International Workshop on:

Inter-comparison of space and ground gravity and geometric spatial measurements

October 16-18, 2017 - Strasbourg, FRANCE

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Separating Height and Mass Signals in the Gravity Time Series of the Medicina Station, Italy

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Thanks to a long-established collaboration between the Department of Physics and Astronomy (DIFA) of the University of Bologna, Italy, and the Federal Agency for Cartography and Geodesy (BKG), Frankfurt, Germany, a superconducting gravimeter (SG) has been operating continuously at the Medicina station, near Bologna, since the end of October, 1996. Absolute gravity measurements were also performed twice a year in order to provide an independent validation of the relative records. Local crustal movements in the area have been monitored by means of two permanent GPS stations and a VLBI antenna. The reference points of the different instruments have been surveyed repeatedly with dedicated levelling campaigns in order to constrain possible differential vertical motions within the Medicina site. Finally, environmental parameters such as water table levels and temperature data have been acquired regularly. Recently, three soil moisture sensors were installed at different depths in close proximity to a rain gauge. Such auxiliary information is of crucial importance for separating the geometric and mass contributions in the continuous gravity time series, both at long and short time scales. This study has shown that the long-term behavior of the time series is mostly controlled by the natural land subsidence. In the southern Po plain, where Medicina is located, the rate of natural subsidence is large, up to 2 mm/year. However, non-linear long-period features, associated to soil water content and to the anthropogenic contribution to subsidence, are also clearly recognizable. At the annual time scale, a prominent seasonal cycle is observed in the gravity data. This signal is caused by variations of the hydrological loading both in terms of mass contribution and of local vertical displacements. At the base of the pillar on which the SG is installed, the height variation can exceed 2 cm for a water table lowering of 2 m.

*Speaker

Volcano deformation in the Central Andes and the Main Ethiopian Rift: Perspective from integrating InSAR, GNSS and gravimetric observations

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It is generally accepted that many subsurface processes including the migration of magma and/or hydrothermal fluids can cause volcanoes to deform. Given the complexity of not only the causative processes but of the mechanical behaviour of the Earth's crust, the interpretation of deformation signals is challenging. Here we report on our research in Bolivia and Ethiopia where enigmatic volcano deformation has been identify primarily by satellite remote sensing techniques followed by ground-based GNSS and gravity surveys to characterise the processes behind the deformation.
In southern Bolivia, InSAR data from 1992 to 2011 identify a 150-km-wide ground deformation anomaly centered on Uturuncu volcano. Static gravimetric data show that the anomaly is situated above a regional Bouguer gravity low and data inversions propose a complex assembly of vertically elongated low-density bodies which connect a large and partially molten magma reservoir (the Altiplano-Puna magma body, APMB), located _˜20 km beneath the deforming surface with the surface. Using deformation and dynamic microgravimetric data coupled with numerical modelling we show that subsurface stress changes are likely caused by the episodic reorganization of an interconnected vertically extended mid-crustal magmatic plumbing system composed of the APMB and a domed bulge and column structure. Measured gravity-height change gradients point toward low-density hydrothermal fluid migration as the dominant process behind the deformation. Orthometric height changes from leveling and GNSS observations in 1965 and 2011/12 along a regional leveling line that crosses the InSAR deformation anomaly demonstrates that the deformation at Uturuncu has likely been occurring for at least half of a century.

In the Main Ethiopian Rift, satellite geodesy shows ground deformation at several large caldera systems over the past 20 years. Joint deformation and gravimetric observations at two of the calderas (Alutu and Corbetti) over a two-year period between 2014 and 2016 show that residual (after correcting for deformation effects) gravity changes at Aluto follow a complex spatio-temporal pattern which is inconsistent with the spatially coherent pattern of ground deformation observed by InSAR geodesy. This may allude to a decoupling between the sources responsible for deformation and gravity changes. Our interpretation of the gravity changes are predominantly caused by shallow-seated (

In contrast, residual gravity changes at Corbetti point towards a deeper-seated (> 5 km depth)

*Speaker

source compared to Aluto. This source likely coincides with the source of significant uplift recorded at the caldera with mean annual InSAR line-of-sight velocities of up to 7 cm/year in the centre of the caldera. Our preliminary interpretation of deformation and gravity data alludes to volume and density changes in an upper-crustal magmatic reservoir as the source behind the recorded uplift.

The advantages of a field deployable system comprising an iGrav superconducting gravimeter

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Terrestrial gravity measurements, especially those carried out by high-precision superconducting gravimeters (SGs), have increasingly been used in hydrological studies, including inter-comparisons to global hydrological models and GRACE. SGs are usually permanently installed in buildings or in underground observatories under well controlled temperature and low-noise conditions. However, the hydrological interpretation of SG time series recorded in such conditions is in most cases hindered by disturbance of natural local hydrology due to the observatory building itself. We present an outdoor deployable system comprising iGrav SG and a minimized field enclosure for integrative monitoring of water storage changes. We furthermore compare the available gravity variations to near-by observatory SG located inside a building. It is shown that the system performs similarly precise as SGs that have hitherto been deployed in observatory buildings, but with a unique sensitivity to hydrological variations in the surroundings of the instrument. Gravity variations observed by the field setup are almost independent of the depth below the terrain surface where water storage changes occur. Hence, the field SG system can be directly used to quantify the total water storage changes in an integrative way. In contrary, the time series recorded by observatory SGs are strongly influenced by processes occurring below the foundations introducing yet another unknown parameter needed for inter-comparison of space and ground gravity.

*Speaker

Geodynamics and gravity change in Greenland - status and results of absolute gravity measurements collocated with the GNET GNSS stations.

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In studying the nature of vertical land movement in glaciated areas it can be of interest to have collocated measurements of the vertical land movement and gravity change.
A possible scenario is that the vertical movement is caused by changes in the ice load, having two effects: one coming from the present day ice mass changes and one coming from past ice mass changes, e.g. during the deglaciation of the last ice age. These two signals can be described as elastic rebound (ER) and glacial isostatic adjustment (GIA).

