In retrieval procedure of TROPS, the atmospheric and ionospheric parameters profiles, which including the pressure and temperature profiles of neutral atmosphere and the electron density profiles of ionosphere, are retrieved from RO observation. In user interface of TROPS, the retrieval results and the statistical analysis will be provided. The retrieval procedure and the user interface of TROPS are brief introduced in this report.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-454

Research on BDS user integrity augmentation

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Based on Chinese Academy of Surveying and Mapping in Hebei, Guangxi, Sichuan and other provincial CORS network upgrading for BDS station, this paper carried out the study on BDS user integrity augment.

In term of the key technology of BDS user augment, we carried out GNSS Network Difference which is compatible with BDS, GNSS RTK which is compatible with BDS and BDS Network RTK, and the three key technologies are extensively tested in Hebei, Guangxi, Sichuan. Test work has shown that the positioning accuracy of GNSS Network Difference compatible with BDS is superior to 1m in plane and 2m in height within the range of 200km.GNSS RTK compatible with BDS can arrive cm-level positioning accuracy within the range of 30km. BDS Network RTK can arrive cm-level positioning accuracy within the range of 100km.

In aspect of BDS user integrity monitoring, taking the GNSS network differential compatible with BDS for example, we conducted MSIM algorithm study taking known monitoring station as the standard, as well as RAIM algorithm research taking error of unit weight as the standard, to achieve detection and identification BDS satellites which have gross error and a substantial increase in BDS positioning availability and reliability of the user station.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-455

Zone-corrections: a new augmentation information for decimeter-level SBAS system

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The main objectives of satellite-based augmentation system (SBAS) are providing integrity positioning with better accuracy than stand-alone GNSS. The primary correction data streams of the SBAS include satellite orbit, clock, and ionosphere corrections. They are expected to be used with code observations. For more precise applications users could use the SBAS orbit and clock corrections together with dual frequency code and carrier phase observations to compute precise point positioning (PPP) solution.

Current reported user positioning accuracy of SBAS could reach sub-meter. It is a big improvement over the legacy PNT service. However, its applications in real-time positioning of 0.1-0.2 meter accuracy is limited. In this paper we propose a new type of SBAS augmentation information: zone-correction. It is defined to augment the existing SBAS orbit and clock corrections, and applies to regions covering up to one million square kilometers.

To evaluate the benefits of the zone-correction for SBAS user positioning, we use the GNSS data of the Crustal Movement Observation Network of China (CMONOC) as SBAS reference and user stations. Data analysis are design in three steps. Firstly, real-time data of 20 well distributed stations is used to calculate augmentation information, including zone-correction. Secondly, the augmentation information is broadcast via simulated streams. In the final step, the other 240 CMONOC GNSS stations apply the augmentation information and perform real-time kinematic PPP to derive their positions. One week data are processed and results show that convergence time of PPP using the new augmentation information is shorter than 2 minutes and positioning accuracy is around 0.1 and 0.15 meter in horizontal and vertical directions.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-456

The influence of measurement error of satellite Center-of-Gravity on the baseline of formation flying satellites

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The baseline determination, or the relative orbit determination, is one of the key technology to realize formation flying satellites mission. During baseline determination using GNSS, the coordinates of the GNSS antennas with respect to the center-of-gravity in the respective satellite-fixed systems must be known. Obviously,the measurement error of the satellite center-of-gravity will influence baseline determination of formation flying satellites. Fortunately, the coordinates of the GNSS antenna with respect to the antenna of the payload instrument (such as SAR) can be measured accurately, and the useful baseline is usually the distance between the payload instruments of two satellites. The connection between the baseline of two antennas of payload instruments and the baseline of two satellites center-of-gravity is established. The baseline of two gravity recovery and climate experiment (GRACE) satellites center-of-gravity and the baseline of two antennas was computed by using the global positioning system (GPS) data observed December 8, 2005. The results of computation show that the measurement error of the satellite center-of-gravity makes the baseline error of two satellites center-of-gravity greatly than that of two antennas. The two antennas baseline error is about 10 percent of the two satellites center-of-gravity baseline error.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-457

Characterizing the cycle slip occurrences of Multi-GNSS measurements recorded in the IGS MGEX Project

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Since 2011, the International GNSS Service (IGS) has started the Multi-GNSS Experiment (MGEX) project (Dow et al., 2009; Montenbruck et al., 2014). To best utilize the MGEX data, cycle slip detection and correction is a crucially important procedure in MGEX data analysis.

This work uses the cycle slip detection and repair method in Liu (2011) to study the cycle slips occurrence rate (CSOR) of the major GNSS systems in operation today: U.S. GPS, Russian GLONASS, European Galileo, Chinese BDS, and Japanese QZSS. The CSOR with respect to the types of satellite orbit is also examined, namely, Geostationary Orbit (GEO), Inclined Geosynchronous Orbit (IGSO), and Medium Earth Orbit (MEO).

Our preliminary study analyzed the 1-Hz MGEX satellite data. The statistics of cycle slip occurrences are: 94 cycle slips in 7937441 epochs of GPS data (CSOR: 11.843 CPE, 1 CPE=10^{-6} cycle slip per epoch); 18 cycle slips in 6228382 epochs of GLONASS data (CSOR: 2.890 CPE); 7 cycle slips in 777953 epochs of Galileo data (CSOR: 8.998 CPE); 464 cycle slips in 5729779 epochs of BDS data (CSOR: 80.980 CPE), and 0 cycle slip in 253845 epochs of QZSS data.

We find that there are 464 cycle slips in 2615453 epochs of GEO data (CSOR: 177.407 CPE), 119 cycle slips in 15666833 epochs of MEO data (CSOR: 7.596 CPE), and 0 cycle slip in 2645114 epochs of IGSO data. It is interesting to see that in the BDS data, all the 464 cycle slips occur to GEO satellites and no cycle slip occurs to MEO or IGSO satellite.

The findings from this study will help GNSS analysts to understand the MGEX data quality better thus appropriate strategy can be developed to process different satellite data of different cycle slip occurrence characteristics.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-458

Precise orbit determination of BeiDou geostationary satellites

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For navigation purposes, the geostationary satellites could provide permanent availability for the regional users. However, the almost invariable tracking geometry from ground stations to the satellites increases the correlation of the solved-for parameters in the process of precise orbit determination. Together with the weak tracking geometry due to high altitude, this makes the task of achieving high accuracy orbits a big challenge.

In the effort to incorporate BeiDou geostationary satellites into operational Trimble RTX service, the RTX orbit team has achieved an accuracy of ~5 cm in radial and cross-track components, and ~1.5 m in along-track in the sense of orbit overlap errors. To achieve such quality of orbits, the following aspects were important: enhancement of tracking constraint, fine tuning of the force model, proper parameterization to reduce correlation, careful data preprocessing to exclude outliers and maneuvering satellites, and optimal management of initial orbits to improve convergence of the solutions.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-459

"A Field Test of Land-based GNSS-R Receiver System"

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The GNSS reflectometry (GNSS-R) has been considered as a new approach to monitor different properties of reflect surface qualitatively and quantitatively. The characteristics of GNSS signal are changed and transformed through reflecting from the surface of object. And this change can be modeled and calculated inversely to achieve the goal of monitoring the object surface. A field test has been implemented aiming at investigating the sea surface properties by using a coastal-based 4 channel GNSS-R receiver system. This receiver is capable to acquire direct and reflected signal of GPS and Chinese BeiDou system (BD) simultaneously. The different level of products are demonstrated by signal processing such as Delay Calculation of Direct and Reflected Signal and Delay Doppler Map (DDM) of Reflected Signal. By introducing the Zavorotny-Voronovich (Z-V) scattering model of signal reflection on sea surface, the further products like Sea Level Height (SLH), Significant Wave Height (SWH) and Wind Speed above the sea surface can be obtained.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-460

The study of Ionospheric Grid Model for BDS Augmentation System

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The measurement accuracy of GNSS is limited by kinds of error sources, in which the ionospheric delay is one of the major errors for user positioning as complex changes and hard to be predicted. As a high-accuracy and real-time model, Ionospheric Grid is provided in regional SBAS like Wide Area Augmentation System (WAAS) and European Geostationary Navigation Overlay Service (EGNOS), to correct ionospheric delay for widely-used single-frequency receiver users. Chinese regional satellite navigation system (BDS) also provides Ionospheric Grid correction to its authorized users. The current accuracy of Ionospheric Grid of BDS is evaluated. The results show that limited by the distribution of monitor stations, the efficiency of Ionoshperic Grid correction is reduced in the regions with not enough Ionospheric Pierce Points (IPPs). The paper studied on the improvement for BDS Ionospheric Grid Model, applying the Adjusted Spherical Harmonic Analysis (ASHA) model to transfer the ionospheric variation. The comparative analysis of the new model and the original one for BDS is presented and the results show that the correction accuracy for the edge of the service area is greatly improved based on ASHA.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-461

This is my abstract title:Research on High Accuracy Prediction Model of Satellite Clock Bias

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Time basis of satellite navigation system is achieved by the satellite clock bias (SCB) prediction, while the SCB prediction accuracy will also affect the positioning accuracy of real-time navigation users. With the development of our Beidou satellite navigation system, the accuracy requirements of the SCB prediction is higher and higher, general quadratic polynomial extrapolation method have failed to meet the SCB forecast accuracy for each satellite. There is an urgent need to develop the SCB prediction program for each satellite, here we use a combined method of least squares and auto-regressive model (LS+AR) from the Earth Orientation Parameter(EOP)forecasting, to predict and assess SCB with data from IGS. Results show that the combined LS+AR method can improve the SCB forecast accuracy effectively.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-462

Real-time troposphere delay modeling using GNSS Precise Point Positioning and IGS-RTS products

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The availability of IGS Real-Time Service (RTS) products makes Precise Point Positioning (PPP) a very powerful technique to process GNSS (Global Navigation Satellite System) signals in real-time. There are still, however, some limitations of PPP. A significant change in satellite geometry is required to efficiently de-correlate troposphere delay, receiver clock offset, and receiver height. Wroclaw University of Environmental and Life Sciences (WUELS) is developing regional troposphere delay models to support numerical weather prediction (NWP) models and PPP-RTK positioning. The fully operational model works in near real-time (NRT) regime over area of Poland. Although the latency of NRT model is sufficient for NWP, a minimum latency is required to support precise positioning. One possibility is to provide a short forecast of ZTD using the distribution of meteorological parameters. Another option is to take advantage of IGS real-time service (RTS) and reduce the latency of estimated ZTD to minimum.
Using the original GNSS-WARP software, a number of Polish EPN stations was processed in a simulated real-time conditions over one week long test campaign. The resulting ZTDs were compared to ZTDs obtained with NRT strategy. The mean error of estimated ZTD was 3.0mm, mean value of residuals was -9mm, with standard deviation of 13mm. The residuals with respect to reference solutions exceed 20mm in some epochs. Although the accuracy of the obtained results is not enough even for NWP support, the advantage of the presented solution is the low-latency and high-temporal resolution of derived ZTD.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-463

A partial GNSS ambiguity resolution for single-differenced carrier phase measurements

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*Reliable phase ambiguities resolution is essential to high precision GNSS applications. Once the integer ambiguities are fixed correctly, attitude solutions can achieved with a relatively good level of accuracy. By forming double-differencing (DD), the common errors (e.g. Atmosphere delay, satellite clock error and receiver clock error) can be eliminated simultaneously. Thus, the DD model is adopted by almost all of the commercial attitude determination products. However, the DD ambiguities (real-valued) are usually highly correlated, which is not good for efficiently searching for the correct integer ambiguities, and might even lead to largely bias to attitude solutions. A new type of GNSS receiver, multi-antenna synchronized GNSS receiver, can eliminated both satellite and receiver errors simultaneously by forming receiver-between single-difference (SD), but the line bias is still existed, which increase the difficulty of SD ambiguity fixing. In this work, we presents a new SD ambiguity fixing algorithm. In this algorithm, we first propose an **ambiguity substitution approach**, which separates the common real initial phase of all SD ambiguities from the integer ambiguities effectively by an additional parameter, thus the searching region of integer ambiguities is narrowed and consequently increase the efficiency and probability of correct fix of ambiguities. Next, the algorithm is validated by using several ground tests, including different ambiguities combinations and different number of ambiguities to be fixed. Through the results we proved an optional case to choose the reasonable ambiguities combination. It also demonstrated that the new algorithm can improve the accuracy of attitude determination in both static and kinematic situation efficiently.*

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-464

A new method of describing the reliability of instantaneous GNSS-RTK positioning with the use of Network Quality Indicators

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The subject of the research is the reliability of determining position in carrier phase-based relative GNSS real-time kinematic (RTK) technique. One of the most important elements in this technique is incorporating observation biases (ionospheric and tropospheric delay as well as ephemeris errors) into the positioning model. The use of spatial models of these biases determined based on observations from reference station networks in Network RTK approach (so-called ionospheric and geometric correction terms) make it possible to eliminate biases and obtain high accuracy position of rover (±1-3 cm) even for distances of 70-100 km from the reference station. The accuracy of ionospheric and geometric correction terms depends both on the assumed model and on current measurement conditions. Strong disturbances of ionosphere or weather fronts can substantially degrade the precision of spatial correction terms, making it difficult or even impossible to perform a rover positioning, especially in instantaneous mode. So the high accuracy of correction terms plays a key role in reliability of Network RTK positioning. In this study the discussion on an optimal method of defining the reliability of rover performance is presented and a new method of creating the Quality Indicators for Network RTK performance based on Network-based Stochastic Model is introduced. The basis of the method is to use the estimation of a variance of correction terms obtained on a satellite-by-satellite and epoch-by-epoch wise from a network solution. Two new indicators for ambiguity resolution and position accuracy as well as the method of presenting their spatial distribution over the network area in the form of Maps of Network Availability and Accuracy are presented and analysed in detail.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-465

Multipath mitigation for short baseline based on dual-antenna clock-synchronized GNSS receiver

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GPS multipath,unlike most of the errors affecting GPS short baseline solution, cannot eliminated by observations differencing techniques. It becomes the bottleneck of the GPS technique to further improve the accuracy of the positioning. Currently, the double-differencing is the common algorithm in GPS data analysis and multipath model constructing. The multipath effects, in form of double-differenced carrier phase residuals, are by nature the differenced baseline multipath between satellites. Only under certain assumptions the derived multipath model can be considered as the baseline multipath model for single satellite. The advantage of the emerging dual-antenna clock-synchronized GNSS receiver, is that its single-differencing between antennas is able to eliminate both satellite and receiver clock errors, functionally equivalent to classical double-differencing. Using such single-differenced phase residuals, we construct a Multipath Hemisphere Model (MHM) to mitigate the multipath effects for a short baseline under static multipath environment. The MHM method is based on the spatial repeated nature of multipath for the satellite position on the sky. Thus the MHM is satellite-independent. Meanwhile, the sidereal filtering method is based on the temporal repeated nature of multipath for the satellite position after about a sidereal day. Hence the sidereal filtering is satellite-dependent. To evaluate if the satellite-dependence is necessary, we compare the MHM method with the sidereal filtering method. We will report our comparison results.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-466

Loose and tight combining: A comparative study of integration of multi-GNSS observations in precise relative positioning

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Integration of multiple GNSS systems observations is nowadays the crucial issue in the development of precise positioning algorithms. Overlapping frequencies in GNSS systems support creating double-differences using mixed observations from different satellite systems. This approach is commonly termed as tight combining. The observational model utilizes a single reference satellite for observations from all the integrated systems. This approach forces taking into account not only time and coordinate system differences, but also inter system biases (ISB). The ISB is the difference between receiver hardware delays for different GNSS observations that is present both in carrier-phase and pseudorange data. There are two recognized techniques for handling of the ISB in tight combined processing of multi-GNSS observations: (1) phase and code GNSS observations can be corrected with previously calibrated ISB values, (2) another technique is treating the ISBs as additional parameters in estimation of the relative positioning model.On the other hand, integrating observations from separate GNSS systems can be performed in a loose combining approach. In this method, mathematical model requires separate reference satellites – one for each system. This decreases the number of the unknown parameters in the least squares due to absence of the ISB, however, additional reference satellite also decrease the number of double-differenced observations.This study investigates both approaches for combining of multi-GNSS observations on the basis of GPS and Galileo systems. Quality assessment of both strategies based on kinematic and static positioning results is presented. The observational data were obtained from a hardware GNSS signal simulator.

IAG (Geodesy)

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G05p-467

Assessment of tropospheric delay estimation methods on Precise Point Positioning time series

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Nowadays, Precise Point Positioning (PPP) is an increasingly popular strategy in use for processing of GNSS observations. PPP solutions are based on single station un-differenced observations and are mainly affected by the quality of orbit/clock products, but also by the modeling of the tropospheric delay. In this study, we investigate the influence of the troposphere estimation methods on the results of processing of GNSS data collected at the permanent stations located in mountainous areas, where modelling of tropospheric delay is relatively difficult. GNSS data from 2008 up to 2014 collected at 28 permanent EUPOS (European Position Determination System) stations, including 9 EPN sites, located in the Sudeten and Carpathians were processed in PPP mode using Bernese 5.2 GNSS software. In the processing, different troposphere mapping functions and gradient models were applied. Among others, we evaluated application of GMF, VMF1 and VMF1(UNB) mapping functions and also several approaches to gradient modeling (e.g., tilting, Chen&Herring). Then the resulting time series of station positions (North, East and Up components) and velocity estimates in ITRF2008 were studied. In particular, we focused on the residual oscillations in PPP-derived time series and the character of the stochastic parts as well. We applied Maximum Likelihood Estimation with a combination of white and power-law noise, while the seasonal periods of change in topocentric components were determined using Least Squares Estimation. The results confirms sensitivity of the estimated parameters to the troposphere modeling methods.

IAG (Geodesy)

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G05p-468

Can we use a permanent GNSS Reflectometry station to aid Arctic fjord monitoring?

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Kongsfjorden is an Arctic fjord on Spitsbergen with a cover of landfast sea ice in its inner part and a sporadic occurence of drifting sea ice and icebergs. There, sea ice is regularly monitored by the Norwegian Polar Instiute. A permanent GNSS+R experiment has been set up above Kongsfjorden that accumulates data since July 2013. The location on Zeppelinfjellet (78°54'14''N, 11°52'37''E, 475m above sea level) has an excellent view. Reflection events cover the fjord with a radial range of 3 to 14 km (GNSS satellite elevations of 10° to 2°) and a maximum lateral range of 25 km (azimuth between -50° and 100°). The installed GORS (GNSS Occultation Reflectometry Scatterometry) receiver provides in-phase and quadrature-phase samples. Observations of the differential Doppler between the direct and the reflected link are derived. A Doppler shift (about 0.5 Hz) induced by the reflection geometry is modeled assuming an invariant smooth surface and corrected. Mean and standard deviation of Doppler residuals are retrieved with 1°x1° (azimuth x elevation) resolution to account for spatial variations. Temporal resolution is guaranteed by the daily recurrence of observations. The temporal evolution of example events shows an offset in mean residual Doppler (30-60 mHz) and a significantly increased standard deviation (about 40%) end of May 2014. This is supposed to be related to changing roughness conditions at that time of the sea-ice season in Kongsfjorden. A detailed comparison with in-situ collected sea-ice data is required to prove this roughness effect on GNSS Doppler observations.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-469

Enhancement of Unmanned Aerial Vehicle photogrammetry by high-resolution airborne laser scanning data

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UAV (Unmanned Aerial Vehicle) photogrammetry has developed rapidly in the past decade. This contribution evaluates the accuracy and proposes methods for enhancing the quality of UAV photogrammetry products. Two different autonomous fixed wing UAV systems are used to acquire aerial photographs of study areas with varying characteristics (including urban areas, forests, open fields, etc.). Based on these data point clouds, 3D models and orthophotos are generated.
These UAV photogrammetry products are verified against high-resolution airborne laser scanning (ALS) data, as well as control measurements made with GNSS on the ground and other available orthophotos (e.g. those acquired for large scale national mapping). For this purpose, the geometry of horizontal surfaces or objects that have remained unchanged during different surveying epochs are compared. The detected discrepancies are analysed in order to remove systematic errors and enhance the accuracy of UAV photogrammetry.
Furthermore, the effect of UAV flying height on the accuracy of the results is explored, as well as the optimum number and placement of ground control points. Problems regarding the alignment of certain types of aerial photos are discussed. Some recommendations are given on conducting UAV mapping campaigns cost-effectively and with minimal time-consumption while still ensuring the quality and accuracy of the UAV data products. The use of UAV photogrammetry for different applications instead of more traditional methods (e.g. direct measurements on the ground with GNSS devices or total stations) and a promising combination of UAV and high-resolution ALS data are discussed.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-470

GARCA: Observing-system simulation for GNSS-Reflectometry aboard ISS with GEROS

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GARCA (GNSS-Reflectometry – Assessment of Requirements and Consolidation of Retrieval Algorithms) is a scientific study, funded by ESA and carried out by a consortium of seven European institutions from six countries. The study is part of the Phase A activities of the ESA mission GEROS-ISS. In case of complete funding GEROS-ISS is foreseen to be launched in late 2019.

The key objective of GARCA is to support the assessment and consolidation of scientific requirements and the consolidation of retrieval algorithms for a spaceborne GNSS-R experiment, focusing in particular on the GEROS-ISS concept and its primary and secondary data products (sea surface height and ocean surface roughness). Main work is the development of an end2end-Simulator for the GEROS-ISS measurements (GEROS-SIM), and the evaluation of the expected Level2-data products (L2 performance). Both core modules of the simulation and retrieval algorithms will be largely based on consortium pre-existing codes. Moreover, a GEROS-SIM version will be executable through a web-server, freely accessible to registered scientists. Validation and performance test will benefit from the large amount of GNSS-R data acquired by the consortium members in the last decade. A dedicated GEROS-ISS flight campaign for GARCA will be conducted in summer 2015. In addition work packages are included, aimed to perform Observing-System Simulation Experiments (OSSE) to assess the oceanographic significance of the expected GEROS-ISS measurements and to demonstrate the usefulness of the GEROS-ISS concept. Additional external scientific experts support the GARCA project and are involved in the planned work as beta-testers of the developments and also to initiate the sustainable formation of an interdisciplinary GEROS-ISS user community.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-471

Considerations on indoor navigation based on cheap mobile devices

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Nowadays, almost everyone has their own portable computer in the form of a smartphone. It usually gives the ability of positioning and navigation using GPS signal. This method is not usually effective indoors. For navigation in buildings, other technologies based on completely different solutions should be used. There are many indoor navigation solutions available, based on the additional devices usage. They are effective, but require the purchase of additional hardware. Meanwhile, the user is most interested in the possibility of positioning using the same equipment both inside and outside. The authors of this article, noting this issue, decided to refer to the problem of positioning using bluetooth signal, which the module is built into every modern cell phone. Attempts were made to determine the position using bluetooth transmitters. Accuracy estimation of obtained position and considerations on the possibility of building a network of transmitters for positioning were also performed. For this purpose, experiments were conducted on the test object, where four bluetooth transmitters and one receiver - a mobile phone with Android were used. The signals were recorded using a suitably designed application and then analyzed. Considerations here described, are a part of studies to develop an effective indoor positioning system using various technologies available in today's mobile phones.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-472

Innovative water level monitoring of the Mekong delta

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A strong population increase and climate changes have caused severe modifications in the Mekong Delta. As a consequence, extreme flood events occur more frequently. It is thus important to monitor the coastal areas with dense population like on the banks of the Mekong Delta. The goal of the German-Vietnamese research project Water related Information System for the sustainable Development Of the Mekong delta (WISDOM) is to build an information system containing all the necessary data to support authorities for an optimized resource management. One of WISDOM's tasks is to test the possibility of using the innovative Global Navigation Satellite System Reflectometry (GNSS-R) technique for precise water level monitoring of the Mekong Delta.

