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BOOK OF ABSTRACTS

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GOCE SGG wavelet multi-resolution analysis to the latest Level 2 GOCE baselines

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ESA's GOCE satellite mission, active from 2009 to 2013, has provided remarkable contributions to the computation of the gravity field of the Earth through the use of Satellite Gravity Gradiometry (SGG) data. The present study focuses on the application of SGG processing procedures to the latest released Level 2 GOCE baselines accessible from ESA GOCE Online Dissemination service. At the pre-processing stage, GOCE SGG data were examined with outlier detection algorithms, while Laplace equations were determined for the various baselines in order to identify the optimal one for process. Disturbing gravity gradients (T_{ij}) were computed at satellite altitude in LNOF through the use of EGG_NOM_2 and SST_PSO_2 data according to well established methodologies. Filtering of GOCE SGG data to the Gradiometer's Measurement Bandwidth (MBW) was one of the key aspects of the applied methods. Validation of the results was accomplished by comparing them to disturbing gravity gradients based on the EGG_TRF_2 products and Global Geopotential Models (GGMs) in LNOF at satellite altitude. In this study, the complete GOCE SGG dataset, for mission lifetime, has been used. The computed T_{ij} were then projected to a Mean Orbit (MO) by using GGM T_{ij} gradients at different altitudes, cut in a region encompassing the wider Hellenic and Eastern Mediterranean areas and placed on a 1'x1' grid. 2D Wavelet Multi-Resolution Analysis (WL-MRA) at 14 levels of decomposition was applied to the T_{ij} grid in the area of study, in order to remove satellite tracks appearing as noise. A large number of signal reconstruction scenarios were tested, using different levels of decomposition corresponding to different spatial resolutions. A signal reconstruction using only levels 7 to 14 was finally deemed to represent the best solution both for the T_{zz} and the $-T_{xx}-T_{yy}$ gradients. The final processed and filtered observations refer to components of T_{ij} at the MO level which can then be used for various geodetic and gravity field modelling applications.

Keywords: GOCE, Satellite Gravity Gradiometry, EGG_NOM_2, SST_PSO_2, MBW, EGG_TRF_2, Tij, Global Geopotential Model, 2D WL-MRA

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Poster)

Application of machine learning algorithms to EWT variations forecasting from GRACE/GRACE-FO

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The GRACE and GRACE-FO satellite missions monitor temporal variations of the Earth's gravity field which can be converted to water mass variations and serve as a tool to monitor global climate change. Their data can be used to monitor phenomena related to the Earth's natural processes and directly to the hydrological cycle. However, the existence of a data gap between the two successive missions, poses a problem in earth monitoring missions, as the continuity of the timeseries is interrupted and note guaranteed. GRACE/GRACE-FO mission Level 2 data are usually available as Stokes' coefficients while products based on Mascons (Mass Concentration Blocks) are also available. The advantage of solving with the Mascons method is that it is not necessary to apply filters to smooth the data, while a coastline resolution filter (CRI) also allows better separation of land and sea signals. The recent evolution and development of Machine Learning (ML) methods has been shown to be efficient as forecasting tools, especially in the case of missing data, through the creation of reliable information learning models. The challenges of ML capabilities are related to the complexity of choosing the right algorithm and the right structure of the prediction model. The algorithm evaluation stage is the most crucial one for predicting the unknown values and requires the study of several algorithms of simple and complex form. Within that frame, regression algorithms are chosen to create training datasets for the ML model and predict Equivalent Water Thickness (EWT) values for the GRACE/GRACO-FO data gap between the two satellite missions. The creation of the initial data matrix (Input) X, the response matrix (Output) Y and the analytical evaluation of the algorithm's behavior to the data prediction, are the most crucial for the performance of the forecasting. Three different matrix experiments, three different model validation methods and a final evaluation method of the calculated EWT values have been carried out. The wider Amazon region is selected for the representation of the unknown EWT values instead of a global scale area to reduce the dimensions of the initial matrix, the prediction time, and the evaluation time of the regression algorithms. The evaluation process is completed through three different processing stages, while the prediction of the unknown EWT values is completed separately for each cell of the monthly grid. The reliability of the algorithms is evaluated on all grid cells of the area for each selected month of the prediction period, and results on the appropriateness of the ML-based methodology and the accuracies achieved are drawn.

Keywords: GRACE, Mascons, Machine Learning, Regression Algorithms, Cross Validation

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral/Poster/no preference): Poster

GRAVITY DATA ANALYSIS BY WAVELET TRANSFORM

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Geophysical technology passive source potential method gravitational, satellite gravity ,magnetic, magnetotelluric,earthquake data passive seismic imaging and active source reflection exploration seismology , electromagnetic, ground penetrating radar , etc. are employed for lithosphere subsurface imaging for extractive industries hydrocarbon mining mineral coal ,geothermal , natural geologic white hydrogen and earth crust (continental and oceanic) architecture basin analysis. Geophysical signals are multiscale and nonstationary in character.The multiscale decomposition of the geophysical data takes into account the timescale localization properties of the wavelet transform. In computation dilation property comes first then translation, this is not commutative for wavelet transform.. Spectral leakage smearing of wavelet transform is corrected by synchrosqueezed wavelet transform nonlinear nonstationary signal empirical mode decomposition. The observed gravity anomalies are the superposition of anomalies induced by geologic bodies at different depths. Regional residual anomaly separation is one of the important tasks in gravity inversion and interpretation. The ability of the wavelet transform to improve the resolution of gravity anomaly and use depth estimation from spectrum analysis to analyse the wavelet decomposition results. The maximum decomposition scale relates the dimension of the original data, and the scale can take continuous values with a maximum of half of the data dimension.Continuous Wavelet Transform is tool for the gravity data analysis and interpretation of Bouger anomalies .It provides source parameters such as the location, depth, structure and geometry of geological bodies and interfaces in an easy and effective way without any a priori information and thus can be further used for modeling and inversion. Interpretation of gravity anomalies suffers from the well-known non-uniqueness of the inverse problem. The Continuous Wavelet Transform is a convolution of the input data with a set of functions generated by translations and dilations of the so-called mother wavelet. Assuming the fields to be homogeneous, the Continuous Wavelet Transform technique can be used in order to recover simultaneously the average depth and shape of causative sources. In 3D, wavelet transform exhibits a cone-like structure where top of the cone gives the location of the source. The intersection of modulus maxima lines gives the mean depth of the source. To identify and characterize the causative sources of the anomaly, the WT technique is applied on the gravity data (Bouger gravity anomaly), the mean depth of the sources calculated using WT technique points towards the sediment thickness. Improving resolution of gravity data with wavelet analysis : Gravity data are the results of gravity force field interaction from all the underground sources. The objects of detection are always submerged in the background field, and thus one of the crucial problems for gravity data interpretation is how to improve the resolution of observed information. effects of improving resolution of gravity data with wavelet analysis and spectral method, and revealed the geometric characteristics of density heterogeneities described by simple shaped sources. Joint inversion gravity , magnetic and seismic data is very efficient for precise subsurface imaging lithosphere. Machine learning is employed for wavelet transfor gravity data analysis.