The possibility of separating the causes of vertical movement in glaciated areas has been investigated for some time and they often include the use of data of height and gravity change. This will be elaborated in the presentation.

DTU Space began in 2009 to establish absolute gravity (AG) time series at selected stations in the Greenland Network (GNET). These GNET stations consist of permanent GNSS receivers placed on the bedrock all around Greenland. The gravity measurements are done with the A10 gravimeter.

Here is presented some of the preliminary AG data and some of the challenges in making gravity time series in Greenland. An attempt to separate the effect of present and past ice mass changes in the vertical land movement will also be presented.

*Speaker

The relation between surface gravity change and vertical deformation in the Fennoscandian postglacial land uplift region – modelling and observations.

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The postglacial rebound, or Glacial Isostatic Adjustment (GIA), in Fennoscandia is a well-known and extensively studied phenomenon. Systematic, repeated relative gravity measurements started here in 1966 along the so-called Fennoscandian land uplift gravity lines. The main purpose of these observations was to investigate the GIA-induced gravity change and its relation to the geometrical land uplift. Since the 1990s the relative measurements have been complemented and gradually succeeded by repeated absolute gravity observations.
We present, for the first time, the results from almost three decades of repeated absolute gravity observations and compare with the vertical, geometrical deformation rate from a new land uplift model, released by the Nordic Geodetic Commission (NKG) in 2016. The model relies on more than twenty years of GNSS data from permanent reference stations and repeated national levelling campaigns during the last century. The empirical data are combined with a state of the art GIA model.

The empirical results of the relation between the gravity rate of change and the geometrical land uplift are compared to and confirm a theoretical relation from GIA-modelling (1-D earth rheology, normal mode approach). We discuss important aspects of modelled predictions of the relation, such as dependence on earth/ice model, elastic versus viscous contributions, direct attraction and how the predicted relation varies in time and space.

*Speaker
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Absolut and superconducting gravimetry at Onsala Space Observatory - what we have learned since June 2009

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The new gravimetry laboratory at Chalmers University of Technology, Onsala Space Observatory, has been operating since June 2009 when GWR SG 054 was installed. The first AG campaign took place in July 2009, followed by on average one to two campaigns every year. The main interest in the Fennoscandian area relates to Glacial Isostatic Adjustment , the advantage to re-observe AG at OSO stemming from collocation with permanent GNSS and VLBI instrumentation. Not to forget the SG.; nor a broadband seismometer operated at OSO by Uppsala University.
Among the AG's that have observed at OSO are FG5-233 (Lantḿateriet, Ǵavle, Sweden), FG5(X)-220 (IfE Hannover) and GAIN (an atomic interferometer developed at Humboldt University Berlin).

This presentation will detail the problems, lessons and solutions that emerged.

- SG scale factor: Despite formally exceeding the confidence limits of individual campaigns, the long term average scale factor is well compatible with the one retrieved from one month of GAIN , the latter showing higher stability than the co-observing FG5X-220 in the presence of microseisms, at elevated levels at the occasion.

- SG time delay: Using the seismometer and an earthquake at an antipodal location, the time delay in the SG signal chain could be determined at 0.1 s precision (both use GPS time).

- AG drop noise: In an effort to reduce AG without the usual g-software model but rather using the SG and a model for its drift, and doing that at the drop level, we encountered a campaign with a highly skewed histogram; in microseismic noise, the broadband seismometer helped to bring the drop noise back to more a normal level. By the same token, the time-stamping errors of the AG could be determined (now we provide a time service over a private network).

*Speaker

- When all drops (203,000) are combined in a multi-campaign analysis and reduced with simultaneous (and low-pass filtered) SG data, the formal uncertainty range for the drift model is found at the nm/s2 level. However, the rate of change of g is determined at a value that exceeds the one inferred from GNSS and plausible ratios for with significance. Finding the reasons for this discrepancy will keep us busy.

- Analysis of tides and nontidal perturbations has indicated a range of effects at work while others, in particular from ground water, seem to be benign at OSO thanks to careful siting and construction. A problem still awaiting consistent solution presents itself in the long-period domain where annual cycles and sub-cycles appear anomalous, and reconciliation escapes what models for neither global nor regional hydrosphere, atmosphere, and sea level could explain.

The presentation will highlight a subset of the items above, what items in particular can be resolved on the fly. Finally I shall acknowledge the co-operators for supporting and promoting this work.

Validation of a vertical deformation model for storm surges in the Río de La Plata / Argentina by a high resolution gravity time series.

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Since December 2015, the Superconducting Gravimeter SG038 is operated at the Argentine – German Geodetic Observatory (AGGO) located near the city of La Plata, Argentina, providing a continuous, high resolution record of temporal of gravity variations with highest precision and resolution.
After careful preprocessing of the record and downsampling to hourly resolution, atmospheric effects were removed using numerical weather models. A detailed Earth tide analysis was performed then separating more than 50 wave groups and treating degree three tide generating potential independently by making use of the capabilities of the latest version V60 of the Eterna software package. The residual series exhibits significant non-tidal variations reaching up to several microGal which could not be explained by the applied models but are correlated with extreme weather events in the region.
It is known that wind effects are causing surges at the Rio de La Plata during these events. By using tide gauge observations around the river and a simple empirical astronomical tide model (SEAT) it was possible to compute the propagation of the storm surges landwards from the estuary. The corresponding loading effect in terms of gravity shows excellent agreement with the residual gravity time series. This validates both, the high quality of the gravity time series and the storm surge model, which allows now to isolate other small gravity effects, e.g. due to local water storage changes in the gravity record. As space geodetic techniques like SLR and VLBI are affected as well, but will not have the temporal resolution needed to resolve these effects, the model is proposed to correct for the resulting vertical displacements.