GNSS-R uses GNSS L-band signals' property of high reflectivity at water surfaces. These reflected signals can be used to derive water level heights. Like in positioning, two different GNSS-R altimetry methods exist: the code and the carrier phase. Our research activities focus on the phase-based altimetric application of GNSS-R.

In March 2013, a two-week measurement campaign was conducted in Can Tho City, Vietnam. Several reflection traces have been recorded. To track the direct and the reflected signal separately, two antennas were used. The analysis of the recorded signals shows a superposition of the signal reflected by the water surface with other multipath signals due to the surrounding of the antennas. To filter out the one reflected by the water surface an adapted Hilbert Huang Transform has been applied. In a second step, a Least-Square Method is used to determine the water level height by means of the filtered signal. For this purpose, a model of the recorded observations has been developed.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-473

Advanced GNSS processing techniques and algorithms applied to monitor and forecast the El Hierro (Canary Islands) volcanic eruption process.

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The 2004-2005 seismo-volcanic crisis in Tenerife, and the 2011 El Hierro eruptive process have made it possible to develop a specific methodology to monitor and forecast the evolution of the seismo-volcanic activity, based on near real-time analysis of deformations and related seismic activity. The available GNSS data were specifically processed for early detection of new pressure sources and evolution of the volcanic activity. Sub-daily solutions enhanced with Kalman filtering were used to monitor trend shifts in near real-time, associating the vertical and horizontal shifts to a changing pressure source interpretation that was used to forecast the evolution of the seismo-volcanic activity. Furthermore, daily solutions allowed for a near real-time Mogi pressure source inference as the trend shifts occurred. This procedure allowed a continuous surveillance of the evolution of the magma injection processes during the El Hierro crisis. This experience was used to develop a Multiparametric Monitoring System based on low-cost multi-constelation GNSS++ receivers, seismic transducers and other sensors. Near real-time network data processing up to 1Hz sampling rates, on Debian embedded processors with differential and precise point positioning techniques enhanced with Kalman filtering, from GNSS stations separated only a few kilometers has allowed the inference of volcano surface deformations.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-475

Application of high-resolution regional ionosphere model to processing of national reference networks using Bernese GNSS Software

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Routine processing of GNSS data from the national continuously operating reference network is required for a number of applications, including reference frame maintenance, geodynamic studies, estimation of atmospheric parameters, etc. The processed baselines in such networks are usually of several tens of km, rarely exceeding 100 km. For the ambiguity resolution direct L1/L2 observations or their linear combinations, like wide-line, are used. These observables are sensitive to the adverse influence of the ionosphere. Hence, ionosphere models are often used to support the processing of the national reference networks.

In this study a high-resolution regional ionosphere model is developed and applied to processing of the GNSS data from the selected subnetwork of the EUPOS system. In particular, resulting ambiguity resolution success, coordinate repeatability, and tropospheric ZTD estimates are analyzed. The processing is carried out in Bernese GNSS Software 5.2 using modified GPSEST module that allows importing IONEX files. The results are compared to those obtained with the application of global and regional CODE models. This comparison shows that the application of the regional ionosphere model can successfully be used to support processing of the national reference networks.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-476

Triple-frequency beidou precise point positioning: Modelling and assessments

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BeiDou is the only GNSS system that all BeiDou satellites transmit triple-frequency signals. What benefit can we gain from this resource is the concern of GNSS users. This contribution focuses on the modeling and assessment of triple-frequency precise point positioning with BeiDou. Firstly, three different triple-frequency PPP models namely "IF-PPP1", "IF-PPP2", and "UC-PPP" are developed. Both the IF-PPP1 and IF-PPP2 models use the ionosphere-free (IF) combination(s) to eliminated the ionospheric delay. The IF-PPP1 model forms three sets of dual-frequency ionosphere-free combinations (B1B2, B1B3, and B2B3), the IF-PPP2 model combines the triple-frequency signals to form an optimal linear combination (B1B2B3) which is free of ionospheric delay. The uncombined PPP (UC-PPP) model uses the raw measurements, in which ionospheric delay unknowns are introduced. The positioning performances of these triple-frequency PPP models are assessed by a few MGEX (Multi-GNSS Experiment) stations. Comparative analyses show that the coordinate estimates of all the three triple-frequency PPP models agree well with each other. Compared against the dual-frequency PPP (with B1B2 ionosphere-free combination), no significant improvement can be observed from neither the positioning accuracy nor the convergence speed, suggesting the lower contribution of the third frequency signals (B3) to the current float BeiDou PPP. Finally, the stochastic model of BeiDou PPP is investigated. We recommend a better empirical model for BeiDou PPP.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-477

New features of Anubis tool for GNSS data quality monitoring

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The GNSS software library G-Nut has been developed at the Geodetic Observatory Pecny (GOP) of the Research Institute of Geodesy, Topography, and Cartography since 2011. In 2013, we initiated the development of a new tool exploiting the G-Nut core library for the quality check of data from modern Global Navigation Satellite Systems (GNSS). The tool (G-Nut/Anubis) handles observation and navigation messages stored in RINEX 2.XX or RINEX 3.XX formats. It supports all available GNSS constellations and their augmentations such as GPS, GLONASS, Galileo, BeiDou, QZSS, and SBAS.

The poster presents new features and enhancements of the G-Nut/Anubis version 1.3 released in January 2015. The pre-processing mode has been improved to detect and estimate cycle slips from all available constellations, frequencies, and signals. If navigation data are available G-Nut/Anubis provides a standard point positioning (SPP) in a standalone mode for any global constellation, i.e. GPS-only, GLONASS-only, Galileo-only, and BeiDou-only positions. All quantitative and qualitative characteristics are collected in a single file using a plain text format, which can be visualized with an additional plotting tool provided along with the Anubis. New version 1.3 is also capable of collecting navigation messages from all constellations and merging them into a single file in the RINEX 3.02 format. Before release, G-Nut/Anubis was extensively tested via processing data from full IGS Multi-GNSS Experiment (M-GEX) and EUREF archives. The software is disseminated under the GNU General Public Licence v3. Both pre-compiled linux binaries and a full source code are available on the GOP web site www.pecny.cz.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-478

A novel single-difference ambiguity fixing approach with multi-antenna synchronized BeiDou receiver

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Multi-antenna synchronized BeiDou receiver is a new type of receivers that multiple antennas share the same receiver clock. Using the receiver, single-difference carrier phase observations are able to eliminate both the satellite and receiver clock errors simultaneously, which promotes single differences equivalent to classical double differences. Comparing with double differences, single differences have more observations and redundancy, which improves BeiDou positioning accuracy and reliability. However, single-difference ambiguities are naturally not integer due to the presence of inter-receiver fractional uncalibrated phase delay. Hence, single-difference ambiguities cannot be fixed to integer values directly. In order to achieve single-difference ambiguity fixing, we design an ambiguity substitution approach, which separates fractional uncalibrated phase delay and single-difference ambiguities effectively, thus narrows the searching space of ambiguities and improves the efficiency and correctness of integer ambiguity fixing. Unlike the traditional uncalibrated phase delay corrected method, it is an uncalibrated phase delay absorbed one. Comparing with the single-difference float solutions, the single-difference fixed solutions reduce the root mean square values and improve the repeatability in east, north and up component of baseline solutions significantly.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-479

Evaluating smartphone navigation sensors performance for driving event and maneuver reconstruction

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In recent years, the continuously increasing capabilities and the decrescent selling prices of contemporary smartphones and mobile devices have made them ideal candidates for the collection of vehicle navigation data for various purposes. Their use is particularly prominent in the scene of Intelligent Transportation System (ITS) applications, the development of road inventory tools as well as for advanced research in transportation studies. However, depending on the scope of their use, the quality requirements (accuracy, availability, continuity, etc.) of a computed navigation solution can vary dramatically ranging from very loose (tens of meters) for comfort to more stringent (meter) standards for monitoring and safety-critical applications.

This article attempts a performance characterization of two contemporary smartphones (iPhone 5s, HTC One S) for ITS applications that call for high positioning accuracies, such as driver assistance systems. Specifically, it evaluates their ability to reconstruct a number of specific driving (e.g. braking, accelerating) and maneuvering (e.g. turns, U-turns, zigzags) events collected using a running vehicle at varying speeds. Test data include GNSS positions, tri-axial accelerations and gyroscope measurements. Data processing involves the computation of a reference trajectory using a tactical-grade integrated GNSS/INS system. Data analysis is based on cross-comparisons of the vehicle navigation solution (position, velocity and attitude) and its error estimates obtained using the smartphones against the reference trajectory.

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IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-480

Alternative GNSS antenna calibration in terms of bernstein-bezier polynomials

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The reference point of an antenna is not physical fixed, but caused by electromagnetic components and their interaction. Therefore, a calibration of the antenna is required for precise point positioning. The calibration is either performed in an anechoic chamber or via the so-called Hannover concept in the field. In the latter one, two antennas are set up close to each other with a common clock, and one antenna is rotated by a calibrated robot. The code phase and the carrier phase corrections (GDV and PCC) are determined from the apparent changes in the short baseline vector.

The current approach uses spherical harmonic functions and the corresponding Stokes coefficients to model the GDVs and PCCs. Because the spherical harmonics are orthogonal on the full sphere, but all measurements take place in the upper hemisphere of the antenna, the determination of Stokes coefficients gets unstable very fast and only low resolutions are possible. Furthermore time-differentiated observations remove all constant components in the spherical harmonics and also the orthogonality of this base system.

As an alternative, a linear combination of spherical Bernstein-Bezier polynomials (SBB) is implemented on a triangulated hemisphere. Each base function is defined only on a spherical triangle, and determined by harmonic polynomials of the three barycentric coordinates. A continuous model is achieved by minimizing the bending energy during the estimation of the coefficients of the linear combination. Due to their local support, the functions could handle the inhomogeneous data distribution, and missing observations below the horizon will not affect the stability. Only one SBB polynomial per triangle contains a constant and so the problem of the differentiated observations is also reduced.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-481

Benefits of receiver clock modeling in GNSS navigation

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Kinematic GNSS (Global Navigation Satellite Systems) single point positioning (SPP) requires epoch-wise estimation of a receiver synchronization error w.r.t. GNSS system time due to the low long-term stability and the generally poor accuracy of the receiver's internal quartz oscillator. Applying a miniaturized atomic clock (MAC) and modeling its behavior in a physically meaningful way – instead of epoch-wise estimation – improves the precision of the up-coordinate and makes the parameter estimation more robust and reliable. This approach is called receiver clock modeling (RCM) also enabling SPP with only three satellites in view.
At first, we briefly discuss the frequency stabilities of three different MACs that were characterized in terms of Allan deviations at Physikalisch-Technische Bundesanstalt, Germany. Compared to manufacturer's data we found some significant differences.
In order to analyze the clock performance when connected to GNSS receivers, a kinematic experiment was carried out with a van. The data analysis with and without RCM are implemented in an extended Kalman filter and a sequential least-squares adjustment (SLSA), respectively. We assumed two clock states: time offset and frequency offset. In the Kalman filter RCM is applied by using given appropriate two-state clock process noise models, the SLSA applies a linear polynomial for the clock behavior which is updated each consecutive measurement epoch. Both approaches show similar results compared to epoch-wise estimation: improved precision of up-coordinates by up to 58%, enhanced internal and external reliability, increased availability and prolonged continuity. Additionally, RCM also improves velocity estimates based on Doppler observations.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-482

Tests of use of MEMS based INS/GPS integrated navigation system for areas with limited visibility of GPS satellites.

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Nowadays, along with the advancement of technology, the dynamic development of miniaturization in electronics can be noticed. Currently produced micro gyroscopes, accelerometers, magnetometers and GPS receivers have accuracy performance impossible to achieve few years ago. Thanks to this development, it is possible to build mobile integrated navigation systems based on satellite (GNSS) and inertial observations (IMU). This solution allows to support the satellite navigation results by the sensors of the IMU unit. This increases the frequency of the received coordinates and improves the accuracy of obtained navigational solutions. Beyond the aforementioned advantages of all integrated systems, there are also those that result from the applied integration architecture. Application of tightly - coupled architecture permits to perform measurements for areas with limited visibility of GPS satellites. The following study presents the use of MEMS based INS/GPS an integrated navigation system to navigate through areas where may be limited visibility of navigational satellites. Used device was designed and build on the University of Warmia and Mazury.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-483

Impact of Antenna Phase Center Models: From observation to parameter domain

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For precise GNSS applications like positioning, navigation and timing (PNT) as well as for troposphere studies, stable and accurate calibrations of the carrier phase center variations (PCV) for individual antennas have to be provided by calibration institutions. Beside an anechoic chamber calibration, the Institut für Erdmessung (IfE) uses a field approach with a precisely calibrated robot. Ring analyses between different calibration institutions determined with geodetic graded antennas show comparability at the level of 1mm which is a threshold accepted by the International GNSS Service (IGS).

Several contributions and papers discuss the impact of the variability of calibration models on the coordinate or parameter domain, respectively. This can only be a first approximation since complex interactions depending on the processing philosophy, propagates PCVs differently to the parameters, so that unexpected discrepancies on the parameter domain can occur and have to be analysed consequently.

This contribution presents a concept to study the impact of PCVs on the observation and parameter domain. In this concept the PCVs will be formulated not as classical tabulated PCV models but with their corresponding spherical harmonic (SH) coefficients. Finding a transfer function to analytically study the impact of the PCVs on the individual parameter like i.e. coordinates, time and troposphere as well as ambiguities is one of the three main goals in this concept. Exemplarily we will show first results and will study error functions between type and individual calibration models based on the proposed concept.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-484

"Analysis and comparison of different types of clocks applied in space geodetic techniques"

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The knowledge of the frequency or time standards' stability is essential for the development and improvement of various methods of Earth Sciences. This paper is a comprehensive investigation of the stability of the current most common frequency standards. Stability assessment is based on the calculation of various statistics, such as Allan variance, Hadamard variance, Theo. In order to improve frequency standards or for the prediction or modelling of current ones, it is necessary to know the nature and order of the clock or frequency standards' errors. Based on these data, new methods of time determination can be developed. Using the GPS processing results from different IGS stations being part of GFZ's Repro2 project, the values of the noise inherent in electronic systems are characterized. Also, based on discrete linear transformations, we evaluate periodic components of different time series standards (Cesium, Rubidium, Hydrogen maser) associated with the cyclical processes, such as rotation of the satellite, the Earth rotation etc.

The paper contains also the results of the studies related to time transmission from one station to another by means of GNSS and VLBI. It shows the differences that arise in calculating the time difference of a couple of clocks at the stations. These differences are caused by fundamentally different methods of time transmission, despite the fact that identical clock pairs were used.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-485

Using GNSS observations to investigate variations of pluviometry in Northeast of Brazil

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The Semi-Arid Brazilian, located in the Brazilian Northeastern region is the most densely populated semi-arid region in the world. The annual rainfall averages between 500 and 800 millimeters over most of the region and it is confined to a short rainy season. Additionally, the proximity of the tropical Atlantic Ocean imposes strong contrast to the spatiotemporal distribution of rainfall in the coast and in part of the Semi-Arid of the northeast region.
The GNSS (Global Navigation Satellite Systems) technique has been established as a valid tool to sense the amount of PWV in the atmosphere. The direct estimated product is the ZTD (Zenith Troposphere Delay) that can be transformed to PWV by knowing the Pressure and Temperature at the station position. However, such values are not always collected together with the GNSS observations, which can force us to limit the analysis to the ZTD directly.
Applications for this technique were made using data from existing continuous GNSS station in Natal city, situated in the Brazilian Northeastern coastal region.
Firstly, we analyzed the accuracy of using global models of pressure and temperature fields to calculate the PWV at the GNSS station position. To do this, we have compared estimated values of PWV using both global models and local measurements at Natal. The differences provide us a reliable estimate of the error associated with the use of global models to compute the PWV from ZTD measurements for Natal. Secondly, we correlate the estimated time-series of ZTD/PWV acquired since last decade with the pluviometer data from a meteorological gauge station in that city. The analysis shows a direct correlation between the annual seasonal normalized for the ZTD/PWV and rainfall signals considering a significance level of 0.05.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-486

Precise Beidou/GPS Analysis Based on Multi-GNSS Experiment and International GNSS Monitoring and Assessment Service Network

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Chinese BeiDou system has provided full operational service for Asia-Pacific region since end of 2012. Although BeiDou only has a regional constellation currently, it is interesting to investigate how it could contribute to the global solution.

By the end of 2014, there were more than 66 stations capable of tracking both BeiDou and GPS signals in the IGS Multi-GNSS experiment network. However, few of these stations were located in Asia region which was quite important for BeiDou orbit determination. Fortunately, the international GNSS monitoring and assessment service network provide us another choice. It has at least 8 stations in Asia region.

Based on both the Multi-GNSS experiment and international GNSS monitoring and assessment service network, combined BeiDou/GPS data were precisely analyzed. The contribution of BeiDou was assessed by the precise products, such as earth rotation parameters, troposphere and station coordinates.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-487

Validation of GNSS orbits using satellite laser ranging data

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The Center for Orbit Determination in Europe (CODE) is a global analysis center of the International GNSS Service (IGS) regularly delivering products such as precise satellite orbits, station coordinates, Earth rotation parameters, as well as satellite and receiver clock corrections based on a rigorously combined GPS and GLONASS processing. Starting from January 4, 2015, the operational CODE orbit products are based on an extended version of the Empirical CODE Orbit Model (ECOM): additional harmonic terms for the direct solar radiation pressure component were added and the angular argument for the harmonic terms was modified. The new model noticeably reduces spurious effects resulting from deficiencies in the solar radiation pressure modeling. Prior to that extension, ECOM was used for the IGS-style processing for many years. Using the new ECOM we reprocess the CODE product series. In this context additional experiments for the further improvement of the GNSS orbit modelling are planned. In this contribution we quantify the impact on the computed GNSS orbits. Since all GLONASS and two GPS satellites are equipped with corner cube reflector arrays dedicated to Satellite Laser Ranging (SLR), SLR is a powerful tool to validate microwave-based GNSS orbits. The discrepancy between the GNSS orbits and the laser distances (residuals) may serve as an indicator for the radial accuracy of the computed GNSS orbits.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-488

Precise direct georeferencing with GNSS and structure from motion

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Precise georeferencing of images acquired from UAV platforms, normally requires accurate ground control points. There is an interest in exploring as much as possible direct georeferencing systems in order to avoid field work. This paper analyses a methodology of attitude determination of a camera in a light aerial platform, equipped with a GNSS dual frequency receiver. The methodology uses a structure from motion approach, in which many conjugate points are obtained between consecutive images, which have overlaps of around 80%. A bundle adjustment is done in order to obtain relative orientations. Provided that a precise synchronization exists between the GNSS positioning and image acquisition, camera positions are kept as fixed in the bundle adjustment and leaving only camera attitude angles as unknowns. This process requires that the flight has strips in different directions, in order to strengthen the final accuracy.
Tests were done in a light aircraft with a GNSS antenna mounted over the plane. The camera, mounted in a small box attached to a wing support bar, was a AVT Pike, with a 5 Mpixel sensor and a 8mm lens. A cable connected the camera to a data logger inside the aircraft, which triggers the camera and is synchronized with GPS time. A flight was done at a flying height of 300 meters, for which the image resolution on the ground was 6 cm. Images were acquired at a frame rate of 2 Hz, which guarantees an overlap of 80%. Once the exterior orientation of the images is achieved, a DSM was extracted and an orthoimage mosaic was built. Using ground control points in a small test area, for calibration of a small synchronization error, we confirmed a positional accuracy of 20 cm.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-490

Spatial analysis of the interaction between a heterogeneous velocity field and a static GNSS-based reference frame: a Greek case study

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It is well known that the Earth's crust over the Hellenic region exhibits a complicated non-uniform geodynamical behavior due to its fragmentation into several microplates, thus causing a continuous deformation of the geodetic networks in Greece. The common practice of using a static spatial reference system that is realized through permanent GNSS networks in support of cartographic, cadastral and other surveying applications is therefore problematic as it leads to a gradual degradation of the associated reference frame and the expected accuracy in modern GNSS-based positioning techniques. In general, the positioning error for most surveying applications in a static coordinate frame under the presence of a heterogeneous crustal velocity field depends on two factors, namely the velocity difference (both in magnitude and orientation) between the areas where the reference and the rover GNNS stations are located, and also the time difference between the reference epoch of the (static) coordinate frame and the observation epoch. The aim of this paper is to quantify and map the interaction of the heterogeneous velocity field in Greece with the station distribution of various permanent GNSS networks that are currently used for cadastral surveying applications. Using spatial analysis tools from a Geographical Information System (GIS) and a gridded form of a recently computed horizontal velocity field model over the Hellenic region, we identify sets of "permissible regions" around each GNSS permanent station that remain sufficiently stable for cm-level positioning throughout a predefined time period.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-491

Stability of GNSS satellite differential code biases

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The International GNSS Service (IGS) and the international GNSS Monitoring and Assessment System(iGMAS) analysis centers have routinely provided GNSS satellite differential code biases (DCBs), which are assumed to be constant during 1 day or 1 month. The satellite DCBs are estimated together with ionospheric total electron content (TEC) under several ionoshperic hypotheses. The long-term variation and monthly stability of satellite DCBs probably affected by the temporal scale variation of ionospheric TEC. Based on the DCBs published by CODE analysis center during 1998~2013, the long-term variation of GPS satellite DCBs during the same period were analyzed, and then the monthly stability of GPS satellite DCBs were analyzed. Satellite DCBs show a very stable trend, the long-term variations of GPS satellite DCBs are less than 0.1ns per year except a few satellites. The monthly stability of different satellite DCBs are consistent during the same period, which can reach up to 0.1ns during 1998-2002, and basically reach a level of 0.03-0.04ns after 2002. The monthly stability of satellite DCB is influenced by solar activity, for Block IIA satellites which are not changed in more than 10 years, except for PRN8 satellite, the annual average of monthly stability of Block IIA satellites DCB performs at the level of 0.044ns during high solar activity period (2003~2004) and 0.027ns during low solar activity period (2008~2009).The long and short terms stability of GLONASS satellite DCB is also analyzed in detail. The 2013-2014 BDS satellite DCB series from SHAO iGMAS analysis center has been retrieved with global BDS tracking data and the short-term stability also has been analyzed.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-492

Quest for the footprints of severe weather events using heterogeneous geodetic measurements

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The emerging Global Navigation Satellite Systems (GNSS) technology for near real-time monitoring and forecasting of severe weather and nowcasting is investigated. The March 2010 Melbourne/Australia storm was chosen as a case study and GPS observations from the most advanced Victorian state-wide Continuously Operating Reference Station (CORS) network in Australia were used. Different GPS data processing strategies are also investigated for the most robust and accurate precipitable water vapour (PWV) estimation. In addition to the ground-based GNSS, a large range of state-of-the-art observations including satellite to satellite tracking (e.g. GPS radio occultation), radiosonde, radar refractivity, synoptic weather station measurements and Australian numerical weather forecasting (NWP) models are used to investigate the spatio-temporal variability of the troposphere in this research.