Keywords: Gravity Data, Wavelet Transform, Data Analysis, Interpretation

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference (Poster)

The temporal evolution of the physical heights: Theoretical and practical considerations under the prism of the International Height Reference Frame realization

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The future realization of the International Height Reference Frame dictates that except from the accurate determination of the static part pf the physical heights (e.g. orthometric or normal heights or/and geopotential numbers) the associated and indivisible dynamic part (e.g. height or geopotential rate) should be also consistently estimated. However, the temporal evolution of the physical heights is not a straightforwardly solved issue. At the present time, there are multiple factors and problems confining and holding up the robust estimation of the physical heights' temporal evolution. These vary from the current accuracy and resolvable resolution of temporal mass variations from GRACE/GRACE-FO type of missions; shortcomings in the spatial resolution of GNSS-derived geometric height rates; limitations in the accuracy of satellite-only global geopotential models; reference system and reference frame realization of SAR/InSAR deformation rates, etc.. The present study aims to point out the pitfalls of the existing methods, in modeling the temporal evolution of physical heights, both in terms of the spatial scales and accuracy estimated. The latter refer to the combination of GNSS, SAR/InSAR, tide-gauge, geoid, gravity and local orthometric heights at IHRF sites, accounting for both the geometric and dynamic change of a station position. Additionally, we suggest some alternatives which can be used for the first IHRF realization in the direction of the consistent physical height temporal evolution.

Keywords: IHRF, potential rates, GNSS, InSAR, reference frame

Session 1 "Reference Systems and Frames in Physical Geodesy"

Presentation preference (Oral)

GGOS Portal | The future Metadata Platform for Geodetic Data - Feasibility Study and Perspectives

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The services of the International Association of Geodesy (IAG) provide very important and valuable geodetic data, information, and data products that are increasingly relevant for Earth system research, including monitoring of global change phenomena and a wide range of diverse applications such as satellite navigation, surveying, mapping, engineering, geospatial information systems, and so on.

Currently, it is difficult for many people to obtain an overview of all available geodetic products and data. The Global Geodetic Observing System (GGOS) of the IAG aims to fill this gap by developing the GGOS-Portal (ggos.org/portal), which will serve as a unique search and access point (one-stop shop) for geodetic data and products. Data and products will be described by rich metadata and remain physically located at their originating data centers of each contributing IAG service and other data providers. With this future platform, GGOS will contribute to increase the visibility of geodetic data for scientific research and to make other disciplines and the society aware of geodesy and its beneficial products.

Several software packages are available for the realization of such a metadata platform. Two of them are particularly suitable for this purpose: GeoNetwork and CKAN. Based on the community survey conducted in spring 2023, a requirements profile for the GGOS portal was drawn up as part of a feasibility study and compared with the tested functionalities of the two software packages. A particular focus was on testing the metadata harvesting function.

Keywords: GGOS, portal, metadata, visibility, geodetic data

Session you submit your abstract to: Session 6: Data management, dissemination of results and networking of stakeholders

Presentation preference (Oral/Poster/no preference): oral

Altimetry Data Analysis for Coastal Erosion: A Time Series Approach

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Addressing coastal erosion is of paramount importance for the preservation of coastal environments and ecosystems. The needs of geosciences require determining the Earth's gravity field and geoid with very high accuracy on the order of ±1cm for wavelengths ~10km along the coastal front in order to assimilate with other earth observation data, either satellite and terrestrial ones. This precision is essential for understanding Earth's internal processes, ocean dynamics, tectonic plate interactions, as well as studying ice mass balance in oceans, sea level variations, Earth's mass balance on short time scales, and uplift systems on regional and global scales. In this context, the use of satellite altimetry data has proven particularly effective. This study presents the results of a multi-year analysis of altimetry data, focusing on the Aegean Sea, Greece and covering classical low resolution mode (LRM) and SAR/SARin data. Two main analysis methods are used, as a tool to infer the main modes of sea level variation and its trend, i.e., Empirical Orthogonal Function/Principal Component Analysis (EOF/PCA) and Wavelet Transform. Based on the aforementioned approaches, the annual and semi-annual patters are identified in the altimetry time-series, while the trend of sea level variations is devised. The latter is used in combination with a digital terrain and bathymetry model, along with surface deformations from nearby GNSS stations to simulate coastal flooding as a direct impact of sea level rise. Two scenarios, based on a 50-year and 100-year simulation are presented, identifying the areas over the North Aegea Sea which are more susceptible to flooding and hence more vulnerable to erosion.

Keywords: satellite altimetry, time-series analysis, multi-year trend, coastal erosion, vulnerability.

Session 5: Gravity for climate, atmosphere, ocean and natural hazard research

Presentation preference (Poster)

Quantitative Analysis of Nubian Sandstone Aquifer Response to Climate Change Using GRACE and Hydrological Models

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The sustainability of Groundwater Storage (GWS) within the Nubian Sandstone Aquifer System (NSAS), one of the world's most extensive aquifers, is examined using data from the Gravity Recovery and Climate Experiment (GRACE/GRACE-FO) and the Global Land Data Assimilation System (GLDAS) from January 2003 to June 2023. The NSAS extends over four countries: Egypt, Libya, Chad and Sudan. Overall, the GWS shows a significant decline due to decreased rainfall, increased temperatures, and high evapotranspiration (ET). Specifically, after 2009, the NSAS undergoes a concerning GWS reduction at a rate of -1.28 mm/year. During the period of the study, Egypt and Libya display substantial GWS reduction, with Egypt's GWS trends at -1.59 mm/year and Libya's at -2.65 mm/year. These GWS declines correspond with the low annual mean precipitation (Pr) figures of 37.92±0.36 mm/year for Egypt and 42.72±0.84 mm/year for Libya. Additionally, the relatively high ET rates of 33.00±0.36 mm/year for Egypt and 35.88±0.36 mm/year for Libya contribute to the observed GWS reduction, resulting in approximately -1.52 km^3/year in Egypt and -2.75 km^3/year in Libya. On the other hand, Chad sees positive GWS trends at 0.41 mm/year, attributed to increased annual rainfall. These conditions result in a noticeable GWS surplus, estimated at 0.12 km^3/year. Sudan exhibits a positive GWS trend of 1.08 mm/year, supported by an annual mean Pr of 55.68±0.60 mm/year and ET of 48.96±1.08 mm/year. These factors lead to a more balanced GWS trend, with a relatively high temperature (27.31°C/year) contributing to a GWS surplus of approximately 0.43 Km^3/year. We utilize the Empirical Orthogonal Function (EOF) technique to analyze climate parameters impacting groundwater changes. Additionally, our study uses the Seasonal Autoregressive Integrated Moving Average (SARIMA) model to forecast GWS trends over the next decade. Despite the relatively stable precipitation rates, a noticeable increase in groundwater depletion underscores the growing dependence on groundwater resources due to human activities in the NSAS region. This study was supported by the National Natural Science Foundation of China (Grant Nos. 42030105, 41804012).

Keywords: GRACE, groundwater, gravity, Empirical Orthogonal Function (EOF), Nubian Sandstone Aquifer System (NSAS)

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral)

The first realization of NAPGD2022: GEOID2022 and its accuracy estimation

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The North American-Pacific Geopotential Datum of 2022 (NAPGD2022) is scheduled to be adopted soon. As the first realization of this new datum, GEOID2022 is jointly computed by NGS, CGS, and INEGI. NGS and CGS have agreed to adopt the same model to represent the geoid for North America and part of the Pacific. The geoid model is computed using GRAV-D airborne gravity data completed at the end of 2023, the latest satellite-based Earth Gravitational Model GOCO06s, as well as terrestrial and altimetric gravity data from recent years. A new digital elevation model, G22DEM, is constructed by combining TanDEM-X, the USGS 3DEP 1” DEM, and MERIT for gravity and topographic reductions.