*Speaker

Post-glacial sea level without the sea level equation

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Since the seminal paper of Farrell & Clark in 1976, gravitationally self-consistent sea level change has been modelled through solution of the so-called "sea level equation". This integral equation arises due to the ocean load within the problem not being specified a priori, but instead forming part of the solution itself. Over time, this theory has undergone many refinements, and the most sophisticated implementations take account of features like coastline migration, and rotational feedbacks. Nonetheless, the basic ideas underlying the sea level equation remains the same, and its numerical solutions are usually obtained in an iterative manner. Within this talk, we describe a new approach to modelling post-glacial sea level change that does not involve the sea level equation. Instead, we formulate a set of coupled evolution equations for the sea level problem, whose numerical solution can be obtained in a straightforward manner using explicit time-stepping schemes. This approach fully accounts for shoreline migration in a simple and natural manner. Rotational feedbacks have yet to be included, but this will be added in the future. We present a range of numerical calculations to illustrate this method. At present, these calculations are restricted to spherically symmetric earth models, but the method itself has been developed with laterally varying models specifically in mind, and its implementation is trivial given a suitable code for solving elastostatic problems in a laterally heterogeneous earth model. Our approach also allows for a wide a range of linear and non-linear rheological models. Finally, this new formulation of the sea level problem is well-suited to the application of adjoint methods. In a companion presentation by Ophelia Crawford, such applications of the adjoint method to the post-glacial sea level problem will be described along with a range of illustrative numerical calculations.

*Speaker

Global seasonal deformation model derived from GRACE and GNSS time series

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We model surface displacements induced by loading variations in continental water, atmospheric pressure, and non-tidal oceanic loading, derived from the Gravity and Recovery Climate experiment (GRACE) for spherical harmonic coefficients two and higher. The non-observable degree-1 spherical harmonic coefficients are, at first, provided by Swenson et al. (2008). We compare model predictions with geodetic observations at a subset of 689 globally distributed continuous Global Navigation Satellite System (GNSS) sites of the Internatinal GNSS Service (IGS) network. While vertical displacements are well explained by the model at a global scale, horizontal displacements are systematically underpredicted and out-of-phase with GNSS stations position time series. We re-estimate the degree-1 deformation field and geocenter motion from a comparison between our model, with no a priori degree-1 loads, and observations. We show that this approach reconciles GRACE derived loading model and GNSS station positions at a global scale, particularly on the horizontal components. Our results translate into a geocenter motion time series in agreement with those obtained using other geodetic techniques. We also address and assess the impact of systematic errors in GNSS site positions at the draconitic period and its harmonics in the prediction of annual geodetic observations. Our results confirm that redistributions of surface loads derived from GRACE, larger than other hydrological models, combined with an elastic spherical and layered Earth model, can be used to provide first order corrections for loading deformation observed at GNSS sites on both horizontal and vertical components. However, we show that the remaining discrepancies between observations and predictions at a global scale can be explained by a non-elastic rheology of the Earth at an annual time scale. We show that mantle volume variations due to mineral phase transitions may play a role in the seasonal deformation and, as a by-product, use the seasonal deformation mode to provide a lower bound of the transient asthenospheric viscosity.

*Speaker

Solid pole tide in global GPS and superconducting gravimeter observations: signal retrieval and inference for mantle anelasticity

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The mantle anelasticity plays an important role in Earth's interior dynamics. Here we seek to determine the lower mantle anelasticity through the solution of the complex Love numbers at the Chandler wobble period. The Love numbers $h21$, $l21$, $\delta 21$ and $k21$ are obtained in the frequency domain by dividing off the observed polar motion, or more specifically the pole tide potential, from the observed GPS 3-D deformation and SG gravity variation. The latter signals are obtained through the array processing method of OSE (optimal sequence estimation) that results in greatly enhanced SNRs from global array data. The resultant Love number estimates $h21$=0.6248–0.013i, $l21$=0.0904–0.0008i, $\delta 21$=1.156–0.003i and $k21$=0.3125–0.0069i are thus well-constrained in comparison to past estimates that vary considerably. They further lead to estimates of the corresponding mantle anelastic parameters *fr* and *fi*, which in turn determines, under the single-absorption band assumption, the dispersion exponent of α = 0.21±0.02 with respect to the reference frequency of 5 mHz. We believe our estimate is robust and hence can better constrain the mantle anelasticity and attenuation models of the Earth interior.

*Speaker

On Inferring Earth-Structure from GPS Tidal Displacements: a Critical Review

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The recent release of hundreds of GPS-derived tidal displacements with sub-millimeter precision for the semi-diurnal constituent M2 offers promising opportunities to constrain the elastic and anelastic properties of the Earth's crust and upper mantle via data-inversion methods. Formal work on inversion techniques, focussed on ocean-tide loading displacements (OTLD), has only recently appeared in the literature, and an estimate of the asthenosphere's quality factor Q at tidal periods has been put forth for Western Europe. Moreover, the GPS-based tidal displacement field appears sensitive to large-scale lateral heterogeneities for the body tide at inland sites and more so to regional-scale heterogeneities for the load tide at coastal sites. The sub-millimeter precision in the data together with an extensive spatial coverage of GPS stations have long been awaited for in order to infer Earth structure therefrom, and work on this aspect of earth-tide research is expected to grow. Thus, it is timely to revisit the premise of the associated inverse problem, well-stated in the 1970's, and so assess the likelihood of enriching models of the Earth's material and structural properties, beyond those inferred from seismology. Since the 1970's much effort has been devoted to improving ocean-tide models which, now, are well-constrained by altimetry and validated by high-precision gravimeters. In contrast, the Earth structural models used in the computations of OTLD have not evolved much from spherically-symmetric homogeneous stratification, despite major advances in seismology regarding the heterogeneous nature of earth materials at a wide variety of scales. The emphasis of this review is on the potential of OTLD data to estimate Q at the regional scale in light of modern seismological models. A program designed to include material heterogeneities in the construction of an initial model to be used in the data-inversion scheme is also suggested.