Results show strong spatial and temporal correlations between the variations in the ground-based GPS-PWV estimates and the thunderstorm passage. This indicates that the GPS technique can capture significant signatures of the atmosphere and it can act as a complementary technique to the conventional meteorological observation techniques for the studying, monitoring, and potentially predicting of severe weather events. The advantage of using the ground-based GPS is that it can provide continuous observations of the storm passage with a high temporal and spatial resolution while the space-based GPS (i.e. Radio Occultation) can capture the dynamics of the atmosphere with a high vertical resolution. Our recent research through the Natural Disaster Resilience Grant Scheme will be introduced along with our recent major achievements in this frontier area of international effort.

IAG (Geodesy)

G05p - G05 GNSS++: Emerging Technologies and Applications

G05p-493

Assessment of IGS ionosphere map with CMONOC and iGMAS data

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As one of the main products of International GNSS Service (IGS), the IGS global ionosphere map(GIM_IGS) has a very good application precision in most parts of the world. However, when the GIM_IGS is calculated by IGS analysis center, quite a little of GPS observations is used from China and its surrounding area. So, it's necessary to assess the accuracy of the IGS GIM over this area. In this article, we use the real-measured GPS data from 200 IGS sites, 100 Chinese Mainland Tectonic Environment Mornitoring Network(CMONOC) sites and the multi-GNSS data from iGMAS (the international GNSS Monitoring and Assessment System) to form a specific ionosphere products(GIM_China) with data densified in China and its surrounding area. The GIM_China is used as the criterion to assess the accuracy of IGS ionosphere map and the conclusions are obtained as follows: 1) the global average consistency of GIM_IGS and GIM_China is about 0.5 TECu at all the sites included in the comparison. 2) but there is a bias of about 2 TECu between the two GIMs over China and its surrounding area. The assessment with single frequency point positioning for GPS, BDS and Galileo is also conducted with iGMAS data over China.

IAG (Geodesy)

G06a - G06 Unifying Height Systems

IUGG-0313

Investigation of the south-north slope of australian height datum using satellite altimetry data and the earth gravitational model

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Australia is one of the rare countries in the world, where the satellite altimetry tracks pass from north to south and vice versa, sweeping the Australian territory and surrounding oceans. This feature provides a unique opportunity for investigating the north-south-oriented slope in the Australian Height Datum (AHD), which is achieved by computing the gravity potential along altimetry passes around the country using altimeter data and the global geopotential model. For this purpose in this study, 15 years of satellite altimetry observations from Topex/Poseidon, Jason-1 and Jason-2, as well as global geopotential models of EGM2008 and EIEGN-6C3 are used.

Above-mentioned altimetry missions have the same repeat orbits, from which sea surface heights (SSHs) of different cycles are observed along altimeter passes at the proximity to each other. This important feature provides the possibility of constructing the SSH time series along passes at 1-second normal points. Mean Sea Surface Heights (MSSH) of the time series are then computed using Harmonic analysis at each normal point. After that, the MSSH and an Earth gravitational model are used to calculate the Earth gravity potential. The resultant gravity potentials along each altimeter pass are converted to height difference between the Australian north and south level surfaces, which indicates the AHD slopes. The computed north-south AHD slope from this study, eventuated from various passes, ranges between 23.44 cm to 71.88 cm. The results from two gravitational models are compared not only to each other, but also to orthometric height differences computed from GPS observations and a local geoid model, AUSGeoid09, at the nearby tide gauges. Notable consistencies between the results of altimetry and tide gauge are concluded.

IAG (Geodesy)

G06a - G06 Unifying Height Systems

IUGG-0420

Local W0 computation: a case study for Bulgaria

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Significant progress has been made into unifying existing vertical reference systems with the establishment of the European Vertical Reference System in Europe more than decade ago. This successful initiative, however, has revealed some major challenges for small countries such as Bulgaria in their efforts to link their national height systems to European Vertical Reference System. The usage of historical levelling data dating back to the 1980's and gravity data from Bouguer anomaly maps, created even earlier, leads to very wide margins for future discrepancies.

Alternatively, there is the possibility to define a national vertical system based on the computed local W0 geoid value for the whole country and provide an efficient methodology for connecting the National Vertical Reference System of Bulgaria to the global system. In consequence, this presentation aims to provide such a connection by deriving a W0 value for Bulgaria utilizing all available GPS/levelling data in combination with three generations of GOCE-based geopotential models. A validation of the results as far as possible will be made by comparison against independent Bulgarian W0 values obtained as point-values at two tide-gauges on the coast of the Black Sea by accounting for the effect of sea surface topography. In addition, use of three generations of geopotential models provides insight into the performance of the GOCE gravity field models over Bulgaria.

IAG (Geodesy)

G06a - G06 Unifying Height Systems

IUGG-2572

Unification of height reference frames in Europe

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The European Vertical Reference Frame (EVRF) 2007 as the present realization of the European Vertical Reference System (EVRS) is based on a continental spirit leveling network. The comparison of heights given in national height systems against EVRF heights allows the determination of datum offsets of the national height systems with respect to EVRF.

The satellite gravity missions GRACE and GOCE have significantly improved global satellite gravity models in terms of their accuracy and resolution. Together with the increased accuracy also of regional gravity field models as well as the availability of observations at a large number of GNSS/leveling benchmarks, this opens up a new possibility to determine datum offsets: the comparison of measured and modeled height anomalies.

The presentation shows practical results as an outcome of the project 'GOCE+ Height system unification', funded by ESA within their Support To Science Element Programme. Special attention is paid to the consistency of geoid model, ellipsoidal heights and leveling heights. In particular, analysis of closure loops enables to identify systematic effects in the height system realizations.

IAG (Geodesy)

G06a - G06 Unifying Height Systems

IUGG-3110

Realization of a vertical reference system for South America as a densification of an International Height Reference System

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The main purpose of GGOS Theme 1 (Unified Height System) is to provide a global gravity field-related vertical reference system that 1) supports a precise combination of physical and geometric heights worldwide, 2) allows the unification of all existing local height datums, and 3) guarantees vertical coordinates with global consistency and long-term stability. Under this umbrella, the present contribution concentrates on the definition and realization of a conventional global vertical reference system (called International Height Reference System - IHRS) and the formulation of appropriate strategies for the precise transformation of the local height datums into the IHRS. The IHRS is based on a geometric component (ellipsoidal heights as coordinates and a level ellipsoid as the reference surface), and a physical component (geopotential numbers as coordinates and an equipotential surface defined by a conventional W0 value as the reference surface). The physical component is based on potential parameters to provide reference to any type of physical heights. The vertical datum unification strategy is based on 1) the physical connection of height datums to determine their discrepancies, 2) joint analysis of satellite altimetry, GNSS times series and tide gauge records to separate crustal movements from sea level changes, and (3) combination of geometrical and physical heights in a well-distributed and high-precise reference frame to estimate the relationship between the individual vertical levels and the global one. The vertical transformation parameters are provided by the common adjustment of the observation equations derived from these methods. As an example, the integration of the South American heights systems into the proposed IHRS is discussed.

IAG (Geodesy)

G06a - G06 Unifying Height Systems

IUGG-4466

Resilience of New Zealand Vertical Datum 2009 in response to the Canterbury earthquake sequence 2010 – 2011

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New Zealand Vertical Datum 2009 (NZVD2009) is the national vertical datum for New Zealand. It was preceded by a set of 13 local vertical datums based on the classical approach using a tide gauge and precise levelling network. NZGD2009 was a break from the classical approach – it uses a quasigeoid model NZGeoid2009 as the reference surface for normal-orthometric heights across the country.

A potential advantage of this approach is that it can be more resilient in the event of widespread damage to tide gauges and levelling benchmarks. This was tested with the sequence of damaging earthquakes and aftershocks in the Canterbury region in 2010 and 2011. These caused significant widespread horizontal and vertical motion of the land as well as soil liquefaction resulting in highly localised and anomalous movements of survey marks, buildings and services. The local height reference tide gauge in the Port of Lyttelton was also severely damaged.

This paper compares normal-orthometric heights derived from precise levelling after the seismic events, with NZVD2009 heights derived from a combination of GPS-observed ellipsoidal heights and NZGeoid2009 geoid heights. This comparison will quantify the resilience of the vertical datum to seismic events, particularly during the post-seismic response and recovery phase when heights are needed to reinstate drainage services while on-going aftershocks cause sequential vertical motions of the land, survey marks and services.

IAG (Geodesy)

G06a - G06 Unifying Height Systems

IUGG-5546

Study of vertical datum unification in North America

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We have investigated the geodetic boundary value problem approach for the unification of the existing vertical datums in North America. The indirect bias term, the GOCE geoid omission error, the systematic levelling datum errors and distortions, and the data errors are four important factors affecting the practical implementation of this approach. These factors are investigated numerically using the GNSS-levelling and tide gauge stations in Canada, the USA, Alaska, and Mexico. The results show that the indirect bias term can be omitted if a GOCE-based global geopotential model is used in geoid computation. The omission of the indirect bias term simplifies the linear system of equations for the estimation of the datum offset. Because of the existing systematic levelling errors and distortions in the Canadian and US levelling networks, the datum offsets are investigated in eight smaller regions along the Canadian and US coastal areas. Using GNSS-levelling stations in the US coastal regions, the mean datum offset can be estimated with a 1 cm error if the GOCE geoid omission error is taken into account using local gravity and topographic information. In the Canadian Atlantic and Pacific regions, the datum offsets can be estimated with 2.3 and 3.5 cm uncertainty, respectively, using GNSS-levelling stations. However, due to the very limited number of tide gauge stations, the datum offset error can reach one decimetre in the Pacific regions. With the available GNSS-levelling stations in Alaska and Mexico, the datum offsets can be estimated with less than 3 cm error. The results of this study demonstrate the importance of the aforementioned four factors in the practical implementation of the GBVP approach for the unification of the levelling-based vertical datums.

IAG (Geodesy)

G06b - G06 Unifying Height Systems

IUGG-1718

GGOS Bureau of Products and Standards: Inventory of standards and conventions

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In 2014, the organizational structure of GGOS has been re-aligned to increase its effectiveness and operability. The existing GGOS components have been kept, but their tasks and responsibilities have been clarified and partly redefined. As a consequence, the responsibilities of the two Bureaus have been extended and also their names have been changed. The former Bureau of Standards and Conventions (BSC) has been renamed into the Bureau of Products and Standards (BPS).

This presentation gives an overview about the redefined organizational structure of the BPS, its mission and goals as well as the interactions with other IAG components. The work of the former BSC (which will be continued by the BPS) concentrated on the compilation of an inventory of the standards and conventions used for the generation of IAG/GGOS products. As a result a document of about 80 pages has been compiled which is currently under review by an external board. In this presentation we will summarize the major findings of this product-based inventory, addressing the following major products and topics, such as the terrestrial and celestial reference frames, the Earth Orientation Parameters, GNSS satellite orbits, gravity field models and vertical reference frames. Some examples will be highlighted, indicating that there are several shortcomings and deficiencies. As a major outcome of this inventory, the BPS will provide recommendations on how to resolve inconsistencies and gaps.

IAG (Geodesy)

G06b - G06 Unifying Height Systems

IUGG-2490

A proposal of geopotential determination using precise optical-atomic clocks onboard satellite and on ground based on Doppler cancellation system

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Different from traditional way, here we propose an approach for determining the geopotential using high-frequency-stability microwave links between satellite and ground station based on Doppler cancelation system. Two precise optical-atomic clocks or oscillators are equipped onboard a satellite and at a ground station, respectively. The ground oscillator emits a signal with frequency fa towards the satellite and the satellite receiver (connected with the satellite oscillator) receives this signal with frequency fb which contains the gravity frequency shift effect and other signals and noises. After receiving this signal, towards the ground station the satellite oscillator emits two signals which have the frequencies fb and fc, respectively. Via Doppler cancellation technique, by a combination of these three frequencies the geopotential difference between the satellite and the ground station can be determined based on gravity frequency shift equation. For arbitrary two stations on ground, based on similar procedures as described above, we may determine the geopotential difference between these two stations via a satellite. With this approach, if the geopotential at a definite point on ground (e.g. a datum point) is given, the geopotential at an arbitrary point on ground can be determined. Since optical-atomic clocks with stability around 10E-18 have been generated, the proposed approach in this report is prospective for precisely determining the geopotential globally. Further, based on this approach a unified world height system could be realized with high accuracy. *This study is supported by National 973 Project China (grant No. 2013CB733301 and 2013CB733305) and NSFC (grant Nos. 41174011, 41210006, 41429401).*

IAG (Geodesy)

G06b - G06 Unifying Height Systems

IUGG-2697

A new best estimate for the conventional value of W0

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At present, the most commonly accepted W_0 value corresponds to the best estimate available in 2004, i.e. 62636856 m^2s^{-2}. However, recent computations based on the latest Earth's surface and gravity field models shows a clear offset from this W_0 by about -2 m^2s^{-2}. According to this, in the frame of the Working Group on Vertical Datum Standardisation, four different teams working on the computation of a global W_0 value were brought together to calculate a new best estimate of W_0 and to outline the conventions needed to guarantee the reliability and repeatability of its realisation. This new W_0 value shall be introduced as the global height reference level, as a defining parameter for a new geodetic reference ellipsoid, and as a reference value for the estimation of the constant L_G (defining the transformation between Terrestrial Time and Geocentric Coordinate Time). This contribution provides a closing report of the achievements oriented to the introduction of the new W_0 value as a formal IAG geodetic convention.

IAG (Geodesy)

G06b - G06 Unifying Height Systems

IUGG-4225

Future of interactions between time and frequency metrology and geodesy

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General relativity has been included in the physical models used in time and frequency metrology for decades, notably because the rate of frequency standards depends on the gravitational potential and the velocity at a level highly significant with respect to their frequency accuracy.

As noted by many authors, the problem may be reversed with accurate clocks and accurate frequency comparison techniques providing a means to compute the difference of gravity potential between the locations of the clocks. In order to be useful for geodesy both clocks and frequency comparison techniques should be accurate to the $1\text{x}10^{-17}$ *level (about equivalent to 10 cm in height) and below, and should be operated on different continents. Because this level of accuracy is already achieved for some clocks and anticipating that accurate frequency comparison techniques become available, such comparisons of accurate clocks could, in the future, help establish a worldwide vertical datum. It is therefore essential to develop interactions between time and frequency metrology and geodesy in this specific domain.*

A possible new definition of the geoid and/or a new reference value of the gravity potential on the geoid W_0 *are the responsibility of the International Association of Geodesy. Such new definitions, together with the emergence of new accurate frequency standards, will have implications for the reference timescale TAI (International Atomic Time) presently defined as 'a coordinate time scale defined in a geocentric reference frame with the SI second as realized on the rotating geoid as the scale unit'. The institutional aspects of time and frequency metrology will also be reviewed.*

IAG (Geodesy)

G06c - G06 Unifying Height Systems

IUGG-1159

Scientific roadmap towards height system unification with GOCE

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GOCE allows the determination of geoid heights with an accuracy of 1-2cm and spatial resolution of at least 100 km. An important application that will benefit from this is the global unification of the (over 100) existing height systems. GOCE will provide three important components of height unification: highly accurate potential differences (geopotential numbers), a global geoid- or quasi-geoid-based reference surface for elevations that will be independent of inaccuracies and inconsistencies of local and regional data, and a consistent way to refer to the same datum all the relevant gravimetric, topographic and oceanographic data. The paper summarizes results of a project supported by the European Space Agency and specifies a scientific roadmap on how GOCE can support world height system unification.

IAG (Geodesy)

G06c - G06 Unifying Height Systems

IUGG-1232

How important is the demand for a unified world height system?

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I have been asked, sometimes provocatively, "why do we need a unified global height system?" It may be a valid question. At one extreme, physical geodesists see this as an ideal and one of the remaining unsolved problems, lagging behind the "geocentricisation" (my invented word) of horizontal datums. At the other extreme, engineering surveyors and others do not necessarily care whether their heights are in a unified frame. Of more concern is that many other disciplines beyond geodesy that use heights on a global scale commonly assume that they all refer to the same level, not understanding that various height datums may be offset by as much as a few metres. This presentation will attempt to distill the pros and cons of a unified global height system, using "what-if" scenarios for the users of heights that assume they all refer to the same level. Conveners permitting, this presentation will encourage interactive feedback from the audience.

IAG (Geodesy)

G06c - G06 Unifying Height Systems

IUGG-2895

Definition and realization of an international height reference system

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Long term monitoring of the vertical component of the Earth surface needs a standardized defined and realized global reference relating the geometry and the gravity field of the Earth. For Earth system monitoring the heights are main parameters for global changes.

The objective is to define standards and conventions for a global physical height based on existing developments and results of projects and to draft and implement relevant products.

The International Height Reference System (IHRS) shall connect the Earth gravity field (gravity, potential) with the geometry of the Earth and the timescale. Five conventions relating the vertical reference level, vertical coordinates, the tidal system, the unit of length, and the spatial reference of the position for the potential define the IHRS.

The IHRS is realized by combination of a station network, a global gravity model and values for a set of parameters as an International Height Reference Frame (IHRF). The IHRF has strongly to consider the conventions for the definition of an IHRS. The IHRF needs conventions how the elements can be derived. We have to distinguish between the IHRS, physical heights derived in the IHRF (most important for applications and users) and the unifications of existing physical height systems aligned to a defined and realized IHRS.

IAG (Geodesy)

G06c - G06 Unifying Height Systems

IUGG-4772

Relation between local (quasi)geoid models and mean dynamic topography estimated from the filtered GOCE-based static gravity field models

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The GOCE satellite mission has brought a significant improvement in modelling of the low-frequency part of the Earth's static gravity field. New precise GOCE-based satellite-only geopotential models provide a valuable basis for a unification of height systems. They are fully independent from local vertical datums (LVDs), however they are considerably affected by a stripping noise due to their omission error. On the other hand, in many countries there exist detailed local (quasi)geoid models that include the high-frequency part precisely modelled from terrestrial gravity data. Such input data are usually related to LVDs and can suffer from deficiencies of local vertical networks. This can yield inconsistencies that need to be treated.

In our study we test the local (national) geoid or quasigeoid models with respect to the static gravity field observed by GOCE. We use nonlinear diffusion filtering to reduce the stripping noise of the geopotential generated from the GO_CONS_GCF_2_DIR_R5 geopotential model up to degree 300. At oceans, the geopotential numbers are filtered at points on the DTU13 mean sea surface whose 3D positions are precisely given by satellite altimetry. On lands, we filter differences between the geopotential numbers generated from this model and ones derived from the local (national) geoid or quasigeoid models, both evaluated at points on real topography. Such an approach aims to estimate inconsistencies of the local (quasi)geoid models as well as their relation to the mean sea surface at coastal areas. Finally we discuss how the achieved findings can help in process of a realization of the World Height System.

IAG (Geodesy)

G06p - G06 Unifying Height Systems

G06p-345

Wo determination for Argentinean height system unification

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The estimation of the zero-height geopotential level plays a fundamental role in the definition and realization of a global reference surface that allows the integration of the existing Local Vertical Datums in a global one. The main objective of this study is to obtain a representative estimate of the zero-height geopotential value over the continental part of Argentina using Helmert orthometric heights, GPS measurements over a network of benchmarks (BMs) and a high-accuracy GGM (Global Geopotential Model), containing data only from the satellite mission GOCE (Gravity field and steady-state Ocean Circulation Explorer) or from a GOCE/GRACE (Gravity Recovery and Climate Experiment) combined GGM. Within the present work the Argentinean LVD zero-level geopotential value is determined from the latest GOCE and GOCE/GRACE GGMs determined by the time-wise and direct approaches (TIM-R5 and DIR-R5, respectively) by estimating directly the gravitational potential at available trigonometric BMs that belong to the country's national network. A Least-Squares based adjustment is also employed to remove any possible dependencies with height. Our previous results, computed with information from EGM2008, show that the best possible estimate at present is 62 636 853.9 m^2s^{-2}; however, improvements are sought employing the latest GOCE and GOCE/GRACE GGMs along with a more extensive network of GPS/Levelling benchmarks.

IAG (Geodesy)

G06p - G06 Unifying Height Systems

G06p-346

The gravimetric boundary value problem in spheroidal approximation and its role in the height datum problem

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In this presentation the linear gravimetric boundary value problem is discussed in spheroidal approximation. The input to the problem is gravity disturbances, using the known Earth's topography as boundary and corresponds to an oblique derivative problem. From the physical viewpoint, it has many advantages and can serve as the basis in establishing a world vertical datum that supports geometrical and physical heights world-wide with high precision. Adopting the spheroidal approximation in this boundary value problem, an integral equation results which can be solved analytically using successive approximations. However, the mathematical model becomes simpler and can be solved more easily by applying certain permissible approximations: neglecting the Earth's topography, a spheroidal normal derivative (Neumann) problem is obtained. Under the spherical approximation, the result is a normal derivative problem plus suitable corrections. In this case, neglecting the Earth's topography, the solution corresponds to the well-known spherical Hotine integral. Finally, the relative errors in the above approximations and derivations are quantitatively estimated. From these estimates we conclude that the spheroidal approximation has to be taken into account in order to achieve the highest accuracy.

IAG (Geodesy)

G06p - G06 Unifying Height Systems

G06p-347

Vertical reference surfaces in the North Sea area: review and numerical validation

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The chart datum is the relevant reference surface at sea. While it is defined by the Lowest Astronomical Tide, LAT, uniformly in all neighbouring states of the North Sea, its realization is different in each. Available literature often looks at a specific country only. Here, we are working towards a comparative study with emphasis on the differences between definition and the actual realization. Next, we will carry out computations to show how well the various realizations match to independent data. We expect the results to support our theoretical findings.

Moreover, it is important to connect LAT to the geoid, which is the most natural reference surface for heights. We validated the consistency of state-of-the-art geoid models at different resolution with altimetry and tide gauge data from the North Sea area. Variations of the water level due to ocean circulation and tides were accounted for using output from a hydrodynamic model, which is run by the Federal Maritime and Hydrographic Agency of Germany. We found that the various data sets agree in the range of several centimeters if the geoid is represented with moderate spatial resolution. Seen from a different angle, our results are also of interest as external validation for the gravity field models.