Using the same datasets, NGS and CGS independently compute geoid models using both analytical solutions and the method of Stokes-Helmert. The final geoid model is a combination of these independently derived models. To assess the accuracy of the geoid models, independent datasets such as three geoid slope validation surveys, GNSS/leveling data, altimetry data, and water/tide gauge observations over lakes are used. The dynamic GEOID2022 will also be developed along with several other derivative products, accompanied by accuracy estimates. This presentation will highlight the development of GEOID22 (beta), including marine and land data validation and compilation, and their combination with satellite altimetry-derived marine gravity data, reprocessing of GRAV-D, the reference EGM, computation, comparison, combination of NGS’s and CGS’s geoid models, and the evaluation of static GEOID22.

Keywords: geoid, gravity, datum

Session 1: Reference systems and frames in Physical Geodesy

Presentation preference (Oral)

CG-5 Processor: A MATLAB-based GUI to process Scintrex CG-5 gravity data

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Relative gravity measurements are indispensable in understanding the Earth's subsurface processes and serve as an essential tool in various scientific and industrial fields. The Scintrex CG-5 Autograv Gravity Meter is a commonly used instrument for relative gravity measurements due to its high precision and accuracy as well as ease of use and versability while acquiring and processing gravity measurements. This process involves several steps to ensure accurate and meaningful results when CG-5 is used for field surveys. The CG-5 Processor is a MATLAB-based Graphical User Interface (GUI) designed for the efficient processing of the relative gravity data acquired with the CG-5 gravimeter. Operating within the MATLAB environment, the GUI introduces two independently fundamental features: (1) the "Process Densification File" and (2) the "Process Calibration Line". The former is dedicated to estimating gravity values during a multi-day gravity campaign, along with gravity anomalies by integrating GPS/GNSS measurements, while the latter focuses on determining new calibration constants and scale factors to enhance the accuracy of the CG-5 measurements along a calibration line. Both features encompass essential functionalities, ranging from data entry (involving CG-5 and GPS/GNSS data) to pre-processing (comprising data clustering and employing a statistical 3σ-rule to remove blunders) and main processing (incorporating among others the computation of daily drift correction, gravity anomalies, gravity values, normal gravity values, scale factor, and calibration constants). Designed for users of varying programming and/or geodesy expertise, the GUI ensures a user-friendly experience. It produces detailed outputs in the form of graphs, images, and tables, establishing it as a valuable tool for a wide range of gravity-related applications. This work provides an analytical overview of the software, detailing its diverse functionalities. Results obtained from processing raw relative gravity measurements are also presented.

Keywords: CG-5, Relative gravity measurements, 3σ-rule, Calibration, MATLAB GUI

Session 2 (Co-organized with the IAG QuGe Proect): Novel technologies in terrestrial, airborne and satellite gravity field determination

Presentation preference (Poster)

Impact of GRACE-FO LRI on the high-frequency domain of a combined static Earth gravity field solution

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The impact of the GRACE Follow-On (GRACE-FO) Laser Ranging Interferometer (LRI) is evaluated on the higher harmonic degrees of the estimated static Earth gravity field with respect to the GRACE-FO K-Band Ranging (KBR) system by comparing combined static Earth gravity field solutions using LRI and KBR data respectively. Additionally, each gravity field solution is compared with existing static Earth gravity field models.

For GRACE-FO, the LRI/KBR observed range-rates included in the respective Level-1B (L1B) data products are used as satellite-to-satellite tracking (SST) data. Furthermore, the L1B data products derived from the on-board accelerometers, star camera assembly, thruster activation data, the GRACE-FO precision orbit determination (POD) and the Global Positioning System (GPS) receivers are used. Additional data are used from another sources, e.g. other satellite missions (Gravity Field and Ocean Circulation Explorer (GOCE), Gravity Recovery and Climate Experiment (GRACE)), etc..

The processing chain for each combined static Earth gravity field solution starts with a certain data preprocessing (correction of range-rates, removal of gross outliers, etc.). Subsequently, the formulation of the normal equations (NEQs) system takes place by combining selected pre-processed data from the various sources. Finally, the gravity field solution is generated by performing a complete least-squares adjustment.

The combined static Earth gravity field solutions obtained from the different datasets and the existing static Earth gravity field models are discussed, e.g. comparison between signal and error degree variances, identifying differences in the higher harmonic degrees, etc.. Conclusions are drawn about the potential impact on the static Earth gravity field of the laser ranging system which shall replace the microwave ranging one on future gravity missions.

Keywords: GRACE-FO, LRI, Static gravity, Combined gravity field model, Satellite gravimetry

Session xx you submit your abstract to

Session 3: Static and time-variable global gravity field modelling

Presentation preference Oral

Future satellite gravimetry: The quantum leap?

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Quantum sensors such as cold-atom interferometers (CAI) are one of the most promising novel sensor technologies in the context of future satellite gravimetry, to replace or be hybridized with classical electrostatic accelerometers. The main advantage of CAI sensors is their close to flat error spectrum over the whole spectral range, with the potential to provide significantly better and more long-term stable acceleration measurements in the long wavelengths as well as a stable scale. Quantum accelerometers can either be used to measure nongravitational accelerations in satellite-to-satellite tracking mission concepts (low-low and high-low), or gravity differences on very short baselines in the frame of a gradiometer concept. Based on the results of several science studies on the future potential of quantum gravimetry, in this presentation we will give an high-level summary of the main conclusions.

Independently of the mission concept, it has to be noted that currently instrument errors are not the dominant contributor in the total error budget. Errors resulting from temporal aliasing are relatively larger by a factor of 10 to 1000. Therefore, in order to be able to exploit the benefits of quantum sensors (and also other novel sensor technologies) at all, it is important to put the focus in parallel on strategies to reduce the temporal aliasing problem, which might be achieved by improving the measurement geometry and related space-time sampling of the target signal by means of enhanced multi-pair constellations, or by advanced parameterization strategies. From the viewpoint of instrument error contributions, for satellite-to-satellite tracking missions it turns out that also a significant progress of inter-satellite ranging technologies is required to fully exploit the benefits of quantum/hybrid accelerometers. Regarding gravity gradiometry, a very high sensor performance of 10-14 to 10-15 m/s2/sqrt(Hz) is required to achieve reasonable sensitivity for the temporal gravity field. The main limitation turns out to be the necessity to comeasure the attitude with very high precision, not only to exploit the high accelerometer performance, but also for separating linear and rotational acceleration effects. Only a full 3D-gradiometer set-up will enable us to tackle this problem at all.Based on the results of numerous extensive numerical closed-loop simulation experiments, in this contribution we quantify the individual error sources contributing to the achievable gravity field performance. We identify and summarize in a systematic way the goods, prospects and odds of quantum sensors for future gravity and mass transport monitoring from space, in order to set the current expectations of this new technology on solid grounds.