*Speaker

Preliminary study of combined earth tide model, Schwiderski OTL model and the Baltic Sea tidal loading in NSiWT tilt observation, Lohja, Finland

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Tidal loading of the tide gauge based mass variation model of the Baltic Sea is combined to with Schwiderski ocean tide loading model and connected with observed earth tide tilt observations of modern interferometric NSiWT tilt meter together with modern earth model.
The Schwiderski ocean tide loading model do not contain the Baltic Sea loading modelling and some wave groups fit well to model tilt together with the Baltic Sea loading. Harmonic tidal diurnal K1 and P1 and semidiurnal S2 and K2 wave groups make correction best to NSiWT observation toward earth tide model. Diurnal O1 and Q1 and semidiurnal M2 and N2 have deviating features. It is interesting, that combined Schwiderski OTL and the Baltic Sea model tilts do not correct at all M2 NSiWT observation toward earth tide model tilt.
The interferometric NSiWT tilt meter has internal calibration and scale is therefore well deternined and stable.

*Speaker

Some theoretical aspects of normal mode theory in linear viscoelastic bodies

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Since the 70s, the development of rheological models to study the Earth's response to surface and tidal loading has advanced considerably. These models, characterised by a spherical symmetry, have seen a very broad range of applications in various fields of geodynamics, such as glacial isostatic adjustment, post-seismic deformations and the tidal deformations of the Earth and terrestrial planets. The "Love numbers" for a given Earth model are traditionally computed by the "viscoelastic normal modes" (VNM) method, based on the Laplace transform of the equations governing the quasi static deformations of a SNREI Earth model. Despite the success of the VNM technique, it is now well documented that it presents some weak points. For example, for finely-layered models or for layers with extremely low values of viscosity and/or a generalised Maxwell rheology, the computation of the Love numbers may be practically difficult. This arises from the numerical stiffness that is inherent in the multi-exponential nature of the VNM solution. Here, a new method is described, taking advantage of a long forgotten time-domain exact formula for the inversion of the Laplace transform, the so-called "Post-Widder (PW) formula", first obtained in the 30s. The pro and cons of the PW formula are discussed, and a few examples are given for case studies in which the traditional VNM method encounters difficulties. By a suite of examples, it is shown that the PW formula can be successfully applied to models with complex generalised transient rheology and it is very efficient for the computation of very short wavelength deformations, induced by fluctuations of small scale components of the cryosphere.

*Speaker

Influence of the Earth mantle rheology on the Chandler wobble period and quality factor and on the gravity-to-height changes ratio under surface loading at intermediate timescales

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Over the whole timescale of geophysical processes, the Earth rheological behaviours are extremely diverse. It is well known that the Earth mantle rheology ranges from mostly elastic with slight anelastic dissipation in the seismic frequency band, to viscoelastic at the Glacial Isostatic Adjustment (GIA) timescale. Even so, at intermediate frequencies, observations of the Earth deformations are sparse, preventing a complete understanding of the Earth rheology. In this work, we thus focus on two kind of processes at intermediate time scales, namely the deformations due to loading at the Earth surface and the Chandler wobble. Both are dependent on the mantle rheology and their study might help filling the gap in our understanding of the mantle behaviour at intermediate frequencies.

We first deal with the computation of the Love numbers and the gravity-to-height changes ratio for a surface loading on an homogeneous Earth model with different mantle rheologies. We investigate the frequency dependency of the induced deformation and the influence of elastic and viscosity parameters, considering both the amplitude and phase of the gravity-to-height changes ratio. We obtain a continuous transition between the short-term and the long-term fluid regime, with the viscosity of the mantle being decisive in the timescales at which this change occurs although it does not affect the extent of the viscoelastic domain. Then we similarly study the influence of the rheological parameters on the Chandler wobble period and quality factor for a Burgers rheological model, showing that for viscosities values commonly found in the literature, the quality factor mostly depends on the Kelvin viscosity and is more sensitive than the period to this parameter. As a conclusion, we will briefly show how these results may be related to geophysical observations to put additional constraints on the Earth mantle rheology.

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On the efficiency of subtracting loading models from GNSS vertical times series

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Within this research, we tested the efficiency of subtraction of the loading models i.e. atmospheric, hydrologic and non-tidal ocean loadings from the Global Navigation Satellite System (GNSS) vertical records. It is widely acknowledged, that the loading effects should be removed from the GNSS time series prior to the estimates of the horizontal and vertical velocities. On the one hand, the loading models can be removed directly from the GNSS data with no interest in leaving the spectral properties of GNSS time series intact. Other ways, the loading models can be removed in more sophisticated way than a direct subtraction. We employed data from more than 350 permanent IGS (International GNSS Service) stations, derived as the official contribution to ITRF2014 (International Terrestrial Reference Frame). We proposed the method of optimal subtraction of loading effects by applying the Improved Singular Spectrum Analysis. The advantage in the proposed method lies in no artificial loss of energy in the Power Spectrum Density between 4 and 80 cpy observed comparing to the case when environmental loadings have been subtracted directly from the position time series. Finally, we estimated Dilution of Precision (DP) of the vertical velocities of the ITRF2014 series. For 81% of analysed stations, the DP was lower than 1, which means the improvement in the vertical velocity uncertainty due to more efficient modelling of time-varying seasonal signals in the loadings.

*Speaker

Geophysical Fluid Layer Modelling for Geodetic Applications

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The Earth System Modelling group at Deutsches GeoForschungsZentrum (ESMGFZ) in Potsdam is routinely processing a number of geophysical background or correction models for geodetic applications. Those include the Atmosphere and Ocean Non-Tidal De-Aliasing Product AOD1B of the GRACE mission, Earth rotation excitation functions, and surface crustal deformations. All products are consistently processed from identical global mass re-distributions in atmosphere, oceans, and the continental hydrosphere. The data-sets all start in 1976 and are routinely updated once per day. In addition, 6-days-long predictions are provided for near-realtime applications. All data and its associated documentation are publicly available via www.gfz-potsdam.de/en/esmdata.