IAG (Geodesy)

G06p - G06 Unifying Height Systems

G06p-348

Practical applications of up-to-date geopotential value W0 after its worldwide acceptance

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After adopting up-to-date geopotential value W_0 = 62 636 856.0 m^2s^{-2} or improved value W_0 = 62 636 854.0 m^2s^{-2} practical applications of this value should start. Main application uses W_0 for connecting local vertical datums (LVDs) to new World Height System (WHS). This activity provides vertical shifts among W_{0i} of LVDs and adopted W_0. Evidently it will be the possibility of geopotential model testing by our methodology with the use of GPS/leveling and adopted W_0. The connection of LVDs to WHS makes possible to connect gravity data to unified gravity system. When new value W_0 will be adopted it is necessary to introduce parameters of level ellipsoids and to introduce new value $L_G = W_0/c^2$ for the realization of the relativistic Atomic Time scale for IAU purposes. The process of W_0 research should continue not only for geodetic applications but also for study of ocean level variations.

IAG (Geodesy)

G06p - G06 Unifying Height Systems

G06p-349

Revised determination of geopotential value at the polish tide gauges using GPS data and geoid model

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The potential value of the Gauss-Listing geoid W_0 represents the fundamental geodetic parameter. Global geopotential value can be introduced as the conventional reference level for the realization of a Unified Global Height System. One of the global W_0 determination method is based on the tide gauge averaging. This work provide W_0 value for tide gauges located along the Polish coast.

The study concerns computation of the gravity potential using water level data at tide gauges in Wladyslawowo, Ustka and Swinoujscie, geoid undulations from global geopotential model EGM2008 and ellipsoidal heights of tidal benchmarks from GPS, which were obtained using revised data from two campaigns of Baltic Sea Level Project. Moreover, regional sea surface topography models were utilized in order to validate the mean W_0 results obtained from tide gauge averaging.

IAG (Geodesy)

G06p - G06 Unifying Height Systems

G06p-350

Deformation of Chilean Vertical Network due Co/post-seismic effect of the Maule earthquake (2010) based on GRACE and GPS data

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The Maule earthquake (February 27, 2011) has been one of the strongest earthquakes occurred in recent years in the world. The deformation of the crust gravimetry. However, the estimate of the possible vertical deformation produced by Co/post-seismic effects and their implications on the Chilean Vertical Network (CHVN) has not been discussed. This article presents an estimation of the deformation of CHVN via an indirect approach based on GNSS and GRACE observations. Time series were used from 2007 to 2013 from 10 GPS permanent stations surrounding the region most affected by the earthquake. A set of 104 monthly spherical harmonic gravity field solutions R05 of the GRACE mission of the GFZ, JPL and CSR expanded up to degree and order 60 centers were used. The results obtained after removing the hydrological effect of GPS time series, long term variation of the geoid, the hydrological effect by means of GLDAS solutions and post-glacial uplift of GRACE solutions showed a few centimeters in geometric component (dh/dt), and deformation around of a millimeter in the geoid (dN/dt). However, the deformation of the geoid must be taken into account after a few years intervals (e.g. 10 years) considering purposes for maintaining consistency of the vertical reference networks. In addition, we applied a model for determining Co/post-seismic vertical deformation by using the linear and cyclical components as well as a jump function. Our strategy is presented as an alternative to the indirect restoration of the vertical deformation of the CHVN.

IAG (Geodesy)

G06p - G06 Unifying Height Systems

G06p-351

Analysis of systematic effects in the national vertical reference system of the Czech Republic

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The paper focuses on systematic effects present in a national implementation of the vertical reference system. The vertical reference Kronstadt-57 (Bpv) used in the Czech Republic is based on Molodensky's normal heights. For the reconstruction of geopotential numbers normal field of Helmert's spheroid and the respective telluroid construction should be taken into account. Moreover, the geopotential numbers have to be transformed to the zero-tide system in order to comply with IAG standards. Still, such a geopotential number is influenced by the gravity values incorporated in the so-called normal corrections. Besides the main source of distortion – Potsdam gravity reference – we identified other sources of errors incorporated in gravity information, including neglected technological corrections, like the height of a line of sight. The focus is on the identification of various systematic effects contained in geopotential numbers. All these effects are analysed and modelled. Finally, by the back-propagation of the respective models, we can make hypothetical re-adjustment of the levelling network to the physically (almost) correct state. The proposed procedure enables us to recreate the true geopotential in the levelling network, even in the case when the original field books are not available. It is important to note that the work is related to the unification of the vertical datum, enabling a better comparison and connection of neighbouring national vertical reference systems.

IAG (Geodesy)

G06p - G06 Unifying Height Systems

G06p-352

Comparison of different approaches to determine geopotential numbers – case study on the Slovak National Levelling Network

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The National Vertical Reference System in the Slovakia uses normal heights according to Molodensky based on the Kronstadt benchmark, practically realised by the National Levelling network (1. and 2. order). In the past, the "classical" method, i.e. the combination of the relative elevation differences with gravity reduction based on simple Bouguer anomaly) was used for practical evaluation of the heights. Nowadays we are preparing a new realization of height system based on geopotential numbers. This new realization will be in accordance with the EVRS and its last realization. The paper deals with a description and comparison of different methods to compute geopotential numbers, especially with the determination of gravity for the leveling points where this value is not directly measured. The first method is based on the reverse transformation of the Complete Bouguer Anomaly grid into the point gravity value using the software CBA2G_SK which utilizes a database of detailed gravimetric mapping within the area of Slovak republic. The next method is based on a recent global gravity field model, which is subsequently improved by the residual terrain model approach using a local detailed DEM of the Slovakia. The calculated gravity was then used to determine new normal heights according to Molodensky on the Slovak parts of the leveling lines included in UELN and on local levelling lines (area 30x30km) around the EVRF2007 Datum Point EH-V Pitelova (UELN- 1905325).

IAG (Geodesy)

G06p - G06 Unifying Height Systems

G06p-353

Differential geometry of equipotential surfaces and its relation to parameters of Earth's gravity field models

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According to adopted conventions the notion of an equipotential surface of the Earth's gravity potential is of key importance for vertical datum definition. The aim of this contribution is to focus on differential geometry properties of equipotential surfaces and their relation to parameters of Earth's gravity field models. Within this concept one can apply a number of tools. The discussion mainly rests on the use of Weingarten's theorem that has an important role in the theory of surfaces and in parallel an essential tie to Brun's equation (for gravity gradient) well known in physical geodesy. Also Christoffel's theorem and its use will be mentioned. These considerations are of constructive nature and numerically their content will be demonstrated for high degree and order gravity field models. The results will be interpreted globally and also in merging segments expressing regional and local features of the gravity field of the Earth. They may contribute to the knowledge important for the realization of a World Height System.

IAG (Geodesy)

G07a - G07 Geohazards Monitoring

IUGG-1235

Latest geodetic findings on ismetpasa segment of North Anatolian fault

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North Anatolian Fault (NAF) is notorious for great earthquake producing features in Turkey. It extends from its Iranian border in the east to Marmara Sea in the west with a length of approximately 1200km, and separates the Eurasian Plate and the Anatolian Plate. It has similarities to the San Andreas Fault in California in USA in a way that both faults have right-lateral strike slip faulting mechanism, similar lengths and linearity as far as their poles of rotation are concerned. NAF is considered to be one of the longest and most active fault systems in the world, and thus has been the stage of 11 major earthquakes (M_w>6.7) since 1939. Two of these major earthquakes occurred in the Ismetpasa segment of the fault, located 350 km east of Istanbul in north-central Anatolia, the Asia Minor. The Ismetpasa segment of NAF has a characteristic that a few fault zones in the world: its aseismic fault slip feature, also referred to as creeping. In the far and recent past, many researchers have investigated this creeping motion by conducting various measurement methods from conventional surveying techniques to modern techniques such as GNSS, LIDAR, InSAR. Over a decade our research team have conducted monitoring campaigns on this fault segment. This paper will give detailed accounts of latest geodetic findings as well as documenting the past studies carried in a chronological perspective.

IAG (Geodesy)

G07a - G07 Geohazards Monitoring

IUGG-1485

Multidisciplinary studies along seismically active Naga-Disang Thrust Belt in NE India

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The Naga- Disang Thrust is also known as E-W trending " Belt of Scuppean" between Dhauki Fault in the west and Mishmi Thrust of the Eastern Himalayan Syntaxis in the east. As Belt of Schuppean lies between two past Great earthquakes (1897 Shillong Earthquake 8.7M an 1950 Arunachal-China border 8.7 M),therefore the assessment of seismic hazard potential in north eastern part of Himalayan terrain has become very essential. There was no great earthquake after 1950. The Belt of Schppean is identified as "seismic gap" after these two great earthquakes in NE Region.

Attempts are made in the present studies to evaluate the seismic hazard assesment along the Belt of Schppean by using multi-disciplinary approach. The surface evidences of Naga Disang Thrust are delineated SRTM data. The faulting evidences such as abrupt changes in relief of topography due to the steep dipping beds influenced by the faulting The Belt of Scuppean marks the southern boundary of the Brahamputra valley. The transverse lineaments across the Belt of schuppean indicate the post tectonic activities. The seismological data is used to constrain the seismic gap along the thrusts. The crustal velocities estimates along many campaigns sites, located across the thrust, are used to constraint the crustal strain accumulation along the Belt of Scuppean. The presence of Schuppen is marked by a change in high crustal velocity from Indian plate to low crustal velocity in Mishmi Suture as well as Indo Burma Ranges. The difference in crustal velocities results in building up of strain along the Schuppen which may trigger a large earthquake in the NE India in future.

IAG (Geodesy)

G07a - G07 Geohazards Monitoring

IUGG-1763

Remote Sensing and GIS Contribution to the Detection of Areas Susceptible to Earthquake Hazards. The Case Study of Northern Greece

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The contribution of remote sensing and GIS techniques to earthquake and hazard analysis was investigated in N-Greece in order to contribute to the systematic, standardized inventory of areas that are more susceptible, to earthquake ground motions and to earthquake related secondary effects (soil amplification, liquefaction, slope failure). The knowledge of areas with aggregated occurrence of causal ("negative") factors influencing earthquake shock and, thus, the damage intensity, can be integrated into disaster preparedness and mitigation measurements. By combining morphometric analysis (from ASTER- and SRTD-DEM data) and visual interpretation based on Landsat 8 satellite data and derived images as Water Index (NDWI)-images, areas with relatively higher soil moisture and recently deposited sediments were identified that are generally more susceptible to soil amplification and liquefaction. The resulting maps of weighted overlay procedures, aggregating causal, morphometric factors influencing the susceptibility to ground motion, allowed to distinguish areas with higher, medium and lower susceptibility. Sentinel radar data provide information of the structural pattern, especially the detection of larger fault zones. Thus, the GIS and remote sensing tools contribute to an overview of sites at relatively higher damage risk and the recognition infrastructure prone to earthquake hazard.

IAG (Geodesy)

G07a - G07 Geohazards Monitoring

IUGG-2543

Real-time Earthquake Magnitude Estimation by the GEONET real-time analysis system: REGARD

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Geospatial Information Authority of Japan (GSI) and Tohoku University have jointly developed a real-time analysis system in the Japan's national GNSS network, GEONET: the Real-time GEONET Analysis system for Rapid Deformation monitoring (REGARD). The goal is to estimate the magnitude and finite fault models for large earthquake in real-time. The obtained magnitude is free from the saturation problem, thus it constrains the size of a subsequent tsunami and potentially improves the tsunami warning system that rely only on the seismic data. Currently REGARD involves about 1300 GNSS stations, RAPiD algorithm (Ohta et al., 2012) for automatic event detections, and two real-time fault modeling routines: a single rectangular fault modeling routine and a slip distribution fault modeling routine.

We evaluate the two fault modeling procedures for the 2003 Tokachi-oki earthquake, the 2011 Tohoku earthquake and the 1707 Hoei type Nankai trough earthquake in the real-time situations. The real-time waveform data for the Nankai trough earthquake are based on the simulation (Todoriki et al., 2013). Both routines gave magnitudes with high variance reduction over 90% for the 2003 Tokachi-oki earthquake and the 2011 Tohoku earthquake within 3 minutes. Moreover, the slip distribution model provided reasonable magnitude for the simulated Nankai trough earthquake, which was based on heterogeneous dynamic fault rupture.

IAG (Geodesy)

G07a - G07 Geohazards Monitoring

IUGG-2929

Seismology-based identification of dam-forming landquake events

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Floods resulting from the bursting of dams formed by landquake events can lead to serious bank erosion and inundation of populated areas near rivers. Seismic waves can be generated by landquake events which can be described as time-dependent forces (loading/unloading cycles) acting on the Earth. In this study, we conduct inversions of long-period (LP, period ≥ 20 s) waveforms for different source mechanisms (e.g., single force, double-couple faulting, isotropic, and general moment tensor). Results show that the single-force mechanism better explains the observed seismograms generated by landquake events. We then perform inversions for the landquake force histories (LFHs) of six dam-forming landquake events (DFLEs) in the world, which provides quantitative characterization of the initiation, propagation and termination stages of the slope failures. The LFHs are parameterized in the time domain as a sequence of 50%-overlapping isosceles triangles with a half-width appropriate for resolving the complexities seen in the observed seismograms. When the results obtained from LP waveforms are analyzed together with short-period (SP, 1-3 Hz) seismic signals, we find a relatively strong late-arriving seismic phase (dubbed Dam-forming phase or D-phase) recorded clearly in the SP waveforms at the closest stations, which potentially marks the time when the collapsed masses sliding into rivers. Consequently, our approach to analyzing the LP and SP waveforms developed in this study has a high potential for identifying DFLEs in near real-time using broadband seismic records, which can provide timely warnings to residents downstream of the impending floods.

IAG (Geodesy)

G07a - G07 Geohazards Monitoring

IUGG-5280

Assessment of the consistency of GPS and strong-motion records of the Mw9.0 Tohoku-Oki 2011 earthquake

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GPS networks are mainly used for supplementing seismic data for the Earth surface motions focusing on earthquake characterisation and rupture modelling. However the potential of processing of 1Hz GPS records using Precise Point Positioning (PPP) mode can provide real-time or near real-time information of seismic wave propagation and seismic rupture. Most studies have shown differences between the two systems at very long periods (e.g. >100sec) and static displacements. The aim of the current study is the assessment of the consistency of the displacement time-series derived by GPS and strong-motion records for relative short-period (<50sec). For this purpose, the records of the dense GPS (GEONET) and the strong-motion (KiK-net and K-NET) networks in Japan were analysed for the case of the Mw9.0 Tohoku 2011 earthquake.

The comparison of the displacement waveforms of the very closed spaced (distance<100m) GPS and strong-motion sites showed that the two datasets are generally consistent at relative short-periods (<50sec). However, it is shown that the consistency of the records is depended on the period band, due to the GPS noise at the relative low-period (<3-4sec) and the mis-recording of the strong-motion sensor due to the potential rotation and saturation of the sensor for the relative long-period (40-80sec). Furthermore the consistency seems to be depended on the direction of the excitation signal and the distance from the epicentre.

IAG (Geodesy)

G07a - G07 Geohazards Monitoring

IUGG-5724

Imaging geodesy: monitoring centimetric ground displacements using slant-range TerraSAR-X measurements

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SAR imagery and GNSS data are widely used in order to monitoring deformation phenomena impacting the Earth surface (e.g. landslides, subsidence, volcano deformations and glacier motions) and infrastructures (e.g. buildings, dams, bridges). In particular, Differential SAR Interferometry (DInSAR) is a well-known technique that allows the production of spatially dense displacement maps with centimeter to millimeter accuracy. However, it is based on SAR phase information and it may suffer for lack of coherence among the considered images. Nowadays SAR sensors achieve positioning accuracies in a global reference frame in the meter range and even better, thanks to the higher amplitude resolution (up to 0.20 m pixel resolution using Staring SpotLight mode of TerraSAR-X and PAZ) and to the use of on board dual frequency GPS receivers, which allows to determine the satellite orbit with an accuracy at few centimetres level.

The goal of this work is to exploit the SAR slant-range measurements reaching centimeter accuracies using only the amplitude information of TerraSAR-X imagery. The methodology proposed is devoted to evaluate the positioning accuracy of a stable natural and man-made Persistent Scatterers (PS's) (e.g. corner reflectors) along the SAR line of sight. For the experiment, the troposphere signal propagation delay has been corrected using GNSS permanent station data and the known geophysical effects inducing periodic and secular ground displacements has been considered. The preliminary results shown that it is possible to achieve a slant-range measurements accuracy with a bias of 10 cm and a standard deviation of 4 cm.

IAG (Geodesy)

G07b - G07 Geohazards Monitoring

IUGG-0191

On the performance of terrestrial laser scanner for natural hazard assessment in Indonesia

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This study focuses on the performance of the Terrestrial Laser Scanner (TLS) surveys for natural hazard assessment related to volcanic eruption, landslide and land subsidence in several locations in Indonesia. In this cases, TLS surveys are useful for several risk mapping and assessment purposes, e.g. deformation monitoring and analysis, potential hazard evaluation and analysis, and for updating the related hazard maps. The study areas for this research are: Galunggung, Papandayan and Tangkuban Perahu volcanoes; landslide prone area of Ciloto in West Java; and the coastal area of Jakarta which is undergoing significant land subsidence. TLS observation environment in the study areas has usually unique and dynamic environment, either related to geomorphology, land cover, surface activity, or local atmospheric variation, which in turn will affect the quality of TLS data and results. This research investigates the quantitative relation between those observation environment variables with the obtained quality of TLS point cloud and the derived digital elevation model and related information. This paper will present and analyze the obtained results. Potential prospects and limitation of TLS for natural hazard assessment in tropical region as Indonesia are also discussed.

IAG (Geodesy)

G07b - G07 Geohazards Monitoring

IUGG-0869

Signatures of droughts and floods in soil moisture and GRACE Data in the La Plata Basin in South America

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Surface-soil moisture is specifically sensitive to changes in precipitation patterns. During droughts and floods extremes in surface-soil moisture can propagate into extremes in total water storage with major impacts on agricultural production and water supply. This study relates soil moisture data from the satellite sensors AMSR-E and ASCAT and the hydrological model WGHM to water storage changes from the satellite gravity mission GRACE. The analysis focuses on extreme weather events in the La Plata Basin in South America. Information on natural disasters, which have been highly destructive in this region, is taken from the International Disaster Database EM-DAT. For the comparison of different parameters, as a first step all data sets are harmonized by conversion into spherical harmonics and filtering. Afterwards the data sets are analyzed via correlation and time shift analysis, and PCA. Results show that most of the strong variations in soil moisture and total water storage can be linked to El Niño and La Niña. Furthermore individual droughts and floods can be identified in the anomalies of soil moisture. For two major extreme periods, the La Plata drought 2008/2009 and the El Niño flooding period 2009/2010, soil moisture serves as indicator for upcoming lack in total water storage. The results also indicate that in the north-western part of the basin several hundred thousand people were affected, although highest hydrological anomalies were observed over the south-eastern part of the basin.

IAG (Geodesy)

G07b - G07 Geohazards Monitoring

IUGG-2297

Regional Crustal Stability Assessment Using Geodetic Observing System

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The crustal stability is one of the important characteristics for evaluating the natural geological environment where the human live and construct. The crustal stability can be evaluated by combining geodetic observations with geophysical and geological data based on the geological structure. An integrative method of the regional crustal stability assessment is proposed by using the data from geodetic observing system and the data from seismic and geological activities. The crustal deformation and gravity temporal variation in the Bohai area of north China are acquired by using the leveling observations during 1977-1998, GNSS data during 1999-2013, and GRACE data during 2002-2013. Main influences of crustal deformation, active faults, earthquake distribution for crustal stability are analyzed. The regional crustal stability is evaluated and the stability change is investigated in the Bohai area.

IAG (Geodesy)

G07b - G07 Geohazards Monitoring

IUGG-4764

An on-demand web tool for automated Earth's surface displacement time series generation from spaceborne DInSAR data

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Differential Synthetic Aperture Radar Interferometry (DInSAR) is, nowadays, a well-established remote sensing technique aimed at detecting and monitoring Earth surface displacement, since it allows generating accurate spatially dense deformation maps and time series. The success of DInSAR is strongly related to the big availability of SAR data which have been acquired during the last 20 years. This already huge amount of data will further increase with the Copernicus Sentinel-1 SAR mission, whose first satellite was launched on April 2014. Sentinel-1 was specifically designed for Earth monitoring; indeed, it operates on a continuous way with a global coverage strategy.

In this context, the availability of automated algorithms and tools suitable to effectively exploit and analyse the existing and future huge SAR data archives, is becoming more and more crucial for the scientific community. In this sense, the European Space Agency (ESA) is creating the Thematic Exploitation Platforms (TEP) whose main goal is to put together data, tools and processing facilities to foster the scientific exploitation of satellite data.

In this work, we show the integration of the efficient parallel solution of the well-known Small BAseline Subset (SBAS) DInSAR algorithm within the G-POD (Grid Processing On Demand) environment, that is part of the ESA Geohazard-TEP. The aim of this activity is to create a free operational web service addressed to users that are not expert in DInSAR processing, which allows them to generate and analyse DInSAR displacement time series in unsupervised way. Experimental results achieved in Geohazards contexts will be presented. Moreover, the strength that such kind of service may have in the creation of new research scenarios, will be thoroughly discussed.

IAG (Geodesy)

G07b - G07 Geohazards Monitoring

IUGG-5222

Motus inter corpora relativus tantum est: a guide on the analysis and interpretation of InSAR time series data

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Interferometric SAR time series data are becoming easily accessible to larger groups of end users. They typically have a diverse background, shifting from scientists in the geophysical domains towards asset managers, construction engineers, public officials, or private parties. Yet, the time series InSAR data, particularly the estimated kinematic parameters, are hard to interpret unambiguously. The first problems to encounter include the effective representation and visualization of the spatio-temporal datasets. In Stevens' taxonomy, InSAR data are of the interval-type, but are often misinterpreted as ratio-type. This relates to the double-difference nature of the estimators, which are essentially datum-free: their normal equation matrices are datum-free or singular. Here we present an interpretation statement, or guide, named Motus inter corpora relativus tantum est, in the words of Christiaan Huygens (1652), claiming that movement between bodies is always and in all aspects relative. Apart from interpretation concerning the relativity of the data, the guide discusses how 'scatterers' should be interpreted, how well their 3D position can be estimated, and how this relates to the idealization accuracy. The quality of the data is explained in terms of precision and reliability, and the application of statistical testing to provide an optimal model formulation.