Keywords: quantum, gravimetry, satellite-to-satellite tracking, gradiometry, temporal aliasing

Session 2: Novel technologies in terrestrial, airborne and satellite gravity field determination

Presentation preference (Oral)

Moho depth estimation in the wider Hellenic and Eastern Mediterranean regions using GOCE gravity data

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Gravity data have been used numerous times in studies with geophysical purposes, such as for the computation of crustal models of the Earth, inversion for subsurface mass modelling, etc.. In this work, GOCE gravity data are utilized for Moho depth estimation in the wider Hellenic and Eastern Mediterranean regions by using two classic methods: the Parker-Oldenburg and the Vening Meinesz-Moritz (VMM) inverse problems. First, complete Bouguer gravity anomalies were obtained in the area under study based on the processing of the latest available GOCE baseline according to well-known procedures. The resulting complete Bouguer anomalies were then used for Moho depth estimation with the Parker-Oldenburg method taking into account different scenarios and hypotheses testing various density contrasts and compensation depths. The other Moho depth estimation method examined, was the one based on the VMM inverse problem, where the various scenarios examined were based on GOCE and GOCE/GRACE Global Geopotential Models (GGMs) from the TIM and DIR approaches. In all the aforementioned methods a significant amount of scenarios have been investigated using different Moho density contrast and initial Moho depth values. A primary validation of the results was accomplished by comparing them to available data from existing crustal models like the CRUST1.0 and GEMMA. Further evaluation of the results was made in terms of comparisons with Moho depth values determined through seismic methods, available from the literature in the area of study. The comparisons provided promising results concerning the agreement between the estimated Moho depths and the ones from seismic methods.

Keywords: Moho, GOCE, GGM, complete Bouguer anomalies, Vening Meinesz-Moritz, Parker-Oldenburg

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference (Oral)

The potential of SWOT altimetry data for validating the accuracy of marine geoid models in the Baltic Sea

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A geoid-based unified chart datum for the whole Baltic Sea – the Baltic Sea Chart Datum 2000 (BSCD2000) – has been recently released for accurate GNSS-enabled bathymetric surveying and navigation; the datum also provides a unified reference for water levels. Although around 2 cm BSCD2000 modelling accuracy can be estimated from comparisons with GNSS-levelling control points on land, no conventional control data is available offshore, where the primary focus should be directed. A proposed solution is to use satellite altimetry data, especially with the availability of the Surface Water and Ocean Topography (SWOT) mission (launched in December 2022) that offers increased spatial coverage and finer sea surface sampling resolution compared to previous satellite altimetry missions. The use of SWOT sea level data provides new research opportunities, such as validating regional marine geoid models (e.g., the BSCD2000).

Since SWOT provides sea surface heights relative to the reference ellipsoid, dynamic topography, which separates sea surface heights from the geoid, is needed. In this study, geoid-referred tide gauge readings and hydrodynamic model data are combined to obtain dynamic topography for the Baltic Sea's coastal and offshore areas. These dynamic topography estimates are removed from SWOT-based sea surface heights to obtain geoidal heights, facilitating the BSCD2000 model offshore validation. The comparisons demonstrate occasional good consistency between the two datasets, also revealing a problematic geoid modelling region in the eastern Baltic Sea. On the other hand, RMSE estimates exceeding a decimeter where geoid modelling is known to be accurate indicate problems with the altimetry data, requiring further investigations. Importantly, however, there appears to be no correlation between the RMSE estimates and distances from the coast, suggesting that SWOT data could be effectively combined with GNSS-levelling data in the near-coast zone for improved validations. The employed methodology represents one of the exciting applications of SWOT altimetry data for geoid determination and geoid modelling validation that has not been applied before.

Keywords: BSCD2000, dynamic topography, geoid, sea surface height, SWOT

Session 1: reference systems and frames in physical geodesy

Presentation preference: poster

Spectral gravity forward modelling of continuous 3D variable density contrasts using an arbitrary integration radius

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For years, the sparse coverage of global terrestrial gravity data has been among the factors limiting global static gravity field models in terms of their resolution. The missing high-frequency signals have therefore often been approximated by gravity information derived from high-resolution digital elevation models of the topography. However, to obtain reliable short-scale gravitational signals, realistically should be modelled not only the shape of the topography but also its density. To this end, we present a new spherical-harmonic-based technique that can cope with any continuous 3D variable density of topographic masses. It can forward-model masses all around the globe but it can also be limited to masses found within/outside some integration radius, thereby yielding near- and far-zone gravitational effects. Thanks to the underlying FFT-based spherical harmonic transforms, the new method can efficiently handle even high-resolution topographies. We discuss that the resulting spherical harmonic series for far-zone gravitational effects may be convergent even on the topography, provided that the integration radius is large enough. A new combined gravity forward modelling approach is thus proposed to efficiently deliver surface gravity maps at high resolutions. The rationale is to split global gravitational effects into near- and far-zone effects. The former are derived by slow but divergence-free spatial methods and the latter are obtained by the new FFT-based spectral method. In numerical experiments, we forward-model lunar topographic masses having density contrasts varying in the 3D space. We show that the differences with respect to constant-density-based modelling may reach up to 150 mGal. The new method is implemented in CHarm, a C/Python library for high-degree spherical harmonic transforms available at https://github.com/blazej-bucha/charm.

Keywords: Topographic potential, 3D variable density, Spherical harmonics, Molodensky's truncation coefficients, Moon

Session 4: Regional gravity field modelling and geophysical interpretation

Oral

Development of the Next-generation gravity mission (NGGM) as part of the Mass-change And Geoscience International Constellation (MAGIC)

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The Next-generation Gravity Mission (NGGM) is planned to constitute the inclined pair of the double-pair Bendertype constellation MAGIC. In a Phase A science support study, which was complementing two parallel Phase A industry system studies, the key mission parameters have been studied in detail by means of numerous numerical closed-loop simulations, in order to identify the optimum set-up regarding science return, technical feasibility, and costs. The Phase A activities, which also included a thorough analysis of the science impact of the mission for the main application fields, could be successfully concluded in November 2023. In the next Phase B1, on the science side the concept for an operational NGGM and MAGIC ground processor from product Level 0 to Level 3 will be established, and a first prototype will be implemented. Since one of the main goals of MAGIC is to demonstrate pre-operational capabilities regarding significant contributions to operational service applications, in addition to a standard processing line also a fast-track processing line to generate gravity and mass transport products with short latencies of only a few days will be considered.
In this presentation, we will give an overview of the current status of NGGM/MAGIC. Based on a short summary of the main conclusions derived from the Phase A studies, the current status of the NGGM/MAGIC developments will be presented, and the next steps and future plans towards an operational ground processing system will be outlined.

Keywords: temporal gravity field, next-generation gravity mission, numerical closed-loop simulations, ground processor

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral)

The IHRF CC to ensure the long-term sustainability of the IHRS/IHRF

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With the establishment in late 2023 of the IHRF Coordination Center (IHRF-CC), the International Association of Geodesy (IAG) has created a central coordinating body under the responsibility of the International Gravity Field Service (IGFS) with direct adherence to the IGFS Central Bureau (IGFS CB), to ensure the long-term sustainability of the IHRS/IHRF. The IHRF is a geopotential reference system providing both potential values at its core sites as well as offsets of national and regional vertical datums to the IAG adopted conventional W_o value. The IHRF is composed of distinct yet collaborative modules taking care of the main components and activities foreseen for the IHRF CC as a product center. These refer to the network maintenance, conventions and standards update, coordination of combination activities and finally, the main arm of the IHRF, the associate analysis centers which are the main local and regional bodies performing potential determination at the IHRF sites. In this work we outline the main structural components of the IHRF, their duties and responsibilities, the interoperability and cooperation with the rest of the IGFS services and GGOS and early steps for the organization and planning of the IHRF normal activities. The first realization of the IHRF is presented, along with activities for the generation of an IHRF cookbook, built-up of the IHRF front end and dissemination and promotion activities, as well as results from potential determination using various approaches.