This contribution will describe the latest product version released by ESMGFZ in spring 2017. We will discuss in particular the improved long-term consistency achieved by reducing both artifical drifts in the ocean and land simulations as well as jumps associated with occasional ECMWF model changes. Further, we will demonstrate that the sub-daily variability is substantially improved due to the newly imposed separation of atmospheric pressure tides and its associated oceanic response. And finally, the quality of the 6-days-long is evaluated against the (subsequently available) final products in order to discuss the prospects of using geophysical background information in rapid GNSS network processing.

*Speaker

Determination of long-term trend and time-varying seasonal oscillations from gravity records using Singular Spectrum Analysis

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Singular Spectrum Analysis (SSA) is a non-parametric method applied to estimate the non-linear trend, seasonal signals and noise from various time series without prior analysis of the time series character. This approach consists of two complementary stages: a decomposition of the original time series into a sum of components and a reconstruction of particular components which are of interest. In this research, we used the SSA approach to determine long-term trends and seasonal signals (annual and Chandler wobble periods) from superconducting gravimeter (SG) observations. The SSA approach takes an advantage over commonly used Least Squares Estimation by extracting trend which is non-linear and amplitudes of seasonal signals which may change over time. We used 1-minute gravity data from 9 stations located worldwide included in the International Geodynamics and Earth Tides Service (IGETS). The length of SG observations ranged from 15 to 19 years. Before analysis was performed, the local tides, atmospheric (ECMWF data), hydrological (MERRA2 models) and non-tidal ocean loading (ECCO2 models) were removed. In the first step of study, we extracted non-linear trend using SSA adopting one-year lag-window. For all stations, long-term trends occur in the first Reconstructed Component (RC). We noticed that the main variability of the SG data stems from the long-term changes included in the 1st mode which explains approximately 96% of the total variance of SG records for Strasbourg station. In the second step of our study, we determined the annual and Chandler wobble signals for all stations which are characterized by time varying amplitude.

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How do the Different Noise Levels Affect the Estimates of Seasonal Signals?

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The following research focuses on the estimates of seasonal signal from Global Navigation Satellite System (GNSS) position time series under different noise levels being present in data. Seasonal signal, which is commonly modelled by two periodic signals of annual and semi-annual frequencies and amplitudes constant over time. However, the amplitudes may vary slightly over time, as the geophysical phenomena which cause the seasonal changes are not constant over time. In this presentation, we give an overall analysis of seasonal signals estimates for a set of 174 IGS (International GNSS Service) stations processed by Jet Propulsion Laboratory. With a use of synthetic benchmark of a character of real GNSS position time series, the annual and semi-annual changes were determined with Wavelet Decomposition (WD), Singular Spectrum Analysis (SSA), Chebyshev Polynomial (CP) or Kalman Filter (KF). We show that ignoring the variations in the amplitude of the seasonal signal results in a bias of the spectral index of a power-law noise towards flicker noise. For a high noise level, KF tuned with the autoregressive process produces a smaller misfit between synthetic seasonal signal and the estimated curve. For a low noise level, KF, SSA and CP produce comparable results. For real GPS data, SSA and KF can model 49-84% and 77-90% of the variance of the true varying seasonal signal, respectively.

*Speaker

Geocenter motions and Earth figure changes as seen by ITRF2014

Laurent Métivier * [1], Hélène Rouby [1], Paul Rebischung [1], Zuheir Altamimi

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The up-to-date solution of the International Terrestrial Reference Frame, entitled ITRF2014, presents particularly large vertical velocities across Greenland, South East Alaska and the Antarctic Peninsula, compared with the previous solution ITRF2008. We investigate here the geophysical origin of this frame evolution and its implication in terms of geocenter motions and Earth figure changes. Using GNSS station velocities we calculate degree-1 and degree-2 Spherical Harmonics Coefficients (SHC) of the solid Earth figure changes at different dates. We show that these SHC are close to those predicted by Glacial Isostatic Adjustment models except for zonal SHC. Our results indicate that the center of figure of the Earth is currently moving towards North Pole with respect to the center of mass and that the solid Earth oblateness is increasingly diminishing. These changes in solid Earth figure are probably due to recent ice melting in Greenland and Antarctica and have tended to increase regularly during the ITRF2014-GNSS timespan. Finally, we investigate Earth's J2-rate and we confront our results to independent observations.

*Speaker

Limitations, Challenges, and Prospects of Different Space Geodetic Techniques used for the Determination of the Geocenter Motion

Krzysztof Sosnica *† [1]

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A redistribution of mases in the fluid layers of the Earth, e.g., in oceans, atmosphere, cryosphere and land hydrology, induces changes in the center of mass of surface loads which can be observed as a translation of the solid Earth relative to the center of satellite orbits. By definition, the international terrestrial reference system (ITRS) shall be geocentric, i.e., with the origin in the center of mass being defined for the whole Earth, including oceans and atmosphere. However, due to the surface mass redistribution, Earth's center of mass varies unceasingly. The practical realization of the ITRS situates the origin in the mean position of the center of mass from the long-term analysis using geodetic techniques which are, on the one hand, most sensitive to the Earth's center of mass, and on the other hand least perturbed by external forces. Geocenter motion is typically defined as an instantaneous translation vector of the origin between two terrestrial reference frames. One frame has its origin in the Earth's center of mass and determines the Earth satellites' motion as being coincidental with the orbital focal point of artificial satellites. The second frame is realized by a subset of international terrestrial reference frame core stations whose coordinates can be considered as well-determined and reliable. Theoretically all satellite techniques can be used for the estimation of the geocenter motion. However, recovery of geocenter motion using DORIS or GNSS data is challenging due to orbit modelling issues for satellites equipped with large solar panels, modeling of the signal delay in the atmosphere, estimating clock parameters, biases or forming double differences of observations. SLR constitutes currently the best technique for the recovery of the geocenter motion, however, geocenter motion estimated from SLR suffers from the inhomogeneous distribution of SLR stations, which cause a substantial network effect, and some correlations between estimated empirical orbit parameters and the Z component of the geocenter. Moreover, the geocenter motion cannot be properly derived from SLR data when only the global translation vector is estimated without accounting for relative station displacements caused by surface load density variations. As the mass redistribution influences not only on the translation parameter of the Earth's center of mass, but also on surface loads causing the relative displacements between ground stations, the geocenter motion can indirectly be observed by all techniques capable of determining station coordinates: VLBI, GNSS, SLR, and DORIS. Moreover, GRACE K-band observations, despite being insensitive to direct translations of the reference frame origin, can support the recovery of the geocenter motion by complementing load surface displacements in the areas with no core stations. This study will summarize all space geodetic techniques and methods used for the recovery of the geocenter motion with a discussion of limitations, challenges, and prospects of alternative and supporting techniques of the determination of the geocenter motion.