IAG (Geodesy)

G07b - G07 Geohazards Monitoring

IUGG-5283

Velocity field of Cocos, Caribbean, Panama and Nazca plates in southern Central America

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Costa Rica is a very small country that has territory on three tectonic plates: Cocos, Caribbean and Panama; furthermore, the Nazca plate is adjacent to the southernmost part of the country. These four plates interact along 5 plate boundaries that pose a persistent seismic hazard for the country: three subduction zones and two transform fault zones. Large magnitude earthquakes have occurred on one of the transform boundaries and on the three subduction boundaries, with recurrence times of several decades. The other transform boundary (across central Costa Rica) has produced moderate size earthquakes up to Mw 6-7 that have caused extensive damage due to their shallow source and proximity to large population centers.

Knowing the relative plate velocities across these boundaries, together with how the slip heterogeneity distributes on the fault surfaces, are extremely important to assess the seismic potential; such information is not available for some of these plate boundaries. We are using a dense CGPS network in Costa Rica, including a site on the Cocos Island (the only emerged portion of the Cocos plate) plus sites in Panama and on the San Andreas Island (Colombia) in the Caribbean Sea, to construct a regional velocity field to constrain details on the slip partitioning along all these plate boundaries, as well as to search for plate rotations. We include data from older campaign GPS surveys as well. Some stations show evidence for transient motion, and for coseismic and postseismic deformation resulting from large earthquakes. We will present results of this analysis and preliminary interpretations based on the GPS velocities and earthquake history.

IAG (Geodesy)

G07c - G07 Geohazards Monitoring

IUGG-0410

Multi-scale and temporal-stage integrated survey technology for site displacement and deformation monitoring in Geotechnical Engineering

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Engineering monitoring is essential in evaluating the site deformation characteristics and safety of a structure. In geotechnical engineering, the structure deformation mechanisms due to the interactions among different objects, such as the 3D deformation of a shield tunnel caused by neighboring structures and the tunnel lining anomalies induced by adjacent slope instabilities, are rather complex. Using multi-scale and temporal-stage surveying data from different sites provides a way to examine these interactive mechanisms. It is thus important to develop a methodology which could integrate multi-scale and temporal-stage survey data from different sites in a unified reference.
Based on three different ways of choosing fixed reference points, namely the macro-, meso- and micro-scale, we propose a multi-scale and temporal-stage integrated survey technology in this paper, and develop a novel process for site deformation monitoring. Numerical simulation experiments using physical models demonstrate the applicability of our new integrated monitoring technique by analyzing the accuracy of the single timing parameters and temporal parameters of deformations and displacements. The results show that the absolute displacements are affected by cross-scale error accumulations, and thus have lower monitoring ability, whereas the relative deformations not affected by these, and thus have better monitoring ability. In addition, complete full-scale covariance matrices have to be evaluated after the accomplishment of each scale and temporal adjustment in order to ensure that the subsequent deformation analysis is correct.

IAG (Geodesy)

G07c - G07 Geohazards Monitoring

IUGG-2347

A multi-parameter monitoring system of a large French landslide: data, results and future perspectives

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Landslides are one of the major natural threats to human lives, settlements and infrastructure, causing enormous human suffering and property losses. Understanding the mechanisms influencing landslide dynamics is limited by the lack of dense and multi-parameter data. Nowadays landslide monitoring systems are more diffused and offer a temporary strategy to ensure public safety prior to definitive remediation or vulnerability-reducing works. They also provide accurate observation data enabling to improve the expertise and decision making.

Since 2009, INERIS has been running a multi-parameter observations system placed along the West border of the very active zone of Séchilienne rockslide, where large cracks regularly open. This near real-time system is based on an integrated technological platform and combines in-depth microseismic, hydrogeological and geotechnical monitoring as well as meteorological and three-dimensional surface displacement measurements. The main time series obtained from this system includes the microseismic activity per day, the cumulative displacement and the daily rainfall. All these data are made available through INERIS cloud monitoring platform "e-cenaris" created.

Indeed rainfall is one of the triggering factors of this landslide, but it is difficult to look for a relation between hydrology and kinematics in such complex geological conditions. The correlations between microseismic surges, acceleration phenomena of the surface and intense rainfalls have been visually and statistically analysed. However, it is not clear whether to define accurate qualitative similarities between such variables. Other studies are ongoing; in spite of data gaps and short-term monitoring, which complicate the study of this unstable slope.

IAG (Geodesy)

G07c - G07 Geohazards Monitoring

IUGG-2424

3D analytical and numerical modeling of the surface displacement, strain and gravity changes in the vicinity of magmatic bodies.

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Thermo-elastic strains and stresses play a considerable role in the stress state of the lithosphere and its dynamics, especially at pronounced positive geothermal anomalies. Theoretical formulae for the calculation of the thermoelastic and viscothermoelastic deformation field due to the magmatic bodies embedded in an elastic and viscoelastic halfspace. The formulae for the gravity anomaly due to the non-uniform extension connected with thermoelastic deformation is derived as well. In the paper we describe two methods for including the topographic effects in the thermo-viscoelastic model, too. First we use an approximate methodology which assumes that the main effect of the topography is due to distance from the source to the free surface and permits to have an analytical solution very attractive for solving the inverse problem. A numerical solution using Finite Element Method (FEM) is also computed. The comparison of the result. The results show that for the volcanic areas with an important relief the perturbation of the thermo-viscoelastic solution (deformation and total gravity anomaly) due to the topography can be quite significant.s obtained using both, analytical and numerical techniques, shows the qualitative agreement of the vertical displacements.

IAG (Geodesy)

G07c - G07 Geohazards Monitoring

IUGG-3158

Mitigation of atmospheric effects for monitoring dangerous alpine glaciers using ground-based radar interferometry

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Glacier break-offs can cause avalanches migrating far down into inhabited valleys. They are a critical geohazard in mountainous areas and need to be monitored. Terrestrial radar interferometry seems to be particularly suitable for this task because microwave signals penetrate fog and clouds over distances of several km, measurements can be made virtually continuously, and the wavelength facilitates sub-mm resolution. However, separating actual from atmospherically induced apparent displacements can be very challenging.

Previous work has addressed this problem primarily in terms of physically motivated models imposing severe regularity constraints on geometry and atmospheric dynamics. The design of methods enabling real time monitoring of complex terrain with turbulent atmosphere is a largely untouched subject. We present a data driven approach based on geostatistics to fill this gap.

In particular, we use stochastically motivated interpolation to predict atmospheric phase delays using stable areas. For validation, we employ radar data obtained every 2 minutes over 3 months from a monitoring campaign in the Swiss Alps. The data cover an area of 13 km^2 wherein stable rocks surround a fast moving ice tongue observed from a distance of 6 km. We compare our results to those obtained using high-pass filtering, parabolic surface fitting and other methods commonly referenced in the literature.

First results indicate that stacking of about 12 hours is needed to sufficiently mitigate the atmospheric variations whereas only 2 hours are needed with our current method. Further reduction of the required time span – and thus real-time capability – is envisaged through improved modelling of the spatio-temporal characteristics of the atmospheric signal.

IAG (Geodesy)

G07c - G07 Geohazards Monitoring

IUGG-4378

Pit mine slope stability monitoring by high resolution tiltmeters

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Mining is one of the basis of industrial development. Depending on local geology, there is high potential for hazard related to slopes sliding, ground surface collapse into caverns/voids, origin of fractures, or rock-bursts. As time is fundamental parameter in the development of hazardous geomechanical processes, monitoring techniques became crucial for hazard control.

We applied geophysical and geodetic methods in both deep and open-pit mines, mainly the coal ones that are often subject to significant or catastrophic deformation. In particular we introduced high resolution inclinometry aimed at the control of stability of an open-pit coal mine steep slope with a historical castle built on it.

We installed two tiltmeter stations in a horizontal gallery excavated through sediments and crystalline basement forming steep slopes of the mine. Two couples of high resolution ASNS horizontal pendulums with 10^{-4} arc sec resolution were setup 140 m and 400 m deep into gallery. Two-component tilts are used to prepare a vector graph showing azimuth and velocity change. Based on long-term data, during 2010-2013 we recognized a special tilt cycle usually happening in winter with a sharp change of tilt azimuth and increased velocity. This cycle was accompanied by significant rock-slides down to mine at nearby slope. Respecting time correlation we could say that this anomalous tilt had actually predictive character. In 2014-2015 the event changed its character to less impressive slow-down without clear trend, which reflects mine development with back re-deposition of overburden material and progress of mining front.

Tiltmeter stations proved efficient in monitoring slope stability in highly active geological environment and continue to act as substantial part of mine monitoring system.

IAG (Geodesy)

G07c - G07 Geohazards Monitoring

IUGG-4429

Subsidence and shallow faulting hazards in central Mexican metropolitans

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Land subsidence in metropolitan areas due to intense groundwater extraction is a major human-induced geological hazard that affects buildings and urban infrastructure and results in severe economical consequences for both individuals and local government administrations. In Mexico City, which is the second largest metropolitan in the world, subsidence rates exceed 370 mm/yr resulting in continuous structural damage to houses and infrastructure. Other cities in central Mexico have been subjected to subsidence since the '80, as a result of their large urban expansion, population increase and aggressive groundwater extraction rates. The continuous subsidence results in severe damage to urban infrastructure and civil structures.

Using InSAR and GPS observations, we have monitored land subsidence in 17 cities in central Mexico, including Mexico City, Morelia, Aguascalientes, Celaya and other cities. The combination of high temporal-resolution continuous GPS observations and high spatial-resolution InSAR observations allow us to evaluate hazard development through time, as well as identify localized areas with high subsidence gradients and shallow faulting. Cartographic products based on these techniques have been merged with other population, hydrology and meteorology data sets. This approach allows a better hazard assessment and provides information for other purposes, such as vulnerability for shallow faulting, land use zonation, and other decision support elements that are useful for water resource management agencies.

IAG (Geodesy)

G07p - G07 Geohazards Monitoring

G07p-354

Determining vertical displacements along the Tuzla Fault (Izmir-Turkey) by precise levelling technique

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The intense seismic activity around the Aegean Sea and its region, including large parts of Greece and Western Anatolia, has been the most significant geodynamic phenomenon in the Eastern Mediterranean region in the past century. The study area, Izmir, is situated between 26’ 15^0 –28’ 20^0 E longitude and 37’ 45^0 –39’ 15^0 N latitude in the Aegean region of Western Anatolia, which is the third largest city with a population of 4 million in Turkey. The Tuzla Fault is about 42-km long on the ground, that passes through Izmir Bay in the north and Kusadasi Bay in the south with a NE-SW lineament trending. The focus of the study is to determine the vertical displacement by precise levelling technique on the Tuzla Fault and its vicinity. A levelling route with eight benchmarks along the fault line was established. Between 2009 and 2012 six precise levelling campaigns were performed. The collected data were processed by using global testing and least squares adjusment method to evaluate the displacement in vertical. The results of this study specified that vertical displacements are not significant as were expected for this period. Besides this study is differentiated from the previous studies due to the techniques applied for the first time in the study area.

IAG (Geodesy)

G07p - G07 Geohazards Monitoring

G07p-355

Analysis of land displacements an urbanized area in Curitiba, Brazil

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The environment we live in is a system that undergoes constant changes in terms of natural phenomena and human intervention. Recently the Paraná State suffered with these elements. According to the Municipal Coordination of Civil Defense of Paraná (COMDEC) in the city of Morretes, in March 2011, was decreed emergency state because there were 2.450 houses damaged, 85 homes destroyed and total of 15.178 people were affected. In Brazil 80% of the 10 greatest natural disasters are related to flooding and landslides. Besides focusing on natural disaster prevention investments should be high on the issue of pre- disaster management. Thus, it is possible to ensure timely removal of the population at risk areas leased time. In Brazil, there are not studies related to this subject. This fact indicates that research is relevant and which will contribute to the development of the monitoring and alerts scenario of natural disasters, specifically in detecting of land displacements. Given the foregoing, is being deployed a network of GPS monitoring in an urbanized area in Curitiba, Brazil. This network consists in two networks: one outside of the unstable area and another inside of the unstable area. In the first network GPS data will be collected, however, in the second, GPS surveys, geodetic measurements with terrestrial techniques are being made.

IAG (Geodesy)

G07p - G07 Geohazards Monitoring

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A new algorithmic method to identify ground strike points from individual return stroke data provided by Lightning Location Systems

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A new algorithm, provisionally named groupGCP, developed aiming at grouping individual return strokes detected by Lightning Location Systems (LLS) into ground strike points (GCP), is presented. The criteria for grouping decision and determination of centroid (ground strike point) positions are based on the k-means clustering method. However, the exact metric to be considered for both criteria can be chosen by the user, allowing the use of error ellipse scaling equations instead of Euclidean distances when location error information is available. The algorithm was created in such a way that it is capable of determining the number of strike points (k value) numerically according to a maximum distance also defined by the user which, in turn, depends on the location accuracy of the LLS. Maps of the number of GCPs per flash can be generated from long-term databases of lightning occurrence, allowing not only its use for scientific studies but also for applications in hazard mitigation and lightning protection techniques. Some examples are presented and discussed.

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Application of terrestrial laser scanning for fluvial transport monitoring in riverbed: Case study Lomniczka River, Karkonosze Mts.

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The fluvial transport is the main surface process responsible for the contemporary dynamic change of the relief in the Sudetes Mts. (Poland). The knowledge of this process is usually gathered by the hydrological measurements what gives a good understanding of the river flow, however, the information of the bedload movement in the rivers is still insufficient. Particularly, this applies to the largest clasts persisting in the riverbeds, i.e. boulders over 256 mm. The question therefore arises, to what extent this fraction is a mobile component of the bottom of the mountain streambeds.
The answer to that question is presented in this work as the case study Lomniczka River (Sudetes Mts.). The investigation was carried out by monitoring 30 m long steep section of the river using terrestrial laser scanning (TLS). TLS was performed annually using Leica ScanStation C10 scanner in the period 2011-2014. In order to eliminate the systematic errors and assure the best accuracy of the data, all four measurement campaigns were carried out with the same geometrical conditions.
High accuracy of the data was proven by the small RMSE of the simultaneous georeferencing and point cloud registration, and achieved 2-6 mm depending on the campaign. Dense point clouds were compared to each other using the Iterative Closest Point (ICP) algorithm to produce high resolution Digital Elevation Models (DEMs), and finally to detect displaced stones. The highest dynamic of the fluvial process resulting in the boulder displacement up to 2.3 m was observed between years 2012-2013. Obtained differential DEMs shown the alternating zones of erosion and deposition of the finer fractions of sediment in the local sedimentary traps. TLS confirmed its potential to monitor the fluvial transport in the riverbed.

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Quality assessment of airborne laser scanning data for landslide study in forested areas

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LiDAR technology has become recently a standard tool used for detection, mapping and monitoring of landslide areas, especially in forested or difficult to access regions. The activity of landslides can be monitored by employing the multi-temporal Airborne Laser Scanning (ALS). This requires data collection at a certain time according to the landslide activity what does not always match the optimal period for performing the scanning. The intense vegetation has the significant impact on the quality of point clouds and subsequent products used in landslide studies.
This work assesses the quality of ALS data collected for landslide studies. The investigation was carried out for the study area of about 40 km^2 located at the edge of Roznow Lake (Poland). The scanning was performed two times: first on the beginning of April, and then in July 2010; both times using the same Riegl LiteMapper laser scanning system operating with the same parameters. ALS data accuracy was estimated by comparing it with the reference data collected directly in the field using GNSS technology.
Results obtained for two data sets showed significant quality decrease for the period of intense vegetation; for example, in forested areas the vertical accuracy of ALS data has changed from 0.19 m in April to 0.74 m in July. Moreover, the density of terrain points significantly decreased (up to 30%) in the latter period. This caused that the scanning performed in July was not fully valuable in determining the amount of displaced landslide material. Beside the quality assessment of the ALS data, this work also discusses the accuracy of estimated volume of the relocated landslide material.

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The PS-InSAR Time Series Analysis Application in Land Subsidence Monitoring

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Abstract: *Interferometry synthetic aperture radar (InSAR) has the characteristics of wide coverage, high spatial resolution, without interference of clouds etc., and has been widely used in large areas of ground subsidence monitoring. This paper studied the PS-InSAR time series analysis method, and get the analysis results with 1mm accuracy of time series of urban ground subsidence respectively by the Permanent Scatters (PS) method and short baseline set (SBAS) method, proving that the two methods have good consistency in subsidence monitoring, Then we compared and analied the key technology of the two data process methods. In the last part of this paper, we compared and cross verified the surface subsidence results obtained by InSAR and GNSS/precise leveling finally.*

Key words: *ground subsidence; PS-InSAR; time series linear*

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Continuous kinematic GPS monitoring of a glacier lake outburst flood

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Natural glacier events such as ice avalanches, debris flows or glacier lake outburst floods (GLOF) may have hazardous impacts on the downstream area of the glacier and can cause severe destruction. In Kyrgyzstan, the Inylchek Glacier is the second-largest glacier in the world. In spring, a glacier-dammed lake is formed (Lake Merzbacher) by melt-water which drains suddenly at least once a year within a few days causing a destructive flood. To understand the mechanism of the GLOF, it is essential to study the kinematic behavior of the lake's ice-dam before, during and after the outburst.

GFZ and CAIAG jointly operate a GPS monitoring network with a base station and a station located directly on the moving glacier adjacent to the ice-dam providing continuous 1Hz GPS data. The GPS data is processed with GAMIT/Track and daily horizontal and vertical positions are estimated. During higher glacier dynamics when the station suddenly moves, shorter time slices are processed.

Irrespective of the general motion of the ice-dam during the year, the GPS time series show a significant change in the ice-dam's behavior shortly prior and after the GLOF. Especially the vertical position increases before the GLOF and decreases rapidly of almost 20m within three days after the GLOF. Additionally, the surface velocities are 3-5 times higher shortly before and up to 16 times higher during the GLOF. These results show a significant change in the movement of the ice dam and can be used to develop a early warning system for the glacier-dammed lake outburst flood.

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The effect of instrumental precision on optimisation of displacement monitoring networks

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In order to detect the geo-hazards in the Earth, different deformation monitoring networks are usually being established. It is of importance to design an optimal network to fulfil the network quality criteria and obtain a precise and reliable monitoring network. Generally, the same observation plan during the different time intervals (epochs of observation) is considered. Here, we investigate the case that instrumental improvements in sense of precision are used from first to second monitoring epochs. As a case study, we perform the optimisation procedure on a GPS monitoring network around Lilla Edet village in the southwest of Sweden. The network was designed for studying possible displacements caused by landslides. By increasing the observation time it is possible to obtain higher observation precision, and in this study it is assumed that the observation time is longer in the second observation epoch. Then the numerical results show that the optimisation procedure yields an observation plan with significantly fewer measurements in the latter epoch, which leads to saving time and cost in the project.

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Land subsidence detected by persistent scatterer InSAR at Nakagawa lowland in the central part of the Kanto Plain, Japan

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The Nakagawa lowland is located in the central part of the Kanto Plain, which is the largest plain in Japan. In the 1960's, serious land subsidence exceeding 100 mm/year occurred due to over pumping of shallow and deep groundwater in this area. Now, because of pumping regulations by the national and local government, the amount of the land subsidence in this area is decreasing sharply. However, in the Nakagawa lowland, there are still areas where subsidence is exceeding 10 mm/year, and the amount of land subsidence increases in dry years since the amount of groundwater use increases. Therefore, in this study, we examined local characteristics of the land subsidence through interferometric analysis of the persistent scatterer InSAR using ALOS PALSAR data for April 2006 to April 2011. The results show that subsidence areas are concentrated in meandering zones where the subsidence (average displacement rate) exceeds 10 mm/year; this is generally consistent with the results of direct leveling. The meandering subsidence zones are believed to be caused by a geological structure buried under the alluvial plain and groundwater pumping that targets a specific aquifer. On the other hand, we detected a patchy zone (approximately 0.3 km^2) in the study area where the subsidence (average displacement rate) exceeds 15 mm/year. We believe that this zone was formed from consolidation settlement on soft ground due to the residential landfill.

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Groundwater budgeting over deserted area by GRACE, case study at Arabic Peninsular

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Since 1980 the freshwater consumption in Saudi Arabia has led to significant groundwater level depression. The annual water consumption for Agriculture, Public water supply and industry e.g. in 2009 amounts to 19 km^3, where the water source in desert areas mainly depends on fossil groundwater. Total water storage (TWS) estimates groundwater storage changes because surface water and soil moisture anomalies are negligible, due to high evapotranspiration. GRACE models - as a proven tool for TWS - were compared with monitored pumping field measurements but can not show the full groundwater extraction ratio. This study takes into account the geological activities, leakage of internal/external signal, omission error in order to reduce the misclosure.

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Coseismic slip model of the 2014 Kangding seismic sequence from PALSAR-2 interferometry data

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In this study, we use Interferometric Synthetic Aperture Radar to constrain the sources of the two largest events of the 2014 Kangding (Southwest China) seismic sequence, namely an Mw 5.9 event and an Mw 5.6 event that occurred 4 d later. The sequence took place in the Xianshuihe fault, one of the most active faults in southwestern China, located between the Eastern Himalayan syntaxis and the South China. Coseismic deformation estimated from conventional stripmap and ScanSAR PALSAR-2 data collected by the new launched ALOS-2 satellite were used to derive elastic dislocation models for the sources of the two main events. Our best model shows that the first event produced the maximum slip of 0.47 m at the depth of ~9 km and there was no distinct slip on the fault plane of the second event. The estimated geodetic moment is far less than the accumulated energy since the 1955 earthquake, indicating that the seismic hazard possibility on the Kangding segment is still high.

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Atmospheric precipitable water in Somma-Vesuvius area during extreme weather from groundbased CGPS measurements

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The extensive use of permanent GNSS stations, currently operating for geodetic purposes, offers a tool for a dense and reliable remote sensing of atmospheric water vapour (WV).

Here the tropospheric delay observed on some continuous CDGPS (Continuous Differential Global Positioning System) stations of the NeVoCGPS network (managed by Istituto Nazionale di Geofisica e Vulcanologia for volcanic monitoring) is analyzed and its time evolution during extreme weather conditions is discussed. We focus mainly on the study of the wet component of the atmospheric delay of the GPS signals and the computation of the precipitable water (PW) by using co-located GPS and meteorological stations. Four new stations have been installed the last September aimed at densifying the existing GNSS network in order to try a high-resolution modelling of the PW in the Somma Vesuvius area (Italy). Moreover the use of stations at different altitudes enables use to attempt a retrieval of PW vertical profile.

A number of scientific topics other than the obvious weather forecast and atmospheric general circulation models, can benefit from an improvement of our ability into mapping at local scale the WV content in the troposphere all around a prominent topographic area of interest, as could be an active volcano. Because of the peculiar topography of Mt. Vesuvius, the use of satellite geodetic techniques, for monitoring purposes, as the DInSAR, for instance, may significantly suffer from a poor knowledge of atmospheric heterogeneities.

The ultimate challenge of this study will be, through the time variable mapping of the PW, the evaluation of the feasibility of an early warning system for selected areas highly exposed to heavy precipitations.