Keywords: IHRS, IHRF, potential, physical heights, HSU.

Session 1: Reference systems and frames in Physical Geodesy

Presentation preference (Oral/Poster)

On orthogonality properties of spherical and spheroidal harmonic functions

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Boundary-value problems (BVPs) play a crucial role in determining the external gravitational field. The Laplace differential equation, together with scalar, vector, and tensor boundary conditions, has been used to formulate and solve numerous spherical BVPs. The close proximity of planetary bodies to the rotational ellipsoid has led theoreticians to deal with more complex spheroidal BVPs.

In general, the systematic treatment of BVPs is allowed by the orthogonality of basis functions. This property is taken for granted for the spherical case, as it exactly holds for the scalar spherical harmonics and can be extended for the vector and higher-rank tensor analogues. Equivalent paradigms could theoretically be introduced for the spheroidal geometry. In the first attempt, however, we end up with the lack of this peculiar property for the spheroidal basis functions. Thus, the spheroidal BVPs may seem extremely demanding or impossible to solve. Fortunately, the orthogonality can be restored, although, in a more general weighted sense, that has been examined for the scalar and vector spheroidal harmonics.

In this contribution, we summarise the orthogonality properties of spherical and spheroidal harmonics. For the spherical case, we explain the simplest orthogonality of two scalar basis functions and extend this notion to the vector, second-rank, and third-rank tensor basis functions. For the spheroidal case, we generalise the concept of orthogonality in a weighted sense for scalar and vector basis functions. On the other hand, orthogonal second-rank and third-rank tensor spheroidal harmonics have not been found. Besides, we discuss possible approaches to restore orthogonality for higher-rank tensor spheroidal harmonics.

Keywords: Basis functions, Boundary-value problem, Ellipsoid, Gravitational tensor, Sphere

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference: Oral

Definition of Essential Geodetic Earth Observation Variables (EGVs) with Emphasis to the Earth Gravity Field

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Geodesy determines changes in the Earth's shape, size, gravity field and rotation in space and time with respect to precise and long-term geodetic reference frames. These changes usually reflect variations in the components of the Earth system, variations which in turn are recorded by the geodetic observations. Thus, geodesy plays a crucial role in Earth observation.

Geodesy observes the Earth as a whole, from the interior to the surface, including the atmosphere, with regional and local refinements, and provides a large number of products for this purpose. Moreover, geodetic products are needed for all positioning and satellite navigation tasks, and thus play an elementary role in modern society. So far, however, these products suffer from a lack of visibility for the global society (non-geodetic communities, administration, decision makers, science and others) and in some cases they are also not easy to understand for non-experts. In addition, geodesy as a discipline is also not well known to the public and therefore, there is a need to better promote these geodetic products.

Since the 2023 IUGG General Assembly an initial set of EGVs has been identified and requirements for them are going to be specified. These variables shall be capable to describe and monitor the Earth in a systematic, consistent and sustainable way and shall be important for Earth science disciplines as fundamental data source. The presentation explains the criteria to declare a geodetic variable as essential, identifies possible levels of EGVs and introduces a classification scheme. The relation between EGVs and geodetic products is defined and requirements needed to be met by geodetic observations and products in order to become or contribute to an EGV are defined. Special emphasis will be given to EGVs and geodetic products related to the Earth gravity field.

Keywords: Essential Geodetic Variable, Earth Observation, Geodetic Products, Earth Gravity Field, Reference Frames, Geoid

Session 6 you submit your abstract to

Presentation preference Oral

Towards an improved gravimetric geoid in Albania

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The determination of a high-accuracy and high-resolution geoid is nowadays of indispensable importance as it forms one of the cornerstones of a modern geodetic reference system. With that in mind, the State Authority for Geospatial Information (ASIG) of the Republic of Albania has launched an effort to modernize the gravity infrastructure of the country and as a consequence to make available a high-resolution and high-accuracy geoid model for the country. In that respect, the necessary procedures to establish the first and second order network have been detailed as well as the determination of a first-guess gravimetric geoid based on the available gravity data. In this work, we first focus on the gravity campaigns, data processing, reductions and adjustments carried out in the frame of establishing the reference benchmarks of the second order gravity network. Then the methodological steps followed for the determination of the geoid on a regular 1 arcmin x 1 arcmin grid over Albania, in an area bounded between $38.5° \leq \varphi \leq 43.5°$ and $18.0° \leq \lambda \leq 22.0°$, are outlined. For the geoid determination, the remove-compute-restore (RCR) concept is employed using two Global Geopotential Models (GGMs), namely EIGEN6c4 and XGM2019e, and two approaches for the topographic effects through a residual terrain model (RTM) correction with the spectral and classical computation. Then, the estimation of the geoid is carried out using Least Squares Collocation (LSC) and Fast Fourier Transform (FFT) methods and the validation is performed against both GNSS/Levelling data over Albania and a high-accuracy levelling traverse connecting Durres and Tirana. From the results achieved, the FFT-based geoid presented a mean value of the differences at the 3 cm level and a std of 14.1 cm. When compared to the new levelling traverse the new geoid has shown differences at the ~16 cm level which indicates the bias between the new gravimetric geoid from FFT and the new Albanian vertical datum. The relative differences over the measured levelling BMs is at the 1-7 mm level. A first guess hybrid geoid was also determined, after the parametric fit with the 3rd order polynomial model, reaching the

12.7 cm agreement with the old vertical datum, which is very satisfactory considering the fact that the acquired land gravity data manage to cover only a small portion of the gravity variability due to the long distances between them.

Keywords: gravity densification, geodetic infrastructure, geoid modelling, least squares collocation, FFT

Session 1 Reference systems and frames in Physical Geodesy

Presentation preference (Oral/Poster/no preference)

Oral

Revisiting Non-Tidal Atmospheric and Hydrospheric Corrections for Terrestrial Gravimetry

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The atmospheric and oceanic circulation as well as the hydrological cycle drive to a great extent mass redistribution within Earth's fluid envelope at a wide range of temporal scales. These mass anomalies affect gravity measurements recorded by precise superconducting gravimeters. Accurate high-resolution quantification of the instantaneous Earth system state is required to mitigate the manifestation of these effects in the gravity records. In this work, we utilize mass anomalies consistent with the latest GRACE/GRACE-FO non-tidal atmosphere-ocean de-aliasing product AOD1B RL07. Employing ECMWF-derived atmospheric state vectors, we forced the baroclinic general ocean circulation model MPIOM to obtain ocean state estimates, and the hydrodynamic model LISFLOOD to obtain terrestrial water storage estimates. We calculated gravity changes induced by the Newtonian attraction of the mass anomalies and the loading effect that mass anomalies in the atmosphere and hydrosphere exert on Earth's crust. We compare our long ECMWF-derived time series to gravity anomalies provided by ATMACS, a BKG service that features weather-driven gravity anomaly corrections for most superconducting gravimeter sites based on various operational weather prediction models from the German Weather Service. We assess the quality of the current modeling strategy as well as the mass anomaly fields by applying the ECMWF-based corrections to long time series of selected continuously recording gravimeters with a focus on sites in the vicinity of the North Sea and Baltic Sea including Helgoland, Onsala, and Metsähovi.