*Speaker

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Independent geocenter determination with DORIS: disentangling analysis and modeling effects in the realization of the ITRF origin

Alexandre Couhert * [1], Flavien Mercier [1], John Moyard [1], Richard Biancale [1]

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Geocenter motion observation is one of the most demanding applications of high precision geodetic techniques. Currently, Satellite Laser Ranging (SLR) solely contributes to the realization of the International Terrestrial Reference Frame (ITRF) origin. Even though among the space geodetic techniques SLR is the only one that derives well-established geocenter coordinates, SLR measurements are affected by systematic biases and suffer from a nonhomogeneous network distribution of tracking stations. Due to the lack of reliable independently derived geocenter motion estimates, it remains unclear how these errors propagate into the ITRF origin. Consequently, the demonstration of other geodetic techniques to contribute to the Earth's center of mass determination is of utmost importance. The geocenter vector measured by Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) so far ended with a lesser precision, as was to be expected given the less accurate positioning information, and the significant challenges to precise orbit determination (modeling of the non-gravitational forces) presented by the satellites tracked. However, the DORIS (and Global Navigation Satellite System, GNSS) tracking network is uniquely well distributed geographically. Likewise, as a microwave tracking system, DORIS (and GNSS) observations are not limited to cloudless weather, which can adversely create systematic effects in SLR-based estimations. Thus DORIS (but also GNSS) contribution to geocenter motion determination may also play a role. While obtaining independent DORIS-based geocenter time series, this paper shows how DORIS observations can contribute to allow insight into model and geodetic technique errors, and provide an independent assessment of the ITRF origin stability.

*Speaker

Adjoint-based sensitivity kernels for post-glacial sea level change

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We apply the adjoint method to the post-glacial sea level problem in order to calculate the derivatives of measurements with respect to mantle viscosity and ice sheet history. These derivatives, or kernels, quantify the linearised sensitivity of such measurements to their underlying model parameters. The adjoint method, which has previously been used within a range of other geophysical applications, enables efficient calculation of theoretically exact sensitivity kernels within laterally heterogeneous earth models having a range of linear or non-linear viscoelastic rheologies. The kernels have a number of applications within the inverse problem. Firstly, they can be used within a gradient-based optimisation method to find a model which minimises some data misfit function. The kernels can also be used to quantify the uncertainty in such a model and hence to provide understanding of which parts of the model are well constrained. Finally, they enable construction of measurements which provide sensitivity to a particular part of the model space. We illustrate potential applications of this method for studies of glacial isostatic adjustment through a range of numerical calculations relative to a spherically symmetric background model.

*Speaker

Comparison of the semi-empirical land uplift model NKG2016LU and GIA-modelled present-day geodetic variations in Fennoscandia based on different ice models

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Post-glacial rebound is the ongoing response of the Earth and the ocean to the melting of Pleistocene ice sheets. This unloading initiated an uplift of the crust close to the centers of former ice sheets. Today, vertical surface velocities in Fennoscandia reach values up to around 1 cm/year and are dominated by post-glacial rebound, while additional signals caused, e.g., by the elastic rebound from contemporary melting of glaciers, tectonic processes or hydrological loading contribute less.
Along with the crustal uplift, also the geoid undergoes corresponding temporal variations. Geoid rates are of particular interest for (i) the definition and realization of vertical reference frames and (ii) for the inter-comparison of geodetic observing techniques like GNSS and levelling. This is, because the geoid may act as height reference surface and because it allows connecting geometric with physical height values, respectively the corresponding vertical velocities. Thereby, our main interest is to quantify the sensitivity of geoid rates in Fennoscandia as a function of mantle rheology and ice history, and to compare modelled geoid rates and surface velocities with observations.
In the present study, we use different ice histories (i.e., ICE-3G, ICE-5G, ICE-6G) to model the present-day geodetic variations in Fennoscandia using the SEa Level EquatioN solver (SELEN). In turn, we compare the semi-empirical land uplift model NKG2016LU for the Nordic-Baltic region, based on GNSS and levelling, with the modelled present-day geodetic variations to get an insight into the development of ice models throughout time and the significance of model differences for the derived quantities (crustal uplift and geoid rates).

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Variational principles for the elastodynamics of rotating planets

Matthew Maitra *† [1], David Al-Attar [1]

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We present some recent theoretical work on variational principles for the rotational dynamics of self-gravitating elastic planets. Using an approach closely related to Euler-Poincare reduction, we derive a useful form of Hamilton's principle in which a solid planet's motion is partially decoupled into translational, rotational, and internal components. For the case of a two body problem, we obtain the exact equations of motion, and use them to characterise a wide class of relative equilibria. We also consider how Hamilton's principle can be formulated in a planet comprised of both solid and fluid regions, where we must allow for tangential slip across fluid-solid boundaries. Future work will extend this latter variational principle to allow for relative rotation between the fluid and solid regions, and so provide a natural framework to study long period free oscillations and tidal deformation.