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On the impact of rockfall catch fences on ground-based radar interferometry

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Rockfalls are among the major natural hazards in mountainous regions. Critical rockfalls need to be monitored for reliable risk assessment and adequate intervention. Ground-based radar interferometry is a relatively new technique used for hazard monitoring. It offers the potential of determining sub-mm- to mm-level displacements by remote measurements and under all weather conditions. To avoid damage from smaller rocks and debris critical surfaces are often covered by rockfall catch fences. These fences, like other artificial objects (e.g. barriers), may act as reflectors to the microwave radiation. Thus they may impair or invalidate the monitoring measurements.

We have carried out an investigation to identify which parameters of the fences and of the rock-fence-sensor geometry are (most) critical. An experiment was performed in a quarry. The well-defined and stable rock wall was monitored by means of Ground-Based Synthetic Aperture Radar. During the experiment selected parts of the rock wall were temporarily covered with different types of fences varying in shape, size and density of mesh and in various geometrical configurations.

We present results from the analysis of more than 10 distinct scenarios. We show that for surfaces observed through the fence the reflected power can be reduced by 30 dBm and the signal-to-noise ratio is significantly deteriorated. We also observed loss of coherence or interferometric phase shifts corresponding to displacements in excess of 2 mm. For parts of the rock wall not covered by the fences we show the strong impact of side lobes and mixed pixels resulting e.g. in 75% loss of coherence. The results are highly relevant for assessing or ensuring suitability of radar-based rockfall monitoring.

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Subsidence Monitoring Using InSAR and PSI Techniques: A Case Study of Port - Harcourt, Rivers State, Nigeria

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Abstract
Land subsidence is caused by natural and human activities in many countries all over the world. Excessive withdrawal of underground fluid particularly ground water is one of the most important factor of land subsidence formation that can cause extremely expensive damages to concrete buildings, roads, rail tracks, pipelines, well casing and can also cause flood. Nowadays the Interferometry Synthetic Aperture Radar (InSAR) ability to detect the surface deformation in millimeter exactness has been demonstrated in many countries of the world. This study used satellite InSAR technique and Persistent Scatterer Interferometry (PSI) method to measure ground motion over Port-Harcourt city from February 2007 to May 2009. This research was initiated as a pilot project to monitor ground deformation in Port-Harcourt city. The measurement points delivered are derived from an analysis of 18 descending pass from Synthetic Aperture Radar (SAR) images obtained from the processing of ENVISAT radar satellite data with the Stable Point Network (SPN) Interferonmetric software. The analysis of the result from the study area revealed that more than 52.83% of the Port-Harcourt city is undergoing low subsidence velocity of between -2.5 to -5mm/year, while 20.66% of the area is experiencing high subsidence velocity of values of more than -5mm/year. 26.36% indicates a stable ground of velocity values between -2.5 to 2.5 mm/year. 0.12% of the study area revealed a low uplift velocity of between 2.5 to 5mm/year and 0.02% of the area indicates a high uplift with a velocity value of more than 5mm/year. No points are obtained in heavily vegetated region or in areas in descending mode layover. This displacement values are given relatively to a reference point located in the city center.

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Continuous lava extrusion after the 2011 Shinmoe-dake eruption investigated by airborne and spaceborne InSAR

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Shinmoe-dake located to SW Japan erupted in January 2011 and lava accumulated in the crater. Miyagi et al. (2014) analyzed spaceborne SAR data after the last eruption and revealed that lava extrusion was continuing slowly in May 2013. To investigate recent lava extrusion, we applied InSAR analysis to airborne SAR (JAXA's Pi-SAR-L2) data. Observations were carried out from three flight paths on 13 Sep. 2013 and 7 Aug. 2014. DTM used in this analysis was generated by SBAS analysis using RADARSAT-2 data after the eruption. We restricted analyzing area to 1km×1km around the crater, and high coherence was obtained in this area. We assumed non-deformation component to be plane in this area, and corrected its component. Then we estimated 3-D deformation from results for three flight paths. Uplift exceeding 20cm was found, but horizontal component was less than 3cm in most area.

The increasing volume in this period was estimated to 10044m^3. The increasing volume during 13 Sep. 2013 and 16 Apr. 2014 was estimated to 7507-7704 m^3 from results of spaceborne SAR analysis, and then that during 16 Apr. 2014 and 13 Sep. 2013 was estimated to 2340-2537 m^3. Fitting exponential curve to lava extrusion rates estimated from spaceborne SAR, the increase volume in that period was estimated to 2339m^3, corresponding to result of airborne SAR analysis. Miyagi et al. (2014) suggested continuous and slow magma supply to shallow magma chamber based on decay time of lava extrusion rate and theory presented by Huppert et al. (2002). Result in this study suggests that such magma supply has decreased.

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Tenerife-2004 and El Hierro 2011-2014 geodynamic processes using local and regional GNSS networks

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The 2004 seismic and volcanic crisis in Tenerife Island was the reason for designing and implementing two different GNSS networks. And there also were two different objectives: to get a geodynamical model for the island, but also to make a Teide - Pico Viejo volcanic structure deformation analysis. This second micro network was also installed as a basic infrastructure to monitor the volcanic activity using GNSS methodology to evaluate the surface deformation parameter. Afterwards some different institutions as CSIC-UCA, IGN or GRAFCAN installed Continuous GNSS (CGNSS) stations to improve the deformation models.

In 2011 there was an eruptive process in the most western Canary Island known as El Hierro. A CGNSS network and some geodetic marks for episodic surveys were established in the island for geodetic monitoring. The combination of episodic and continuous surveys must be made carefully in order to get real deformation models. Results have to be homogeneous in spite of the different surveying lengths. Methodologies and models should be used in other blocks of the Macaronesia Region to get a more complete view of the area. This paper is related to the different length GNSS data files analysis and how the results were homogenized to improve the geodynamic models, trying to link them to the different processes in the region.

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Thermal and mechanical properties of the nucleus soil at the Philae landing site

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The MUltiPUrpose Sensors for Surface and Sub-Surface Science package on the ROSETTA lander PHILAE operated on the approach to and on the surface of 67P/Churyumov-Gerasimenko. The MUPUS package includes a thermal probe (MUPUS-PEN) equipped with temperature sensors to be inserted into the soil by a hammer mechanism, thermal sensors and accelerometers in the two anchors and an infrared radiometer (MUPUS-TM). MUPUS-PEN was stowed on the balcony of Philae and was nominally deployed using a dedicated deployment device. MUPUS-TM is mounted to the lander in a fixed position at the top of the balcony. MUPUS was designed to measure thermal and mechanical properties of the surface and sub-surface cometary matter such as thermal conductivity, diffusivity and strength and to monitor the subsurface temperature.
The MUPUS thermal probe did, unfortunately, not fully penetrate the near-surface layers of the comet nucleus. This implies a local mechanical strength of the soil of a few tens of MPa. The recording of the MUPUS infrared thermal mapper of suggests a local thermal inertia of 10-50 J m^{-2} $K^{-1}s^{-1/2}$*. The thermal conductivity derived from the thermal inertia is estimated to be* 10^{-2} $Wm^{-1}K^{-1}$ *consistent with a high porosity dust layer covering the surface. Temperature at the landing site was about 90K during night time increasing to about 130K during day time. Least square fitting of the measurements of the radiometer and of the PEN temperature sensors suggest an emissivity of 0.97.*

Members of the MUPUS team are: T. Spohn, J. Knollenberg, M. Grott, C. Hüttig, E. Kührt, I. Pelivan (DLR Berlin), M. Banaszkiewicz, , J.Grygorszuk, W.Marczewski (CBK, Warsaw), K. Kosssacki (U Warsaw), A. Hagermann, E. Kaufmann (OU Milton Keynes), G. Kargl, N. Kömle (ISC Graz), K. Seiferlin (U Bern)

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Geodetic monitoring of severe near-fault activity in southwestern Taiwan and its impact on Geohazard mitigation

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Interseismic fault creep has been known to reduce seismic hazards; however, rapid shallow interseismic creep will continuously damage major structures such as buildings, tunnels, and viaducts which pass through the creeping faults. In this study, extremely rapid shallow interseismic creeps were detected on the Lungchun and Chishan active faults within a 500 × 500 meter area in southwestern Taiwan by geodetic measurements from 3 continuous GPS stations, 16 campaign-mode GPS stations, 8 traverse lines, and 6 leveling routes between November 2011 and November 2014. According to the three dimensional velocity profile, a shortening rate of ~47 mm/yr and a left-lateral rate of ~6 mm/yr are represented across the Lungchun fault, while an extension rate of ~32 mm/yr, a right-lateral rate of ~11 mm/yr, and an uplift rate of ~80 mm/yr are shown across the Chishan fault. In the strain rate field derived from the horizontal velocities, a predominant contraction rate of -0.35 0.06 mstrain/yr and a sinistral shear rate of 0.39±0.05 mstrain/yr occur across the Lungchun fault, while a predominant extension rate of 0.350.07 mstrain/yr and a dextral shear rate of 0.45±0.07 mstrain/yr occur across the Chishan fault. The importance of this research lies on the fact that a major highway runs across the area with a viaduct and a tunnel which both have experienced rapid deformation. We created a dislocation model to predict the behavior of the two-fault system and the model suggests that the viaduct and tunnel will be severely damaged if they are not completely reconstructed in the near future.

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Signature on GNSS PWV estimates of relevant storms affecting Iberia in recent years

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PWV (Precipitable Water Vapour) estimates derived from GNSS (Global Navigation Satellite Systems) observations are nowadays used in many studies focused on atmospheric extreme events. The direct product that is obtained from the GNSS data is ZTD (Zenith Tropospheric Delays), which can be converted into the column of water vapour above the station knowing pressure and temperature. If a sufficient dense number of stations are available, the estimates obtained at discrete points can be interpolated in order to create 2D fields (PWV + time)

In this study, we present results obtained using PWV solutions from the available networks of GNSS stations in Portugal (~70) and Spain (~250). These networks are mainly managed by the National and Regional (Spain) Mapping Agencies providing data in near-real time, which are nowadays also being used for weather nowcasting applications.

We present and discuss the signature on the GNSS derived PWV Estimates for three extremes meteorological events that occurred in Portugal (and extended to Spain) recently: West Portugal (23 Dec 2009); Xynthia (27 Feb 2010); and Gong (19 Jan 2013). The available GNSS data have been processed using the GIPSY-OASIS software, which permits to compute a PWV estimate for each station every 5 minutes. We compare the obtained dynamic surfaces with similar ones obtained using other sensors (e.g., satellite images). In addition, we also validate our results by comparing the solutions for the storm periods with the ones obtained for normal periods.

This study has been conducted in the framework of the SMOG (PTDC/CTE-ATM/119922/2010) and NUVEM (EXPL/GEO-MET/0413/2013) projects, supported by the National Portuguese Science Foundation (FCT) and the GNSS4SWEC (ES1206) Cost Action funded by European Union.

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South Aegean geodynamic and tsunami monitoring platform project: Preliminary results

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The South Aegean is one of the most tectonically and seismically active areas in the world, thus constituting a Natural Laboratory. The South Aegean Geodynamic And Tsunami Monitoring Platform (SEISMO) project, a collaborative initiative undertaken by some of Greece's largest institutes, is an effort to establish a permanent multiparametric platform of networks that combine different (both terrestrial and space oriented) techniques, in order to monitor the tectonic and volcanic activity in the area and produce an on-line database available both to the scientific community and the public.
This platform includes continuous GNSS networks, tide-gauge sensors, accelerometers and seismographs. All data collected are archived and analysed using state of the art processing software.
Raw data and products will be available through a project dedicated portal. The multiparametric data and results gathered will be integrated and combined with the existing archive owned by the participating institutes to produce a thoroughgoing view of the underlying geophysical processes. Our goal is to provide permanent infrastructure and knowledge both to enlighten ambiguous scientific hypothesis and serve as a focal point for further scientific research.

IAG (Geodesy)

G08a - G08 Sea-Level Observation and Modelling

IUGG-0774

A reconciled sea level budget from satellite gravity and altimetry

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A reconciled global mean sea level (GMSL) budget is necessary to understanding the mechanisms underlying changes in GMSL. Two factors dominate variance in GMSL: the steric change (thermal expansion and salinity, measured by the Argo Project) and mass contribution (land water, land ice, covering polar ice sheets and glacier ice caps, measured by GRACE). Theoretically, the GMSL variance calculated from Argo and GRACE should match the altimetry observations. Some previous studies investigated this budget, however, few of them agree well. An amendatory global forward modeling method adopted in this work can improve this situation. In computation, for the altimetry result we take the mean values of the altimetry data from 2003 to 2013 from five processing groups. The steric contribution is estimated from three Argo processing groups and the mass contribution is from three GRACE models. Variations in GMSL shown by Argo and GRACE are closely consistent with altimetry observations. The 2010-2011 La Niña caused the sea level to drop at an amount of 5 mm and to recover in the following several years. This mechanism is understood with the reconciled GMSL budget. The influence of geocenter, mass inversed method and data smoothing techniques applied is also stressed.

IAG (Geodesy)

G08a - G08 Sea-Level Observation and Modelling

IUGG-1511

Upper limit for sea level projections by 2100

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With more than 150 million people living within 1 m of high tide future sea level rise is one of the most damaging aspects of warming climate. The latest Intergovernmental Panel on Climate Change report (AR5 IPCC) noted that a 0.5 m rise in mean sea level will result in a dramatic increase the frequency of high water extremes - by an order of magnitude, or more in some regions. Thus the flood threat to the rapidly growing urban populations and associated infrastructure in coastal areas are major concerns for society. Hence, impact assessment, risk management, adaptation strategy and long-term decision making in coastal areas depend on projections of mean sea level and crucially its low probability, high impact, upper range.

We construct the probability density function of global sea level at 2100, estimating that sea level rises larger than 180 cm are less than 5% probable. An upper limit for global sea level rise of 190 cm is assembled by summing the highest estimates of individual sea level rise components simulated by process based models with the RCP8.5 scenario. The agreement between the methods may suggest more confidence than is warranted since large uncertainties remain due to the lack of scenario-dependent projections from ice sheet dynamical models, particularly for mass loss from marine-based fast flowing outlet glaciers in Antarctica.

IAG (Geodesy)

G08a - G08 Sea-Level Observation and Modelling

IUGG-1904

Global and regional sea level budgets from GRACE and altimetry

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The partitioning of the sea level budget in contributions from ice-sheets and glaciers, water cycle, shallow- and deep steric expansion, and crustal uplift is still uncertain, especially on regional scales. Here, a global inverse method is employed to estimate the different contributors from Jason-1/2 altimetry and GRACE.

In our method, spatial fingerprints are computed a-priori for each contributing process, applying the sea level equation for mass fingerprints, and empirically for steric fingerprints from modelling and/or ARGO data. Temporal GRACE data and along-track Jason-1/ -2 altimetry is combined to estimate the evolution of these patterns, which allows the partitioning of altimetric sea level into individual sources. This method largely mitigates truncation and leakage problems associated with GRACE resolution, and it does not require external estimates for geocenter motion.

Over 2002-2014, we find a significant global mean steric trend, 1.6+/-0.09 mm/yr of total of 2.7+/-0.08 mm/yr, which hints at ocean warming >700m. This differs from some recent studies, and it may have implications for assessing Earth's energy balance. We find mass loss from Greenland, Antarctica and land glaciers contribute with 1.36+/-0.02 mm/yr, accelerating with a rate 0.04+/-0.01mm/yr^2, while land water storage increases. Regional budgets show a different picture: above average rise near Philippines (14.8 mm/yr) and in the Bay of Bengal (5.6 mm/yr) is 70-90% explained by steric expansion. Negative rates at the west coasts of Europe (-0.7mm/yr) and the US (-0.8 mm/yr) are explained by negative steric rates (down to -1.6 mm/yr), mostly compensated by positive mass rates.

For the Bay of Bengal, exemplarily, we validate our regional estimates using a range of independent models and data sets.

IAG (Geodesy)

G08a - G08 Sea-Level Observation and Modelling

IUGG-2964

Regional sea level change in the North Sea since 1900

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The regional yearly mean sea level of the North Sea is investigated for the period from 1900 until 2012. Variability in both time and space is analysed. The sea level is reconstructed following the approach by Church et al. (2004) where long time series from tide gauges are combined with the spatial distribution of the altimetry data using an EOF-analysis. The area of the North Sea is especially qualified for such an analysis as it has a relatively long and good coverage of tide gauge measurements. The analysis considers yearly means of 14 GIA corrected tide gauges, which are equally distributed over the region. The altimetry data originates from the Topex, Jason-1 and Jason-2 missions and is provided on a 0.5° grid.

The quality of the reconstruction is validated against the altimeter data. The patterns of the spatial variability are well reconstructed. The spatial correlation for the period 1993 to 2012 is in general very good (> 0.6) with lower values in the southwest and northwest. The linear trend of the time period 1993 to 2012 shows the same pattern as the altimetry data, but the trends are overestimated, especially in the German Bight and along the Danish coast. The spatial mean of the reconstruction is compared to earlier reconstructions of this area. The linear trend of the spatial mean for the period 1900 to 2012 is 1.2mm/yr which is a bit lower than the trend reconstructed from tide gauge data only. To study the influence of wind and atmospheric pressure variability on the reconstructed sea level trends surge hindcasts from 1948 to 2012 originating from the CoastDat data set are included in the analysis.

IAG (Geodesy)

G08a - G08 Sea-Level Observation and Modelling

IUGG-4980

Refining satellite era estimates of global mean sea level rise

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The satellite era time series of Global Mean Sea Level (GMSL) is a seminal climate data record that describes one of the most robust manifestations of climate change. Accurate estimates of the rate and acceleration of sea level rise are of major importance for evaluating model projections and for adaptation planning. Estimates of GMSL have indicated a decrease in the rate of sea-level rise during the past decade, relative to the preceding decade, with an average rate of rise over the total period (commencing in 1993) of +3.2±0.4 mm/yr. Here we present a refined methodology based on tide gauges and vertical land motion data for assessing systematic error (often termed bias drift) across the TOPEX-A, TOPEX-B, Jason-1 and OSTM/Jason-2 altimeter missions. In contrast to previous results, significant non-zero systematic drifts that are satellite-specific (most notably affecting the first 6 years of the GMSL record), are revealed. Two implications of these drifts are discussed. First, the GMSL rate (1993 to mid-2014) is reduced to between +2.6±0.4 mm/yr and +2.9±0.4 mm/yr, depending on the choice of land motion applied at the tide gauges. These rates are in closer agreement with the rate derived from the sum of the observed contributions, GMSL estimated from a comprehensive network of tide gauge (TG) data with GPS-based land movement applied, as well as reprocessed ERS-2/Envisat altimetry. Second, our corrected GMSL dataset indicates an acceleration in the rate of sea-level rise, independent of the vertical land movement used, that is comparable to the accelerated loss of ice from Greenland, the 20th Century acceleration and to recent projections.

IAG (Geodesy)

G08b - G08 Sea-Level Observation and Modelling

IUGG-0848

Quantifying water-level and land surface changes in coastal Bangladesh using Synthetic Aperture Radar (SAR) and SAR interferometry

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Bangladesh, located at the confluence of three large rivers – Ganges, Brahmaputra and Meghna, is a low-lying country. It is prone to monsoonal flooding, potentially aggravated by more frequent and intensified cyclones resulting from anthropogenic climate change. Sea-level rise, along with tectonic, sediment load and groundwater extraction induced land uplift/subsidence, have exacerbated Bangladesh's coastal vulnerability. Because of the flat topography of the floodplain, on average ~20% or more of the country is inundated annually by floods. However, the magnitude of and the projected sea-level rise relative to the land motion in coastal Bangladesh remain unknown. In the 1960s, Bangladesh constructed embankments or polders around much of the low-lying coastal regions to mitigate relative sea-level rise and flood risks. The subsidence rate of the polders due primarily to erosions tidally-driven sediment compaction and loading are arguably not known at the spatial and temporal scale needed to mitigate or adapt to the Bay of Bengal coastal vulnerability.
The dynamics of the Sundarbans Mangrove forest estuaries are notably different from other parts of the coastal regions. Limited coastal GNSS sites and tide gauges, as well as satellite radar altimetry measured geocentric sea-level rise, while are all critical data sets, lack the fine spatial scale needed to quantify relative sea-level rise at the regional level. We use the Permanent Scatterers InSAR techniques employing the ALOS PALSAR data, and the SAR backscatter coefficients inferred estuary wetland water level change measurements in the Sundarbans to measure land subsidence over example polders, and geocentric estuary sea-level change, respectively, towards quantifying relative sea-level rise in the study region.

IAG (Geodesy)

G08b - G08 Sea-Level Observation and Modelling

IUGG-2157

Reconstruction of sea level change in the South China Sea for the period 1950-2013

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The distribution of sea level in the South China Sea is reconstructed for the period 1950-2012 by using the empirical orthogonal function approach. The method employs empirical orthogonal functions as interpolatory spatial basis functions. The empirical orthogonal functions, derived from multi-mission satellite altimeter data from 1992 to 2012, are combined with the long time series provided by sparse tide gauge records to recover sea level fields over the period 1950-2012. The reconstruction technique is discussed and its robustness is checked through different tests. The reconstructed sea level variations here are then used to characterize sea level trends and interannual variability in the South China Sea. The results show that the regional trends computed from the new reconstruction show good agreement with the trends obtained from the satellite altimetry, the rate of sea level rise from the reconstructed time series is 4.5 °±0.7 mm/yr from 1992 to 2012 and 1.7 °±0.3 mm/yr from 1950 to 2012. Comparison with the trends of thermosteric sea level variations computed from Ishii temperature data indicates that the thermal change of the upper layer of the South China Sea has a significant contribution to the sea level variations. For the longer period, this rate is not significantly different from the rate of global averaged sea level rise (1.8 °±0.3 mm/yr). The interannual mean sea level of the South China Sea appears highly correlated with Nino 4 indices suggesting that the interannual sea level variability in the South China Sea is mainly driven by El Niño-Southern Oscillation events.

IAG (Geodesy)

G08b - G08 Sea-Level Observation and Modelling

IUGG-3014

Estimating extreme sea levels from satellite altimetry around northern Australian coasts

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A changing climate may increase the frequency or intensity of extreme sea level events, resulting in increased coastal flooding and infrastructure damage. Although the time span of satellite altimeter's observations is still shorter than 30 years, an acknowledged minimum period for estimating extreme sea levels, there has been research into investigation of many aspects of extreme sea levels using altimetry data for several years. This paper estimates the present day sea level field and extreme sea levels using hourly tide-gauge data and satellite radar altimeter sea surface heights observed from the 10-day repeat ground tracks over 20 years. Trends in mean sea levels and extreme sea levels are estimated. Changes in extreme sea levels are analysed. Generalized extreme value distribution analysis has been performed. The concepts of estimating extreme sea levels are illustrated in this paper with the results for the area subjected to intense tropical cyclone events around northern Australian coasts.