Keywords: atmospheric and hydrospheric corrections, long-term stability, terrestrial gravimetry, attraction and deformation, numerical weather models, superconducting gravimeters

Session 2: (Co-organized with the IAG QuGe Proect): Novel technologies in terrestrial, airborne and satellite gravity field determination

Presentation preference (Oral)

Scale factor (in)stability of ZLS-B78 - a worst case scenario?

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Terrestrial gravimeters of highest precision are, among other applications, used for local studies on mass transport, e.g., in the hydrosphere or the cryosphere.

Thereby, requirements on observational accuracy and stability of the observational system are high, with time variable signals having amplitudes of only some few tens of mircoGal or less and repeated surveys being conducted over time frames of several years. The Bavarian Academy of Sciences and Humanities uses the spring-type relative gravimeter ZLS-B78 for long term monitoring of gravity variations related to hydrology or glacier mass variations. Measurements are mostly based on the electrostatic feedback system with a range of 50 mGal. The feedback scaling of the instrument was determined in various measurement campaigns by comparison to gravity values derived by absolute gravimeters of type A10 and FG5, or by repeated measurements on a short vertical calibration line in Munich. Here we show and discuss the resulting time variations of the feedback scaling. It is not new that careful monitoring of instrumental parameters is necessary to meet accuracy requirements and provide reliable estimates of time variable gravity values.

However, calibration parameters and their time variations are hardly documented. Since the trend of the linear scale parameter of ZlS-B78 is much bigger than expected - in the order of 0.0025/year - I belief that it is of general interest to document the large trend which I assume to be a worst case scenario. Thereby, one needs to realize that the scaling does not directly map into the amplitude of the time variable signal (which is small, such that even a large scaling uncertainty may be acceptable) but that it maps into the gravity range over which the signal is observed (and which can reach up to 50 mGal in case of ZLS-B78). Ignoring the scaling trend would therefore map into the observed time variable signal with a magnitude of up to 125 microGal/year, which, in many cases, is larger than the expected signal.

Keywords: terrestrial gravimetry, ZLS, electrostatic feedback, calibration, scaling parameter

Session: Poster Session 2

Presentation preference (Poster)

Stochastic modelling of AOD model errors for application in GRACE/GRACE-FO data processing

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De-aliasing based on geophysical background models (BM) allows for a reduction of high-frequency, high-amplitude signal components in GRACE and GRACE-FO data processing. These components are primarily related to the ocean tides (OT) and non-tidal variations within the atmosphere and the oceans (AO), and would otherwise superimpose the target signals stemming e.g. from the hydro- or the cryosphere. In the course of previous studies, it was shown both in closed-loop simulations as well as in real data processing that the incorporation of OT BM error information in terms of error variance-covariance matrices (VCM) yields an enhanced gravity retrieval performance.

In this contribution, we discuss the obvious next step, which is the consideration of stochastic properties of the underlying imperfections of the AO models. A stationary error VCM is derived, as well as a set of non-stationary error models which closely depict the evolution of the AO BM error with respect to space and time. The value of either approach is validated in a set of numerical closed-loop simulations for a single-pair (GRACE-type) gravity mission as well as a double-pair (Bender-type) constellation. Explicit investigations towards an optimal decorrelation period are carried out for the AO error VCMs. Also, the benefit of combining them with the stochastic modelling for other error sources (OT and sensor noise) is shown.

Keywords: GRACE/GRACE-FO, temporal aliasing, background model uncertainties, stochastic modelling

Session 3: Static and time-variable global gravity field modelling

Presentation preference: ORAL

Evaluation of novel airborne gravity levelling methods for bathymetric and geological interpretation in polar regions

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In dynamic gravimetry, i.e. airborne and shipborne gravimetry, levelling methods are used to refine gravity disturbance results based on neighbouring trajectories. In the traditional crossover adjustment, line biases are estimated using gravity disturbance residuals at trajectory line crossings as input to a least-squares adjustment. In an alternative method, the results along the complete trajectory are used to estimate the gravity disturbance field in the survey area and line biases in a one-step least-squares adjustment applying radial basis functions. This makes the bias estimation more robust since the observations are not restricted to a small number of residuals at crossings strongly affected by random errors. As no crossover points are needed for the adjustment, trajectory planning requirements are reduced. Adjustment becomes applicable to a wider range of campaigns. However, precision evaluation based on crossover points is still possible. It might even be more reasonable than in a traditional adjustment since the crossover residuals are not an essential input to the bias estimation. Within the scope of this work, existing methods that estimate line biases are extended to bias estimation based on trajectory segments with inter-segment interpolation. The extended method can be particularly useful for atypical trajectories without a sufficient number of straight lines. The introduced levelling methods are evaluated at the example of two airborne campaigns in polar regions: an aircraft-based survey at the Riiser-Larsen Ice Shelf, East Antarctica, with regular grid, and a helicopter-based survey over Nordenskiöld Land, Svalbard, with highly irregular trajectories due to draped flight mode over rough terrain and poor flying conditions. In the first campaign, the influence of varying grid line spacings on the results of the proposed methods is analysed. Additionally, it is briefly shown how the gravity results are used for sub-ice-shelf bathymetry determination. Application to the second campaign shows that the extended method even enables an adjustment at highly irregular trajectories without straight lines and with few crossover points. The results are compared with terrestrial gravity measurements and some geological interpretations are presented.

Keywords: airborne gravimetry, levelling, adjustment, radial basis functions, bathymetry

Preferred session: 2 (2nd best fit: session 5**)**

Presentation preference: oral

Modernisation of the Swiss Vertical Reference System

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Switzerland operates two height systems: LN02, the official system established on leveling measurements only (no gravity reductions) conducted since 1902, and LHN95, a system based on geopotential values and orthometric heights, although never formally implemented. The uncorrected leveled heights LN02 struggles to meet the contemporary requirements for absolute height determination, made possible by space geodetic technology. The differences between LN02 and LHN95 is currently between 20 up to +40 centimeters. In this context, a study to modernize the height reference system has been launched.

The first concept is to create a new height system named CHVRS based on geopotential values and normal heights compatible with the European height system EVRS. To ensure the long-term stability and accuracy of the reference frame, a kinematic model is proposed for integration into the new height reference system. This model will enable accounting of vertical movements within the Earth's crust in Switzerland, in particular Alpine uplift, which can reach 1.5 mm/year.

Within this presentation, we will present the state of the work, the main key points of the concept and the agenda for the implementation.

Keywords: reference system, reference frame, physical height, normal height, kinematic model, vertical movements

Session 1

Presentation preference: oral

GGMCalc 2.0: A Comprehensive Tool for Computing a Wide Range of Earth's Gravitational Field Functionals

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We introduce an updated and extended version of the GGMCalc software, a powerful tool for computing various functionals of the Earth's gravitational field. This new release offers significant enhancements and improvements over its predecessor.