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Vertical deformation by environmental loading and space geodetic measurements at Mets'ahovi geodetic research station

Arttu Raja-Halli * [1], Maaria Nordman [1], Heikki Virtanen [1]

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Mets'ahovi Geodetic Research Station is becoming one of Global Geodetic Observation System's (GGOS) core sites co-locating all space geodetic techniques together with absolute and superconducting gravimeters. However, the vicinity of Baltic Sea and non-tidal sea level variance together with hydrological and atmospheric pressure changes may produce a vertical displacement of more than 10mm affecting the geodetic measurements made in Mets'ahovi as well as a change of several microGal's in measured gravity. To achieve GGOS's 1mm accuracy goal for co-located space geodetic measurements we need to better understand and model these environmental effects. During 2018 and 2019 we will start satellite laser ranging (SLR) and very long baseline interferometry (VLBI) observations with the new state-of-the-art systems at Mets'ahovi. Here we present preliminary results of calculations showing the contribution of different loading factors on the overall vertical displacement affecting the space geodetic measurements at Mets'ahovi.

*Speaker

Gravimetry and gravity-gradiometry based on atom interferometry

Christian Schubert *† [1], Sven Abend [1], Dennis Schlippert [1], Wolfgang Ertmer [1], Ernst Rasel [1]

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Interferometry with matter waves enables precise measurements of rotations, accelerations, and their differences [1-5]. This can be exploited in fundamental sciences [2,3], but also for gravimetry [4], and gravity gradiometry [2,5].
The Quantum Sensors group at the Institut f́ur Quantenoptik in Hannover pursues several, complimentary approaches. A large scale device is designed to investigate the gain in precision for gravimetry, gradiometry, and fundamental tests on large baselines [6]. For field applications, a compact and transportable device is developed. It features an atom chip source which provides a high flux [7] of collimated [8] atoms. This is expected to mitigate dominant systematic uncertainties [9]. The atom chip technology and miniaturization benefits from microgravity experiments in the drop tower in Bremen and sounding rocket experiments [8,9] which act as pathfinders for space borne operation [10].

This contribution will introduce atom interferometry and our various activities in this field.

The presented work is supported by the CRC 1227 DQmat within the project B07, the CRC 1128 geo-Q within the project A02, the QUEST-LFS, the German Space Agency (DLR) with funds provided by the Federal Ministry of Economic Affairs and Energy (BMWi) due to an enactment of the German Bundestag under Grant No. DLR 50WM1331-1137, 50WM1641, and "Niederśachsisches Vorab" through the "Quantum and Nano- Metrology (QUANOMET)" initiative within the project QT3.

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Mass variations of the Baltic Sea and atmosphere observed with new superconducting gravimeters at Mets´ahovi 2016 - 2017

Heikki Virtanen * [1], Maaria Nordman [1], Arttu Raja-Halli [1]

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Known loading effect of the Baltic Sea was studied with superconducting gravimeter T020 in 1994-2016. Gravity effect can be up to 30 nms-2 and vertical motion 10 mm. In earlier studies we have exploited single tide gauges together with local airpressure and HIRLAM grids.

The new superconducting gravimeters iGrav013 and iOSG022 were installed in Mets´ahovi in 2016. We have modelled the surface of the Baltic Sea into hourly grids using about 30 tide gauges. Stations are located around the shores and the data is downloaded from BOOS and Finnish Meteorological Institute web portals.

We have used SPOTL program package for calculating gravity effect and vertical loading. For atmospheric contribution we have used local airpressure and global services by ATMACS and EOST. Cleaned gravity data were corrected by local tidal mode and also for drift. In addition, hydrological corrections were applied.

Gravity residuals were compared to surface models and different airpressure corrections. We have also used some single tide gauge data to see how the surface models perform.

We present as results standard deviations of time series with different combinations. Some special cases are shown with detailed plots.

*Speaker

Monday, October 16, 2017

TIME	EVENT
12:00 - 14:00	Reception of participants - Welcoming of participants to get their badges
14:00 - 14:20	Introduction of the workshop (amphi Alain Beretz, Nouveau Patio) - S. Rosat and the Scientific Organizing Committee
14:20 - 16:00	1. Comparison gravity - space technique (amphi Alain Beretz, Nouveau Patio) - H. Steffen, J. Arnoso
14:20 - 15:00	› Volcano deformation in the Central Andes and the Main Ethiopian Rift: Perspective from integrating InSAR, GNSS and gravimetric observations - *Joachim Gottsmann, School of Earth Sciences [Bristol]*
15:00 - 15:20	› Separating Height and Mass Signals in the Gravity Time Series of the Medicina Station, Italy - *Sara Bruni, Department of Physics and Astronomy, University of Bologna, Italy*
15:20 - 15:40	› Validation of a vertical deformation model for storm surges in the Río de La Plata / Argentina by a high resolution gravity time series. - *Hartmut Wziontek, Federal Agency for Cartography and Geodesy, Leipzig*
15:40 - 16:00	› Absolut and superconducting gravimetry at Onsala Space Observatory - what we have learned since June 2009 - *Hans-Georg Scherneck, Chalmers University of technology & Onsala space observatory, Chalmers University of technology & Onsala space observatory*
16:00 - 16:30	Coffee break (room 0-01, Nouveau Patio)
16:30 - 18:00	1. Comparison gravity - space technique (amphi Alain Beretz, Nouveau Patio) - J. Arnoso, H. Steffen
16:30 - 17:10	› Geodynamics and gravity change in Greenland - status and results of absolute gravity measurements collocated with the GNET GNSS stations. - *Emil Nielsen, Technical University of Denmark*
17:10 - 17:30	› The relation between surface gravity change and vertical deformation in the Fennoscandian postglacial land uplift region – modelling and observations. - *Per-Anders Olsson, Lantmäteriet*
17:30 - 17:50	› The advantages of a field deployable system comprising an iGrav superconducting gravimeter - *Michal Mikolaj, Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences*