IAG (Geodesy)

G08b - G08 Sea-Level Observation and Modelling

IUGG-4240

Increasing flooding frequency and accelerating rate of sea level rise in Miami Beach, Florida

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Since 2006, the coastal community of Miami Beach has experienced an increasing rate of flooding, which caused severe property damage and significant disruptions to daily life. To evaluate the flooding frequency and its causes, we conducted a temporal analysis of tide gauge, rain, media report, insurance claim, and photo records from Miami Beach of the past 16 years. The analysis shows that most flooding events occur after heavy rain (> 80 mm) during high tide conditions, but also after the fall equinox tides regardless of rain events. We also evaluated changes in flooding frequency over the past 16 years. Our analysis reveals that since 2006, rain-induced events increased by 33% and tide-induced events quadrupled, from 2 events during 1998-2005 to 8-16 events in 2006-2013.

In order to understand the causes for the observed increase in flooding frequency, we analyzed the the nearby Virginia Key tide gauge record. We used the Ensemble Emperical Mode Decomposition (EEMD) technique to evaluate trend change in the record and found a significant acceleration in the rate of sea level rise (SLR) since 2006. The average rate of SLR since 2006 is 9±4 mm/yr, which is significantly higher than the global average rate of 3.2±0.4 mm/yr. We also have looked how SLR in the Miami area relates to the large-scale ocean circulation from a very high resolution global climate model simulation. The model results indicate that a weakening of the entire Gulf Stream system (decrease in kinetic energy) is correlated with increasing sea level in the Miami area. Our results support the hypothesis postulated by previous studies that accelerating rate of SLR along the US Atlantic coast are cause by the weakening of the Gulf Stream.

IAG (Geodesy)

G08b - G08 Sea-Level Observation and Modelling

IUGG-5691

Regional and coastal long-term sea level change assessment from geodetic data

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Considerable progress has been made during the past decade in measuring sea level change and in understanding the climate-related causes of observed changes. New challenges have been identified in coastal regions where spatial and temporal variability of sea level and the underlying ocean dynamics differ significantly from the open ocean.

A long-term satellite-based monitoring of the sea level Essential Climate Variable (ECV) as required for climate studies is provided by the ESA Climate Change Initiative Sea Level Project (SLCCI). We assess in a regional study the quality of the Fundamental Climate Data Record (FCDR) over the German Bight and the Mediterranean Sea. These are ideal test regions, where reliable and long time-series of in-situ data allow a characterization of the error and the comparison of signal and error with the ECV solution.

The first objective is to extract the long-term climate signal with its estimated error in open sea and coastal zone. Altimeter data are validated against geodetic-referenced in-situ data, referred to the Earth's reference ellipsoid GRS80 via the Global Navigation Satellite System (GNSS).

In the second part of the study we consider a "unifying" validation strategy, which combines satellite gravity measurements from GRACE, models and climatic data to assess the altimeter-derived sea level change and the drivers of the change. We derive the net Gibraltar flow from the closure of the water budget at regional scale.

The study highlight the importance of regional multidisciplinary studies to understand and discriminate causes of current sea level changes integrating the various factors that interfere at local scale (as climatic component, atmospheric and oceanographic processes, ground subsidence, etc.).

IAG (Geodesy)

G08c - G08 Sea-Level Observation and Modelling

IUGG-0352

Preliminary performance assessment of HY2 altimetry observations

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Abstract: In this study performance assessment is conducted to HY2 altimetry observations, which are from the China Satellite Ocean Application Service (NSOAS). Firstly, sea level anomalies are computed using observations provided by 44-46 cycle of HY2, and then cross analysis are conducted to evaluate the accuracy. In order to reduce the influence of time varying, the time interval in the comparison is limited to be shorter than one cycle. The crossover RMS differences for HY2 is 9.29cm, which is reduced to 8.29 cm when the statistical analysis only cover those differences within three times the standard deviation. Assuming that the error characteristics are the same along ascending and descending passes over the crossover point, the RMS system error for HY2 is 5.86 cm. When compared with Jason2 observations during the same time period, the standard deviation of the differences is 7.4 cm. Mean value of the differences is around 3.6 cm which may be caused by the environment corrections. Meanwhile, vertical deflections are also computed and the accuracy is also discussed.

IAG (Geodesy)

G08c - G08 Sea-Level Observation and Modelling

IUGG-0365

Extraction of Geoid Heights from ship Borne GNSS measurements

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The geoid is an equipotential surface that coincides with the sea level in the absence of dynamic effects such as tides, wind, ocean currents and other disturbing forces. Geoid heights from global and regional models are widely used for geodetic applications notably in height determination using GNSS measurements. The quality of those models is directly related to the spatial resolution of the data used to create the model.

Space borne gravimetry missions provide gravimetric measurements with global coverage that allows the creation of a more accurate geoid model, especially in ocean-covered areas.

However, space borne missions suffer from a low spatial resolution, which can reach distances of tens and hundreds of kilometers between tracks. Therefore, the marine geoid is usually modeled with lower quality while sometimes the local geoid model does not cover the coastal area at all and a local marine geoid simply does not exist.

Ship borne GNSS measurements may provide a way of overcoming the low quality marine geoid modeling in coastal areas. However, several corrections to the raw measurements must be applied in order to account for errors induced by ship dynamics and other dynamic effects like tides, atmospheric pressure or wind stress.

This paper presents the theoretical background for the method and the results of a case study in the Weser River in Germany. A series of GNSS measurements were carried out aboard a ship and the geoid height along the river was derived. For accuracy assessments of this method, the results were compared to the German Combined QuasiGeoid 2011 (GCG2011). The results are very promising and indicate the ability to extract geoid heights from ship borne GNSS measurements.

IAG (Geodesy)

G08c - G08 Sea-Level Observation and Modelling

IUGG-0534

Impacts of seismic mass redistribution on estimates of recent sea level rise from GRACE

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Time-variable gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) have been widely used to estimate non-steric global mean seas level change. However, global oceanic mass trends obtained from GRACE can be contaminated by regional seismic deformation effects, which are supposed not to contribute to oceanic mass change or non-steric sea level rise. Obvious large-scale mass redistributions due to co- and post-seismic deformations of several large earthquakes have been reported during the GRACE mission period, including the 2004 Sumatra-Andaman earthquake, 2010 Chile earthquake and 2011 Tohoku-Oki earthquake. All these three earthquakes occurred in land-ocean boundary areas, causing mass changes in both land and oceanic areas. Even though the near-field earthquake regions occupy a small part of the global oceanic areas, seismic deformations could still affect the estimate of global oceanic mass trend to a non-negligible level, because of the evidently larger amplitude of the regional seismic deformations. In this study we evaluate the impact of seismic mass changes due to large earthquakes on the GRACE sea level rise, through case studies of the three earthquakes mentioned above. Results show that the impact can reach up to more than 10 percent of the estimated total sea level rate, which is apparently non-negligible.

IAG (Geodesy)

G08c - G08 Sea-Level Observation and Modelling

IUGG-2707

Airborne laser scanning determination of sea surface heights

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Usability of satellite altimetry data for determination near-coast sea surface heights (SSH) is limited due to poor accuracy. Therefore, for regional SSH determination (and also geoid modelling studies) airborne laser scanning (ALS) can be a high-resolution and more accurate alternative over coastal waters. This contribution explores the usability of ALS technique for determining SSH. Issues of backscattering of ALS signal from liquid surface are investigated, alongside with development of low-pass data filtering methods. Also aspects of incorporating tide gauge data into SSH solution are considered in detail. Tidal effect and its spatio-temporal variations over a region of interest are accounted for.
The ALS-based SSH determination methodology developed in this study is tested over a part of the Baltic Sea. Several specially designed intersecting ALS profiles flown at different altitudes are used for SSH determination. Different stages and specific aspects of the case study are presented in detail, including principles of ALS data filtering in the context of marine processes and cross-validation of ALS-derived SSH by using nadir-range ALS profiles and tide gauge readings. The sea level-corrected SSH profiles are compared with a recent regional high-resolution gravimetric model. The detected discrepancies between intersecting SSH profiles and the root mean square error values from comparisons with the geoid model generally remained within 4 cm and 7 cm, respectively. The marine ALS datasets thus have a potential in providing complementary constraints in problematic geoid modelling areas.

IAG (Geodesy)

G08c - G08 Sea-Level Observation and Modelling

IUGG-3102

Sea level variability in the tropical Atlantic during the last decade

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Regional sea level changes in the Tropical Atlantic on spatial scales greater than 500 km are studied for the period 2002 to 2014. The focus is on the relation between the total sea level and its steric and mass equivalent components. The data bases are: monthly gridded sea levels from the Jason-1/Jason-2 satellite altimeters, gridded steric sea levels from Argo floats (provided by Met Office Hadley Centre) and mass equivalent sea level from the GRACE mission. The seasonal sea level signal is dominated by the steric signal. For lower frequencies the mass signal seems to become more important. Starting from 2009 the mass equivalent sea level in the Tropical Atlantic has increased. This increase can be observed from the GRACE data as well as from the combination of altimeter and Argo data and accounts to about 3 cm in a five years period. The onset of this mass Tropical mass increase coincides with a major decrease of the Atlantic meridional overturning circulation at 26°N. The origins of the observed mass accumulation are further investigated.

IAG (Geodesy)

G08c - G08 Sea-Level Observation and Modelling

IUGG-3631

Mean dynamic topography in the partly ice-covered Southern Ocean based on ICESat laser altimetry data

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Radar and laser altimetry provide a powerful tool to monitor the global ocean and to infer a variety of parameters of interest to geodesy and oceanography. In (partly) sea-ice covered areas it is still a challenge to discriminate between sea ice and the actual sea surface and, subsequently, to infer sea-surface heights. The work to be presented here utilized data release 34 of the Geoscience Laser Altimeter System (GLAS) onboard ICESat. We will present a newly developed algorithm that combines a lowest-level approach analyzing the height profiles with additional remote sensing data. Not being dependent on further a-priori information, this algorithm is capable to adapt to different conditions, especially with respect to ice coverage. The extensive test runs included an internal cross-over analysis as well as an intercomparison with multi-mission radar altimetry. It could be shown that the inferred algorithm is robust and working reliably and, therefore, is suited for an automated processing. We applied the method to infer mean sea-surface heights in the Southern Ocean. A respective data grid could be inferred featuring a precision of approx. 5 to 10 cm. Only in regions of higher seasonal ocean variability the resulting precision slightly deteriorates. Also, the method enables to identify artifacts in estimates of the mean sea surface based on multi-mission radar altimetry which might be due to limitations in the data availability at high latitudes. Furthermore, an outlook will be given to infer freeboard heights and, eventually, mean geostrophic velocities.

IAG (Geodesy)

G08d - G08 Sea-Level Observation and Modelling

IUGG-0468

Application of the Multi Adaptive Regression Splines to integrate sea level data from altimetry and tide gauges

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The aim of this paper is to study sea level variations with nonlinear components along the northern coast of Australia using a state-of-the-art Multi Adaptive Regression Splines (MARS). The 20 years of data from multi-satellite altimetry missions (e.g., Topex, Jason-1 and Jason-2) and tide gauges data are integrated using the MARS in order to provide a consistent map of coastal sea level in the area. The MARS is considered for modelling because it is capable of dividing measured sea levels into distinct time intervals where different linear relationships can be identified. In addition, the MARS automatically recognises relevant tide gauges and scores them according to their contributions to the model. The modelling sea level variations by MARS give the mean R-squared (R^2) of 0.62 and Root Mean Squared (RMS) error of 6.73 cm in the study region. Validation of the model against independent tide gauges observations yields a RMS difference of 4 cm and very strong correlation of 99%. The results suggest that the MARS approach can efficiently integrate the two types of sea level datasets. The successful modelling means that sea level can be estimated over the northern Australian coastline to provide coastal sea level predictions at times and positions where no satellite observations are available.

IAG (Geodesy)

G08d - G08 Sea-Level Observation and Modelling

IUGG-0867

Quantification of Baltic Sea Region relative Sea-level rise by using Multi-mission satellite altimetry data and tide gauge sea level series

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The coastal regions of the Baltic Sea (BS) countries are mostly uplifting (up to 1 cm/yr in Fennoscandia) due to glacial isostatic adjustment (GIA) process. The land subsides outside the former ice margin (south coast of the BS) due primarily to the viscoelastic response of the solid Earth resulting from the deglaciation of the Pleistocene ice-sheets. Current global sea-level rise (SLR) is estimated at ~2 mm/yr. However, exact knowledge of the extent and the magnitude of the vertical crustal movements (VCM) and the relative SLR around the BS remain elusive. Moreover, the regional sea level changes are not synchronized with the global SLR. These are mainly affected by ice sheet and glacier melt/accumulation, hydrologic imbalance, seafloor uplift due to GIA, and human impoundment of water in dams or extraction of water from inland aquifers.

The focus of the study is on Estonia, which is located in the eastern shores of the BS, on the VCM hinge line. Several land uplift models have been computed for this area by using geodetic and oceanographic data. To better quantify the relative region SLR, the VCM and SLR are separated by using two steps. First, the 1992–2014 multi-mission satellite altimetry (SA) and long-term (>50 yr) tide gauge (TG) data are combined to obtain improved estimates of absolute (geocentric) VCM at TGs around the BS. This method assumes that the geometry of sea-level is known and can be rigorously accounted for in combinations of TG and SA sea-level records. Regional GPS velocities are used for an independent validation. Second, reconstructed regional mean SLR is calculated by using SA and TG sea-level series corrected with the absolute VCM rates. The results are compared to the reconstructed global mean sea-level trend using multi-mission SA and TG data.

IAG (Geodesy)

G08d - G08 Sea-Level Observation and Modelling

IUGG-3868

Error investigation in the reconstruction of global mean sea level by combining satellite altimetry and tide gauges

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Global mean sea level (GMSL) has not only significant secular trend and seasonal variations, but also inter-annual and decadal variations. The former has been revealed through long term researches, but it is known little about the low frequency characteristics of inter-annual and decadal variations, which demands longer GMSL time series. Serveral results have been published on the reconstruction of longer GMSL time series by combining the spatial functions from satelite altimetry and the long time series of tide gauges. But there are still some problems to be discussed in the reconstruction, such as, 1) the approach to decompose the spatial functions from altimetry sea level time series; 2) the time span of altimetry sea level time series, which will affect the stability of the spatial functions; 3) the grid errors in the altimetry sea level time series, which will lead to the errors in the spatial functions; 4) the influence of the spatial distribution of the selected tide gauges. Steric sea level time series over 1945 – 2012 derived from Ishii's dataset are used to do a series of simulations to analysis the influence of above effects. The original steric sea level time series are used as reference, and different time span of time series are simulated as the altimetry measurements, and the tide gauges time series are simulated by interpolating from the reference in its real locations and average distributions. Through the simulations, the errors are investigated, and optimum strategy is given to achieve the better reconstruction results.

IAG (Geodesy)

G08d - G08 Sea-Level Observation and Modelling

IUGG-5582

Sea level changes in the Black Sea using satellite altimetry and tide gauge observations

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The Black Sea is an isolated sea in the ocean system because of its narrow connection to the Mediterranean Sea through the Turkish straits. The recent studies have revealed that the Black Sea level changes are mainly related to freshwater changes, particularly and affecting coastal risk assessment and coastal management planning. In this paper, a national project is planned to monitor local sea level change and assess its impacts on the Black Sea using satellite data (altimetry and gravity) and terrestrial data (tide-gauges, oceanographic, and gravity, etc.) for the period of January 1993 – May 2014. The results of this study within the project will serve as a first step toward a better understanding of the sea level changes in the Black Sea. For this purpose, all satellite merged maps of sea level anomalies data at 0.125°x0.125° grids are evaluated in the study as well as a few Tide Gauge stations data. Analysis of the data shows that the Black Sea mean sea level has risen over 1993 – 2014 at a mean rate of 3.19 ± 0.81 mm/year and the maximum rate of sea level change is observed in the southeastern part of the Black Sea. In the future, we will further investigate their causes.

IAG (Geodesy)

G08d - G08 Sea-Level Observation and Modelling

IUGG-5585

Investigation on spectral methods for tide-gauge data analyses

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The sea level changes are one of the indicators of climate change and effect the World life today and in future, with reasons such as coastal erosion, saltwater intrusion, inundation etc. Beside the satellite based and oceanographic data, evaluation of tide-gauge data provides valuable input to analyzing and estimating the long-term sea level changes, hence contribute to oceanographic and climate investigations that their results are vital for future planning and precautions for life.
This study investigates and compares various spectral analyzing methods that are Least Square Spectral Analysis (LSSA), Wavelet Analysis and Principle Component Analysis (PCA), in evaluation of tide-gauge data hence clarifies the advantages and drawbacks of each methods from methodological and practical point of view. In this purpose monthly sea level observations collected at four tide-gauge stations surrounding Black Sea coast are considered. The data (Amasra-Turkey, 41°26'N and 32°14'E; Poti-Georgia, 42°10'N and 41°41'E; Sevastopol-Ukraine, 44°37'N and 33°32'E; Constantza-Romania, 44°10'N and 28°40'E) as well as the vertical deformations of the stations are obtained from Permanent Services for Mean Sea Level (PSMSL) global network of tide gauges, with varying time spans between 8 to 84 years. In conclusion, beside the sea level trend, periodicities, correlations among the stations, the regional observing system and the quality of the tide gauge records in the region are discussed and reported over the drawn results of the study.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-507

Analysis of coastal inundation using geodetic data and tsunami model: a case study in Taiwan

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Seawater inundation could damage human property and life, especially for of coastal low-lying areas in islands. Regional sea level rise, extreme high tide, and vertical motion could result in episodic or permanent coastal inundation tsunamis. Therefore, assessment of potential flooding areas due to sea level rise or extreme events in the near future are a critical task for coastal management. In this study, assessment of coastal flooding areas in Taiwan during this century will conducted with considering the regional sea level data derived from tide gauges and satellite altimeter, the crustal deformation from leveling and GPS, and ocean tides. Besides, the extreme flooding events like tsunami are also analyzed by using the tsunami generation and propagation simulated by the numerical model – COMCOT (Cornell Multi-grid Coupled Tsunami Model). The risk assessment of the areas flooded by sea level rise, crustal deformation, tides and tsunami is potentially useful for coastal ocean and land management to develop appropriate adaptation policy for preventing disasters resulting from global climate change.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-509

Optimal threshold level determination of waveform retracking based on least variance criterion

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The waveform retracking can improve the accuracy of the steady Sea Surface Height (SSH) in the coastal region. However, the threshold level is empirically determined. This paper proposes a method for determining the optimal threshold level by minimizing the variance of the steady SSH. First, the waveforms are classified by cluster analysis, and then retracked according to classified waveforms. Secondly the biases and the variances of the derived SSHs by each waveform retracking methodology with different threshold levels are calculated according to the discrepancies of the reconstructed steady SSHs with respect to geoid height of EIGEN6C2 model. The threshold level with least variance is taken as the optimal threshold level. The Envisat altimeter waveform data from March 2002 to May 2010 in the coastal sea around Northern China (33°N~41°N, 117°E~125°E) can be classified into six categories, which are ocean(84.84%), ocean-like(5.94%), pre-peaked(0.95%), post-peaked(0.45%), quasi-specular (2.21%), flat-patch(1.94%) and complex waveforms (3.67%), respectively. Based on the least variance criterion we determine the best waveform retracking methodology and the optimal threshold level. For the ocean-like, pre-peaked and the post-peaked waveforms, the sub waveform retracker is the best retracker, and the optimal threshold levels are 35%, 15% and 10% with the least variances of 0.40, 0.65 and 0.60m, respectively. The OCOG retracker is the best one for quasi-specular and ocean waveforms, and the optimal threshold level are 10% and 55% with the least variances of 0.81and 0.32m, respectively. The threshold retracker is the best one for the flat-patch and complex waveforms, and the optimal threshold levels are 15% and 35% with the least variances of 0.55 and 0.45m, respectively.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-510

Determination of sea-surface height and sea-surface topography in the Mediterranean by means of laser altimetry onboard the GEOHALO mission

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In June 2012 the geodetic-geophysical flight mission GEOHALO was realized using the new German research aircraft HALO (High Altitude and Long Range Research Aircraft). This mission covered the area of Italy with the adjacent Adriatic, Ionian and Tyrrhenian Seas flying several longitudinal and cross profiles. In addition to airborne gravimetry, magnetometry and a variety of different GNSS applications, laser altimetry was an essential part of GEOHALO. It was the first time that long-range (up to 4,000 m) laser altimetric measurements were carried out onboard a jet aircraft using the laser distance meter Riegl LD321-3K. The laser distance measurements were complemented by flight trajectory data based on GNSS, attitude angles based on INS and meteorological parameters in order to infer sea-surface heights and sea-surface topography. The required corrections and reductions of the raw data are discussed. Special attention has to be given to the calibration of the laser distance meter. An evaluation of the obtained results and accuracy was carried out with the help of different models of mean sea-surface height (MSSH) and mean sea-surface topography (MSST). Finally, the acquired experience is discussed and conclusions are drawn with regard to future applications of airborne laser altimetry on different aircraft platforms, but especially onboard HALO. Since the laser distance meter also allows a recording of the full waveform, an outlook is given to the waveform analysis to extract additional sea-surface related information.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-511

GNSS reflectometry for tide gauge levelling

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The GNSS reflectometry (GNSS-R) technique provides valuable information related to the geometry and physical properties of reflecting surfaces surrounding the GNSS antenna, including their vertical distance.
Here, we use sea-surface reflections of GPS signals, recorded as oscillations in signal-to-noise ratio (SNR), to remotely and continuously estimate the GNSS to tide gauge (TG) levelling connection, and thus the ellipsoidal height of the TG.
We develop fully automated approaches to isolate SNR data dominated by sea-surface reflections as well as to mitigate changes in the SNR frequency caused by the dynamic sea surface.
Comparison with in situ levelling at eight sites reveals mean differences at the centimetre level for satellites above 12? elevation, with four sites showing differences of 3 cm or smaller. These differences include errors in the in situ levelling, in the antenna calibration model and in the TG measurements, and so represent an upper bound on our technique's error.
We detected systematic errors at the decimetre level related to satellite elevations below 12? and also differences between results from the L1 and L2 GPS signals larger than 15 cm at Burnie and Spring Bay (Australia). These systematic errors remain unexplained; differences between GPS signals are attributed to receiver-dependent differences in the SNR measurements, while the elevation-dependent error is attributed to unmodelled phase effects such as those caused by tropospheric refraction and sea-surface roughness.
Using our approach, we identify a levelling offset of 1.5 cm related to a TG sensor change in Brest, illustrating our technique's value for TG reference monitoring.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-512

Validation of altimetry-derived Ocean Dynamic Topography by in-situ measurements of ocean currents

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Satellite altimetry measurements together with high-accurate Earth gravity field models can be used to estimate the ocean topography by subtracting the geopotential reference surface from the sea surface. We developed a "profile-approach" (Bosch & Savcenko, 2010 and Bosch et al, 2013) which allows the estimation of so-called instantaneous dynamic ocean topography (iDOT) profiles along individual altimeter ground tracks. In contrast to other methods using a long-term mean sea surface and estimating a mean topography (MDT) our approach provides temporal variations of almost meso-scale structures. The iDOT profiles can be gridded and converted to surface velocities by applying the geostrophic equations.
A complete independent method for measuring the ocean surface velocities are in-situ observations of ARGO floats and surface drifters. After correcting these measurements for wind and Ekman drift they provide an independent data set for comparison and validation of our altimetry-derived surface velocities.
In this study, we compare both data sets for a period of four years using two different methods: (1) based on quarterly averages of 1° gridded data sets (chosen in order to have a sufficient density of the in-situ data) and (2) based on pointwise comparison with iDOTs interpolated to in-situ observations.
It can be shown that both velocity fields agree well with differences smaller than 0.1 m/s on average. Within the pointwise comparison, the altimetry-derived velocities show the same pattern as the in-situ data. However, they are smaller by a factor of almost two due to the smoothing of the iDOTs within the interpolation process. Results are presented for a number of study areas covering the strong western boundary currents.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-513

Modeling the response of the Mediterranean sea level to global and regional climatic phenomena

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Fluctuations in the level of the sea pose an issue of emerging importance, since latest scientific research shows a clear trend in the rise of the sea level. Since the early 80's, satellite altimetry resulted in an abundance of sea surface height observations, forming a database crucial to both oceanographic and geodetic applications. This work presents results on the correlation between Sea Level Anomaly (SLA) with global and regional climatic phenomena that influence the ocean state. Three such phenomena, in the form of oscillation indexes have been investigated. The first one is the well-known Southern Oscillation Index (SOI) corresponding to the ocean response to El Niño/La Niña-Southern Oscillation (ENSO) events. The next index investigated is the North Atlantic Oscillation (NAO) index, which corresponds to the fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low and the Azores high. The last index investigated is the Mediterranean Oscillation Index (MOI) which refers to the fluctuations in the difference of atmospheric pressure at sea level between Algieres and Cairo. The raw data used are SLA values from Jason-1 and Jason-2 satellites for a period of twelve years (2002-2014) within the entire Mediterranean Basin. A regional multiple regression analysis and a principal component analysis between sea level anomalies and these indexes are carried out to model any possible correlation between the Mediterranean sea level response and these global and regional climatic phenomena.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-514

GGOS Theme 3: Understanding and Forecasting Sea-Level Rise and Variability

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Sea level and its change have been measured for more than a century. Especially for nations with long coastlines and important coastal industry, observations of tides, tidal extremes, storm surges, and sea level rise at the interannual or longer scales have substantial impacts on coastal vulnerability towards resilience and sustainability of world's coastal regions.