The software now supports the computation of a comprehensive range of the Earth's gravitational field functionals, including height anomaly, generalized pseudo-height anomaly, geoid undulation, deflections of the vertical, gravity disturbance, gravity anomaly, Bouguer gravity anomaly, gravitational and disturbing potentials and their derivatives up to the third order, gravitational and disturbing tensors, gravity potential and its first-order derivatives, second-order radial derivative of gravity potential, as well as gravity. The numerical results demonstrated the program's stability against underflowing, with non-singular computed functionals at the poles. The outcomes agreed with those obtained from the ICGEM calculation service and GrafLab program, validating the program's accuracy.

Among the key advancements in this version is the flexibility to choose between the Clenshaw method and FFT with Wigner d-functions for the calculations on gridded or arbitrary points. The program now fully supports all gravity field models provided by ICGEM in icgem1.0 format, including Static, Time Variable, Temporal, and Topographic Gravity Field Models. Furthermore, the list of supported reference ellipsoids has been extended. These new features provide greater flexibility in computing the Earth's gravitational field functionals.

The program was developed in Fortran and is cross-platform software. Its user-friendly structure makes it accessible and convenient for academic purposes. With its enhanced capabilities and improved functionality, the GGMCalc software is a valuable resource for researchers in physical geodesy and geophysics studies.

Keywords: Spherical harmonic synthesis, Clenshaw method, Wigner d-functions, FFT

Session 4

Presentation preference: Oral

Contributions of the NGGM and MAGIC constellation to geodesy with an emphasis on the IHRF

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The Mass-Change and Geosciences International Constellation (MAGIC) mission is a collaborative effort between the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA), which will consist of four Earth observation satellites arranged into two pairs, with each agency contributing two satellites. Under NASA's supervision, the GRACE-C (P1) pairs will be developed, while ESA will oversee the development of the Next Generation Gravity Mission (NGGM) (P2). MAGIC aims to deliver mass-change products with superior attributes compared to its predecessors, the Gravity Recovery and Climate Experiment (GRACE) and the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO), including higher spatial resolution, sub-weekly temporal resolution, shorter latency (a few days products), and heightened accuracy. For instance, MAGIC is designed to achieve an exceptional 1-mm accuracy in geoid measurements, along with a spatial resolution of 500km within a 3-day timeframe or, alternatively, a spatial resolution of 150km within a 10-day timeframe. In this study, we focus on the foreseen 30-day Level2a products of the NGGM and MAGIC constellation as Spherical Harmonical Coefficients (SHCs) of the disturbing potential. To simulate the NGGM/MAGIC time series, unfiltered GRACE and GRACE-FO release 06 Global Geopotential Models (GGMSs) from 2002 to 2023 are used. These are appropriately filtered, translated into temporal gravity field data products, and used as simulated MAGIC/NGGM observations, to allow us to explore hypothetical scenarios related to future forecasted gravity field and mass-change products. The focus is placed on estimating how the performance, and more specifically, the accuracy and spatial resolution of the simulated MAGIC/NGGM data contribute to the estimation of equivalent water thickness, gravitational potential, geoid and physical heights either at regional scales or for specific IHRF core sites. Singular Spectrum Analysis (SSA) is employed to complete the time-series in case voids are present. We explore various scenarios for both the tandem mission duration and observational accuracy. Each scenario offers unique insights into potential outcomes, offering an understanding of the anticipated performance of the MAGIC/NGGM missions. Conclusions on the achievable accuracy and its contribution to the realization of the IHRF are drawn along with the impact on the constellation and of NGGM itself as an operational service with emphasis on understanding Earth's dynamic processes and delivering high-precision gravity field data.

Keywords: MAGIC, NGGM, GRACE, GRACE-FO, Spherical Harmonical Coefficients.

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral)

Sensor fusion error and spectral analyses for airborne quantum gravimetry: the AeroQGrav case study

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Earth's gravity field can be reconstructed by adopting several techniques that involve data collected from satellite-, aircraft- and ground-based measurements. Out of these techniques, airborne gravimetry is particularly powerful for remote regions, like mountains or deserts, and also to obtain a higher spatial resolution than satellite gravity measurements. Compared to classical gravity instruments (e.g., inertial units or falling corner cube instruments), atom interferometry offers several advantages like absolute measurements, long-term stability, and high sensitivity.

Multiple sensors are required to exploit the high accuracy that a cold atom interferometer can provide when used on a moving plane. First, the quantum gravimeter needs to be on a stabilized platform to measure accurately along the local vertical. Second, other sensing instruments are needed to isolate gravity by removing the kinematic acceleration. This operation is carried out by deriving the acceleration from the trajectory computed by a geometric positioning engine.

Typical solutions are based on the positions estimated by filtering global navigation satellite system (GNSS) measurements. Separating the kinematic from the sensed acceleration represents one of the main challenges of airborne gravimetry. Depending on the requirements related to spatial resolution and frequency domain of interest, the accuracy and precision of the measured gravity may vary and be limited by the spectral characteristics of the adopted sensors.

Started in December 2022, the Absolute Aero Quantengravimetrie (AeroQGrav) project aims to achieve precisions of 10-6m/s2 after five seconds of signal integration. The AeroQGrav concept includes the fusion of multiple sensors to recover the gravity signal. An inertial measurement unit (IMU) is used to stabilize the platform of the atom interferometer, while an accelerometer is located on top of it to suppress the vibrational noise. A terrestrial laser scanner (TLS), a laser Doppler velocimeter (LDV), and a multi-antenna GNSS positioning setup are adopted to retrieve the kinematic acceleration. Such instrumentation has distinct input, output, precision and spectral operative window.

In this work, we present how to exploit the fusion of TLS, LDV and GNSS measurements to retrieve the gravity signal at multiple frequencies of interest and precision. The whole measurement chain is reconstructed. From a simulated input error signal, the acceleration error is obtained by considering appropriate transfer functions. An error analysis of the recovered gravitational signal is carried out, assessing the benefits and limitations of each employed sensor.

A frequency analysis is reported by evaluating the power spectral density (PSD). This provides a spectral description of the kinematic-derivation limitations affecting the reconstruction of the gravity signal. Regarding GNSS, the simulation includes a software-inthe-loop approach, using the Geo++ GNSMART software. Preliminary results show that a standard deviation of the positioning

error smaller than 1 mm on a 50-second averaging interval is required to fulfil the project requirements.

Finally, the propagation into the acceleration of the platform orientation error is assessed. The analysis includes investigating a multi-antenna approach for GNSS positioning to define the body-fixed frame better and reduce the orientation error.

Keywords: airborne gravimetry, atom interferometry, sensor fusion, GNSS, spectral analysis

Session 2: (Co-organized with the IAG QuGe Proect): Novel technologies in terrestrial, airborne and satellite gravity field determination

Presentation preference (Oral)

Gravitational Inversion: 3-D non-uniqueness vs. 2-D uniqueness and implications on time-variable gravity solutions

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We discuss on gravitational inversion, i.e. the determination of the mass density distribution of a central body when given the observed external gravitational field produced by the mass. This inversion for a 3-D mass distribution is known to be grossly nonunique; whereas that for a 2-D mass distribution on a spherical surface is known to be unique. The latter justifies the surface equivalent-water-thickness, or “mascon” solutions when excluding interior mass transports for the Earth’s time-variable gravity as observed by the GRACE satellite. Here, using the gravitational multipole formalism cast in the framework of linear Hilbert space with the notion of inner product, we do two things further: (i) we prove mathematically that the 2-D gravitational inversion on an arbitrary surface is unique; (ii) we devise an algorithm that leads to the unique exact 2-D mass distribution solution, true to a maximum spherical harmonic degree. This procedure directly reaches refined, and unique, GRACE mascon solution sets that accommodate the actual Earth surface shape including the ellipsoidal figure and the topography.