Tuesday, October 17, 2017

TIME	EVENT
09:30 - 10:30	3. Realization of a terrestrial reference frame (amphi Alain Beretz, Nouveau Patio) - J.-P. Boy, J. Bogusz
09:30 - 09:50	› Geophysical Fluid Layer Modelling for Geodetic Applications - *Henryk Dobslaw, GFZ Potsdam*
09:50 - 10:10	› On the efficiency of subtracting loading models from GNSS vertical times series - *Janusz Bogusz, Military University of Technology*
10:10 - 10:30	› Determination of long-term trend and time-varying seasonal oscillations from gravity records using Singular Spectrum Analysis - *Marta Gruszczynska, Séverine Rosat, Anna Klos, Janusz Bogusz*
10:30 - 11:00	Coffee break (room 0-01, Nouveau Patio)
11:00 - 12:40	3. Realization of a terrestrial reference frame (amphi Alain Beretz, Nouveau Patio) - J. Bogusz, J.-P. Boy
11:00 - 11:40	› Geocenter motions and Earth figure changes as seen by ITRF2014 - *Laurent Métivier, Institut de l'information géographique et forestière*

TIME	EVENT
11:40 - 12:20	› Limitations, Challenges, and Prospects of Different Space Geodetic Techniques used for the Determination of the Geocenter Motion - *Krzysztof Sosnica, Wroclaw University of Environmental and Life Sciences*
12:20 - 14:00	Lunch
14:00 - 14:40	3. Realization of a terrestrial reference frame (amphi Alain Beretz, Nouveau Patio) - J. Bogusz, J.-P. Boy
14:00 - 14:20	› Independent geocenter determination with DORIS: disentangling analysis and modeling effects in the realization of the ITRF origin - *alexandre couhert, CNES*
14:20 - 14:40	› How do the Different Noise Levels Affect the Estimates of Seasonal Signals? - *Anna Klos, Military University of Technology*
14:40 - 16:00	2. Love numbers, rheology, ... (amphi Alain Beretz, Nouveau Patio) - Y. Rogister, S. Rosat
14:40 - 15:20	› Some theoretical aspects of normal mode theory in linear viscoelastic bodies - *Giorgio Spada, Department of Pure and Applied Sciences, University of Urbino "Carlo Bo"*
15:20 - 16:00	› Post-glacial sea level without the sea level equation - *David Al-Attar, University of Cambridge*
16:00 - 16:30	Coffee break (room 0-01, Nouveau Patio)
16:30 - 18:00	Posters (room 0-01, Nouveau Patio)
16:30 - 18:00	› Adjoint-based sensitivity kernels for post-glacial sea level change - *Ophelia Crawford, University of Cambridge*
16:30 - 18:00	› Comparison of the semi-empirical land uplift model NKG2016LU and GIA-modelled present-day geodetic variations in Fennoscandia based on different ice models - *Martina Idžanović, Faculty of Science and Technology, Norwegian University of Life Sciences*
16:30 - 18:00	› Gravimetry and gravity-gradiometry based on atom interferometry - *Christian Schubert, Institut für Quantenoptik, Leibniz Universität Hannover*
16:30 - 18:00	› Mass variations of the Baltic Sea and atmosphere observed with new superconducting gravimeters at Metsähovi 2016 - 2017 - *Heikki Virtanen, Finnish Geospatial Research Institute, National Land Survey*
16:30 - 18:00	› Variational principles for the elastodynamics of rotating planets - *Matthew Maitra, University of Cambridge*
16:30 - 18:00	› Vertical deformation by environmental loading and space geodetic measurements at Metsähovi geodetic research station - *Arttu Raja-Halli, Finnish Geospatial Research Institute, National Land Survey*
19:30 - 23:00	Dinner - Dinner at Restaurant de la Victoire

Wednesday, October 18, 2017

TIME	EVENT
09:30 - 10:30	2. Love numbers, rheology, ... (amphi Alain Beretz, Nouveau Patio) - Y. Rogister, S. Rosat
09:30 - 09:50	› Global seasonal deformation model derived from GRACE and GNSS time series - *Kristel Chanard, LAboratoire de REcherche en Géodésie [Paris]*
09:50 - 10:10	› On Inferring Earth-Structure from GPS Tidal Displacements: a Critical Review - *Pierre-Michel Rouleau, Memorial University of Newfoundland - Grenfell Campus*
10:10 - 10:30	› Influence of the Earth mantle rheology on the Chandler wobble period and quality factor and on the gravity-to-height changes ratio under surface loading at intermediate timescales - *Yann Ziegler, Observatoire de Paris*
10:30 - 11:00	Coffee break (room 0-01, Nouveau Patio)

TIME	EVENT
11:00 - 11:40	2. Love numbers, rheology, ... (amphi Alain Beretz, Nouveau Patio) - S. Rosat
11:00 - 11:20	› Solid pole tide in global GPS and superconducting gravimeter observations: signal retrieval and inference for mantle anelasticity - *Benjamin F Chao, Inst. Earth Sciences, Academia Sinica, Taiwan*
11:20 - 11:40	› Preliminary study of combined earth tide model, Schwiderski OTL model and the Baltic Sea tidal loading in NSiWT tilt observation, Lohja, Finland - *Hannu Ruotsalainen, Finnish Geospatial Research Institute, NLS*
11:40 - 12:00	Closure of the workshop (amphi Alain Beretz, Nouveau Patio) - S. Rosat and the Scientific Organizing Committee

List of participants

- Al-Attar David
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- Bogusz Janusz
- Boy Jean-Paul
- Bruni Sara
- Chanard Kristel
- Chao Benjamin F
- Couhert Alexandre
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- Ziegler Yann
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