Today, the global average observed sea level rise is largely associated with climate related changes. To find the patterns and fingerprints of those changes, and to separate the land motion with sea level signals, different monitoring techniques have been developed. Some of them are local, e.g., tide gauges, while others are global, e.g., altimetry. It is well known that sea level change and land vertical motion varies regionally, and both signals need to be measured in order to quantify relative sea level at the local scale.

The Global Geodetic Observing System (GGOS) and its services contribute in many ways to the monitoring of the sea level. These include tide gauge observations, estimation of gravity changes, GNSS control of tide gauges and the maintenance of the International Reference Frame.

Theme 3 (Understanding and Forecasting Sea-Level Rise and Variability) of GGOS establishes a platform and will be a forum to researchers and authorities for estimating and predicting global and local sea level changes in a 10- to 30-year time horizon. It presents an excellent opportunity to emphasize the global, through to regional and local, importance of GGOS to a wide range of sea-level related science and practical applications.

Recently, a call for participation was issued, which seeks projects demonstrating the value of geodetic techniques to sea level science and applications.

The status will be highlighted.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-515

Subsidence Monitoring with GNSS-controlled Tide Gauges in Indonesia

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Lately major cities in Indonesia have experienced significant regional subsidence rates. Jakarta, Indonesia's capital, with 10 Million inhabitants shows a complex and varying subsidence pattern along the coast, which is mainly driven by groundwater extraction and surface load. Semarang, a 2 million residence city in north-west Java show subsidence rates of several cm per year, clearly visible in the landscape. Such high rates cause major consequences for the local population as well as require actions on the political and governmental level.

To support studies on subsidence, GNSS-controlled tide gauges have been installed in Semarang (2012), Kolinamil (harbor of Jakarta, 2013) and Surabaya (2014). The installations follow the standard of installations of the German-Indonesian Tsunami Early Warning System (GITEWS) project (Schöne et al., 2010). All stations sample sea level data and basic meteorological parameters like wind speed, wind direction and air pressure with a sampling rate of 1 min, as well as 30-second GNSS (primarily GPS) data. In addition, all stations are connected to the national height system by leveling.

The analysis of the acquired data reveal negative subsidence rates of more than 10cm/yr for Semarang, and a few millimeters for Kolinamil (Jakarta). The measurement series of Surabaya is still too short for reliable rate estimates. The resulting values agree to other sources of information, e.g. PSI/InSAR.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-516

Impact of Limited Multi-GNSS Visibility on Vertical Land Movement Estimates

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The number of GNSS satellites and their geometry directly affect the quality of positioning and derived satellite products. Accordingly, the International GNSS Service (IGS) recommends GNSS antennas to be installed away from natural and man-made surfaces and structures, which may affect the incoming signals through severe multipath or obstructions. Following these recommendations, continuous GNSS (cGNSS) stations are generally located in low multipath environments with minimal signal obstructions. However, some applications require GNSS antennas to be installed at specific locations in order to measure local processes. Hence, in support of sea level studies, cGNSS stations must be installed close to or at tide gauges in order to accurately monitor the local vertical land movements experienced by the sea level sensors. However, the environment at the tide gauge might not be optimal for GNSS observations due to the aforementioned station-specific effects, which degrade the quality of coordinate solutions.

This first study investigates the impact of severe signal obstructions on long-term monitoring results by use of simulated and real observations for selected cGNSS stations, and evaluates if the use of multi-GNSS (GPS+GLONASS) constellations will benefit derived results. To investigate these effects, we implemented azimuth and elevation dependent masking in the Bernese GNSS Software version 5.2. We present our preliminary results on the impact of different obstruction scenarios for various latitude bands and combined GPS and GLONASS solutions on coordinate and vertical land movement estimates.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-517

Water in Central Asia - Lake and Reservoir Level Monitoring with Radar Altimetry

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In the arid to semi-arid region of Central Asia, water resources are vital for the growing population and are used intensively, in particular for hydroelectric power generation and irrigation. Due to joint use of water from the transboundary Amu Darya and Syr Darya River (and their tributaries), the economies of the five former Soviet Republics in Central Asia – Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan – are closely interconnected and their economic development strongly depends on the availability of water. In the past decades, the chronic overuse of existing reserves and the impact of global climate change led to an increasing water scarcity in the region.

In addition, lack on information on (regional) water availability pose a challenge for sustainable water resources planning and management. To assist hydrometeorological forecasts and political decision processes, independent and freely available information on water parameters, e.g. lake and reservoir levels, are in high demand.

Over the past years, radar altimetry became a tool for monitoring inland water bodies. New missions and recent reprocessing of data, acquired during previous missions, allow a construction of time series of lake and reservoir levels back to 1993. Such data allow studies of natural changes in the water availability as well as examination of changes in reservoir fillings. We will present results for selected water bodies.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-518

Tide gauge benchmark monitoring – The IGS TIGA project

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The IGS Tide Gauge Benchmark Monitoring - Working Group (TIGA-WG) of the International GNSS Service (IGS) is providing the service to analyze GNSS data from stations directly at or near tide gauges (TG) on a preferably continuous basis. TIGA is recognized by the Global Sea Level Observing System (GLOSS) to provide position and vertical rates for GLOSS tide gauges and is an important contribution of the IGS to the goals of the Global Geodetic Observing System (GGOS), the Global Climate Observing System (GCOS) and the World Climate Research Programme (WCRP).

The primary TIGA product is weekly sets of coordinates, velocities, and accuracy estimates for monitoring vertical motions of Tide Gauge Benchmarks (TGBM). The product is made public to support and encourage other applications, e.g. sea level studies. The service may further contribute to the calibration of satellite altimeters, other oceanographic applications or the establishment of a World Height System.

The Working Group is utilizing the existing infrastructure of the IGS as much as possible without disrupting standard activities. A number of TIGA Analysis Centers (TAC) provides weekly solutions using the IGS reprocessing standards. The TIGA network will additionally include non-IGS stations (TIGA Observing Stations, TOS) meeting the IGS network requirements and are collocated with the tide gauges. The TIGA Product will be generated by TIGA Combination Centers (TCC). The network maintenance and interaction with TOS operators is supported by the TIGA Network Coordinator (TNC), closely related to the support of the TIGA Data Centers (TDC).

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-519

Observing and interpreting sea level variations with focus on the Northeastern Adriatic

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Tide gauges measure local sea-level relative to a benchmark on land. The interpretation of these measurements is, somehow, challenging because they are affected by vertical movements of the Earth's crust, notwithstanding that sea level itself is influenced by a large number of factors acting at different temporal and spatial scales. Space geodesy, namely GNSS observations, has provided the means to measure vertical land motions in a well-defined geocentric reference system such as ITRS. The InSAR PS technique allows detecting, measuring and monitoring vertical ground movement with precision up to 0,1 mm/yr. In 1998, the Italian national tide gauge network was completely restructured, after having experienced difficulties during the last century. It consists of 36 homogeneously distributed stations providing measurements sampled every 10 minutes. We have analyzed the time series of monthly mean sea levels of a subset of these stations by using the Empirical Orthogonal Functions (EOF) with the aim to identify common modes of variability. Local and regional crustal movements at tide gauges need to be averaged out. In the recent past, within a few international projects, efforts were undertaken to install GPS at tide gauge stations. Moreover, monitoring of the Italian territory using SAR data is carried out by different Agencies/Institutions. Among the available tide gauges, we focus on those of Marina di Ravenna and Venice, in the northern Adriatic, since GPS and InSAR time series are available which can be compared and used to reliably estimate vertical crustal motions. In particular, at Marina di Ravenna, almost 18 years of continuous GPS data are available; in the case of SAR, we have analyzed the Radarsat data, during the period 2003-2011, using the PS technique.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-520

Mean Sea Level determination in Deception and Livingston Islands (Antarctica) and its contribute to estimate a precise local geoid.

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In order to establish an accurate value for the Mean Sea Level in the South Shetland Islands, in 2007 the first gauges in Livingston and Deception islands were installed. LIVMAR and DECMAR tide gauges are located in Livingston and Deception Island, respectively. Due to the harsh conditions of the area, with sea ice for long periods of the year, pressure sensors were installed near the coast but deep enough to not be affected by ice. By referencing the bottom pressure sensors to on-shore benchmarks, it was possible to calculate the Mean Sea Level relative to a precise leveling network for the period analyzed. The sensor reference levels were linked to the benchmarks by linear fitting of the instantaneous measurements of the sea level observed by tide staff to the data obtained from the pressure sensors. In order to correlate the two measurements, data from the meteorological station were used. Accurate orthometric heights were obtained in the geodetic reference benchmarks. Orthometric heights were calculated from geometric leveling differences, ellipsoid height were obtained from GNSS measurements and absolute gravity was measured in order to obtain a precise local geoid. Therefore, an experimental geoid model for Deception Island was computed from GNSS, gravimetric and leveling measurements relative to the Mean Sea Level, and also for the area of the Spanish Antarctic Base Juan Carlos I and Johnson's Dock at Livingston Island. The Mean Sea Level and precise geoid are being investigated for the study and understanding of volcano dynamics, as well as provided for both oceanography and geophysics applications that require a gravitational vertical reference system.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-521

The WHU2013 global mean sea surface height model

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By using the Radar Altimeter Database System (RADS) dataset maintained by the Delft University of Technology, a global Mean Sea Surface Height (MSSH) model named WHU2013 MSS is established. The exactly repeat missions selected are 20 years combined Topex/A, Jason-1/A and Jason-2/A data from 1993-2013, 3 years Topex/B data, 3 years Jason-1/B data, 8 years ERS-2 data, 8 years Envisat/B data, and 7 years GFO data. The geodetic missions selected are the ERS-1 phase E and F data, the Jason-1/C data, and the Cryosat-2 LRM data from cycle 4 to cycle 48, which ends in the end of the year 2013. The exactly repeat missions are selected at nearly the year round to eliminate the seasonal signals in the collinear adjustment. By analyzing the signals of sea level variations and that eliminated in the collinear adjustment, a method to eliminate the sea level variation signals in the geodetic missions is given, especially for the high latitude measurements which beyond 66°. Then, the combined Topex/A series dataset from 1993-2013 are collinear adjusted and used as the reference mission. Through the crossover adjustment, and the remove-restore method by using the EGM08 model as reference, the global MSSH model with the latitude from -80° to 84° and resolution of 2′×2′ is achieved after the least square collocation gridding. Compared with the CNES-CLS2011 and the DTU13 MSS model, the accuracy of WHU2013 MSS is estimated to be nearly the same of the others, and more consistent with the DTU13 MSS model.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-522

Satellite altimetry Calibration/Validation at the Australian Bass Strait site in the context of the new missions Jason-3 and Sentinel-3

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The Bass Strait satellite altimetry validation site has been one of 3 reference sites spread around the world for the Topex-Poseidon and Jason satellite altimeter series since the 1990s. There, the absolute calibration attained is at the cm level contributing importantly to the altimetry systems absolute bias estimation and to their drifts monitoring. In 2015-2016 two new accurate satellite altimetry missions will be launched and need calibration validation. The method developed over the years for Jason involves tide gauges, moorings where we measure temperature, salinity, pressure and currents, atmospheric measurements and operational models (ACCESS) to extend measurements and corrections from coastal tide gauges to the cal/val site 25km off the coast under the satellite track. GPS buoys are regularly deployed to reference the in situ sea level measurements to the same datum as the satellites and estimate instruments bias and drifts. While the system is quite operational in view of the Jason-3 satellite, the newcomer Sentinel-3 will have a different ground track, repeat time, and measurement mode. We will show the overall calibration system and the results over the TOPEX-Jason period. We will also show the extension and improvements we are developing in the frame of Jason-3 and Sentinel-3 new missions. In particular, we investigate the possibility and capability of a regional ocean model to test the sensitivity and extend the present system with a mooring under the Jason track to a Sentinel-3a crossover ~10km away.

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G08p - G08 Sea-Level Observation and Modelling

G08p-523

GNSS observation of semi-diurnal and quarter diurnal ocean tidal loading waves

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The ability of the Global Navigation Satellite System (GNSS) to produce precise positioning at the Earth's surface makes it a suitable tool to estimate crustal displacements due to Ocean Tidal Loading (OTL). We estimate horizontal and vertical displacements from 89 permanent stations located in Western Europe, for about a 2 year period (January 2009 to January 2011). The variation of position is estimated by double difference processing with GAMIT/GLOBK (Herring et al., 2010). We optimize our processing strategy, by choosing 2 hour session, shifted by 1 hour.

We show that precise GNSS positioning allows to retrieve with a high accuracy the OTL signal not-only for the semi-diurnal tides, but also for the non-linear quarter-diurnal M4 wave.

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G08p - G08 Sea-Level Observation and Modelling

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Mediterranean Steric Sea Level (SSL) variations between 1993-2014

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We study the variability of the Mediterranean steric sea level (SSL) for the 21 years period 1993-2014. SSL has been estimated from Met Office Hadley Center EN4 dataset which consists of objectively analyzed temeperature and salinity profiles (Argo observations are included) with 1-degree spatial resolution and monthly temporal resolution. We have confined our analyses to the upper 700 m where the main steric changes are expected to take place in order to avoid problems due to the sparser sampling at greater depths.

In this work we analyze SSL annual cycle and the interannual spatio-temporal variability. Linear trends of SSL are estimated, as well as the patterns of variability by means of empirical orthogonal functions. The results are interpreted together with SL variations from altimetry for the same period.

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G08p - G08 Sea-Level Observation and Modelling

G08p-525

Mediterranean sea level variabilty derived by wavelet multiresolution analysis

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Using wavelet multiresolution analysis, the spectral content of monthly maps of sea level anomaly time series on the Mediterranean Sea derived from satellite altimetry over the period 1993 to 2013 is investigated in order to assess its seasonal changes and its nonlinear trend. The multiresolution decomposition has extracted useful the seasonal signals (annual and semi-annual) and nonlinear trend of the analysed time series by means of its signals of 'details' and 'approximations', respectively. Details and approximations signals represent, respectively, the high-frequency and the low-frequency contained in the analysed time series. The amplitude values for the annual signal are less than10 cm with an average of 6.74 cm, while those for the semi-annual signal are mostly less than 4 cm with an average of 1.79 cm. However, the successive smoothing of the analysed time series through the signals of approximations has allowed to better identify the rate and time spans of the increase and decrease of the Mediterranean Sea. The filtered trend has a slope about 2.30 mm/year compared to 2.46 mm/year of the original time series estimated by linear least squares regression.

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G08p-526

ICESat Laser Validation with Airborne LiDAR in SONMICAT-BCN

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SONMICAT - the integrated sea level observation system of Catalonia - aims at providing high-quality continuous measurements of sea and land levels at the Catalan coast from tide gauges and from modern geodetic techniques for studies on long-term sea level trends and also for the calibration of satellite altimeters. Together, these different techniques will allow us to measure the sea level change on the coast of Catalonia.

There is a gap of GLOSS sea level data in the coastal area of Catalonia, although several groups have started to do some acts. SONMICAT is an attempt to fill this gap..

In the framework of SONMICAT project, the sea level infrastructure has been improved by providing the harbour of Barcelona with 3 tide gauges and a GPS station nearby. Furthermore, an airborne LiDAR campaign was carried out in July 2014, with two strips along two ICESat target tracks.

The comparison between ICESat and LiDAR data is presented. A short overview and the major differences between the two technologies are outlined. Advantages and disadvantages with respect to various aspects are discussed.

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G08p - G08 Sea-Level Observation and Modelling

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Temporal evolution analysis of imbituba brazilian vertical datum from tide gauge, GNSS observations and satellite altimetry

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Nowadays, central subjects of investigation in Geodesy stand for establishing Reference Systems by taking in account variations of mass distribution in the Earth System. Such systems are fundamental for structuring the Earth Observing Systems able for determining global changes at 1 ppb in several geometric and physical parameters. In the Global Geodetic Observing System (GGOS) central subjects under consideration associated with mass redistribution are linked to the vertical positioning and in association with the Sea Level evolution in time. In this sense, it is meaning an International Height System (IHS) with global consistency of at least 1cm in its realization and space/temporal control. National Vertical Datum (NVD) around the world must be linked to the IHS and consistent with the referred conditions. Considering these aspects, it was sought to model temporal evolution of Imbituba Brazilian Vertical Datum (IBVD) realized by Mean Sea Level (1949,0 to 1958,0). Analyzes were conducted on time series obtained from continuous GNSS positioning, tide gauge observations and satellite altimetry for the period from 2007.0 to 2015.0. Comparisons were made with available velocity model of the crust for South America obtained from continuous GNSS stations (SIRGAS-CON). The results allowed discriminating local crustal and sea level movements and to estimate and the evolution of MSL in Imbituba. The present position of IBVD related to the IHS as well as related to its initial definition were estimated.

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Calibration of the tide gauge at King Edward Point, South Georgia Island, South Atlantic Ocean

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In 2008 a new pressure tide gauge with Global Sea Level Observing System Number 187 was installed at King Edward Point (KEP), South Georgia Island, South Atlantic Ocean. This installation was carried out as part of the Antarctic Circumpolar Current Levels by Altimetry and Island Measurements (ACCLAIM) programme. In 2013 the KEP Geodetic Observatory was established in support of various scientific applications including the monitoring of vertical land movements at KEP. Currently, the observatory consists of two state-of-the-art Global Navigation Satellite System (GNSS) stations with local benchmark networks. This ties all benchmarks and the tide gauge into the International Terrestrial Reference Frame 2008, and allows the establishment of a local height datum in a global height system through the use of a global gravitational model. In 2014 a tide board was added to the tide gauge, which, together with the GNSS and levelling observations, now enables a calibration of the tide gauge. This will make it possible to include the KEP tide gauge in the Permanent Service for Mean Sea Level (PSMSL) database.

In this study, we will present the results from the calibration of the tide gauge using the GNSS observations from the KEP Geodetic Observatory for the period from February 2013 to present, the levelling campaigns in 2013 and 2014, and geoid undulations derived from a seamless combination of the latest Gravity Observation Combination (GOCO) 03S and Earth Gravitational Model (EGM) 2008 models.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-529

Mean sea surface determination in the Arctic Ocean using CryoSat-2 observations

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In this study we present the upcoming DTU15 mean sea surface (MSS) model and evaluate the model against existing models and independent observations from e.g. the IceBridge mission.

Radar altimetry satellites have for more than 25 years provided the observations needed to construct reliable global mean sea surfaces and mean dynamic topography (MDT). The main focus of these satellites has been the open ocean and the coverage has therefore been limited to only include the ice-free part of the Arctic Ocean defined as 82 degrees North.

Following the launch of CryoSat-2 in 2010 radar altimetry observation suddenly became available up to 88 degrees North and thereby extending the coverage of the Arctic Ocean substantially. Furthermore the introduction of the Synthetic Aperture Radar (SAR) mode increases the amount of useful echoes.

DTU13MSS was one of the first public available MSS models to include CryoSat-2 observation. DTU13MSS and the derived DTU13MDT showed significant improvement in the Arctic as a result of the inclusion of one year of CryoSat-2 observations. Since the release of the DTU13 models the entire CryoSat-2 mission have been reprocessed by ESA and retracked by LARS the advanced retracking system (LARS) to provide more than four years of observations in the Arctic Ocean.

IAG (Geodesy)

G08p - G08 Sea-Level Observation and Modelling

G08p-530

Analysis of tide-gauge data and correlation with flooding incidents in the UK

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On high-tide coasts such as the UK, flooding incidents are generally assumed to be limited to a few hours per day, due to the high astronomical tide relative to the meteorological tide. In this study, we analyse six tide-gauge time-series of ~30 days period and 15 min sampling-rate, which coincided with a flooding incident in the UK in 2013 or 2014. A step-by-step procedure was followed for the analysis of the tide gauge time-series based on spectral analysis techniques for the estimation of the astronomical and meteorological components of the total tide. The ratio of the meteorological versus the astronomical tide was then estimated and correlated with the flooding incidents. From the correlation it is shown that the flooding incident did not always concur with the period of high-tide and was a result of the combination of the type of the tide (i.e. semi-diurnal tide, diurnal tide, mixed type) and a high meteorological tide relative to a low astronomical tide. Based on these cases, it is suggested that a more combined approach should be followed, by including the type of tide and the correlation of meteorological and astronomical tides, for flood risk assessment on high-tide coasts.