Keywords: gravitational inversion, surface mass, time-variable gravity, GRACE

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference (Oral)

CARIOQA-PMP: preliminary results of post-pathfinder mission scenarios simulations in context with Earth observation user needs

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The Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry - Pathfinder Mission Preparation project (CARIOQA-PMP), funded under the EU HORIZON program, shall pave the way for a future quantum-based space gravimetry mission. One objective of CARIOQAPMP is to define advanced scenarios for such missions that can meet scientific user needs. Therefore, science and user requirements and EO parameters to be observed by CARIOQA are identified based on existing studies (e.g. IUGG, MAGIC). During the project, both will be further refined and adapted to possible mission performance assumptions of a quantum space gravimetry mission.

The paper collects and summarizes the user needs for applications in hydrology, cryosphere, atmosphere, ocean, solid Earth, geodesy, climate and globally. Further, EO parameters to be determined by a quantum space gravimetry mission for the same domains are identified, and requirements for temporal and spatial scales and amplitudes to be observed are specified. Some mission scenarios are selected to simulate their performance, and compare it with the defined user needs.

Keywords: quantum gravimeter, gravity field mission, user needs

Session: Poster Session 2

Presentation preference (Poster)

Estimation of gravity variations at absolute stations in the Czech Republic from measurements compatible with ITGRS

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Absolute gravity measurements with the FG5-215 and FG5X-251 gravimeters have been repeatedly conducted in the Czech Republic since 2001. At the same period, the gravimeters regularly took part at 12 international comparisons of absolute gravimeters and the gravity reference function at the reference station Pecný has been continuously maintained through the combination of absolute measurements with the measurements of the superconducting gravimeter OSG-050. The absolute gravity measurements in the Czech gravity network have been significantly extended since 2020 aiming to determine gravity variations at the stations, focusing on seasonal variations. These measurements have already been realized under the scope of CIPM MRA with declared uncertainty of 2.2 µGal. This uncertainty has been reached thanks to extensive investigation of systematic effects, enhanced measurement techniques and data re-processing. On the example of relevant data sets and investigations, we are presenting our approach to reach gravity results fully compatible with ITGRS, which could be characterized by exceptional accuracy with possibility to validate the measurement consistency and also to estimate the gravity variations mainly due to hydrological effects.

Keywords: absolute gravimeter, gravity variations, uncertainty, comparisons, reference

Session 01 you submit your abstract to

Presentation preference (Oral)

CubeSat Constellation and Gravimetry Mission Design using Full-Scale Simulations in the Context of the novel DORT-IM Ranging System

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Due to the dominant error of temporal aliasing in the results of past and current gravity field retrieval missions, e.g. Gravity Recovery and Climate Experiment (GRACE/-FO), simulations using multipair constellations of satellites were created and the results compared to those of past and future planned missions. The possibility of realizing such a multipair mission would be of unrealistic cost due to the large size of the satellites in GRACE and other gravimetry missions. This is mitigated by making use of a novel technology called the Dynamic Optical Ranging & Timing (DORT) ranging system being developed by the startup company Munique Technologies (MUT) in Munich, which is capable of delivering high-precision, micrometer level ranging observations between two 6U sized CubeSats. The inherent benefit of utilizing a small 6U CubeSat platform is the lower developmental and launch costs for the mission. CubeSat components are commonly available as commercial off-the-shelf (COTS) products and therefore are mass produced to make them much more affordable compared to the components of larger satellites. The lower cost of development leads to the ability to launch more satellites into space at different, specified orbits to maximize the performance of the mission. The orbits are determined based on full-scale simulations of the satellite mission using the gravimetry mission simulator created at the Institute of Astronomical and Physical Geodesy (IAPG) at the Technical University of Munich (TUM). Preliminary simulation studies have focused on the trade-off associated with using a smaller platform and therefore sacrificing instrument quality, in the form of higher noise levels in the observations. This downside is counterbalanced by an improved observation geometry allowed by a greater number of satellites. The increased spatio-temporal sampling allowed by a larger number of satellites in orbit for a gravimetry mission greatly reduces the effect of temporal aliasing currently plaguing the monthly gravity field solutions, while using satellites at inclined orbits as opposed to polar pairs can reduce the north-south striping effect present in the results from GRACE/-FO. Through early simulations, it can be shown that even with a degraded performance of multiple onboard instruments for the CubeSat mission, the benefits of more satellite pairs can match and even surpass the performance of current and future planned missions, and could be a viable option for post-MAGIC missions.

Keywords: Satellite Gravimetry, Mission Design, Satellite Laser Ranging, CubeSat, Numerical Simulations

Session 2

Poster presentation preference

Recovery of gravity potential values from regional quasigeoid models at Argentinean stations of the International Height Reference Frame (IHRF)

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In the year 2015, the International Association of Geodesy (IAG) introduced the International Height Reference System (IHRS) as the global standard for the determination of physical heights. Its realisation, the International Height Reference Frame (IHRF), relies on the determination of vertical coordinates (geopotential numbers) on selected stations and can be done through precise regional gravity field modelling.

This study aims to determine high-precision, pure gravimetric quasigeoid models at regions surrounding the five IHRF stations located in Argentina: UNSA, OAFA, UNPA, RIO2 and AGGO. In particular, AGGO (Argentinian-German Geodetic Observatory) is a fundamental geodetic station that co-locates several geodetic techniques together with absolute and superconducting gravimetry. The geodetic coordinates of all stations are given in the Posiciones Geodésicas Argentinas geodetic reference frame (POSGAR07). AGGO and RIO2 are connected to the Argentinean height reference frame.

All five quasigeoid models were determined by solving Molodensky's scalar-free Geodetic Boundary Value Problem (GBVP) with the remove-compute-restore (RCR) scheme. Molodensky's integral formula was calculated by applying the FFT-1D numerical integration method with a Wong-Gore modification of the Stokes kernel. For each model, the long-wavelength contributions of the gravity field were recovered from the XGM2019e Global Geopotential Model (GGM), and the short-wavelength contributions were computed through Residual Terrain Modelling (RTM), using the Argentinean Digital Elevation Model 2.1 (MDE-Ar v2.1). For the regions that include coastal areas, marine gravity anomalies were obtained from the DTU17 altimetry gravity field model. All calculations regarding the quasigeoid modelling were done with the Gravsoft software package.

The surroundings of each IHRF station exhibit distinct topographical and geographical characteristics. Additionally, the coverage and quality of gravity and GNSS/Levelling data, as well as the precision of the GGM and MDE-Ar vary greatly at each station. Because of this, to achieve an optimal precision for each quasigeoid model, the parameters involved in the data processing and in the RCR scheme were determined independently for each region.

The pure gravimetric quasigeoid models are then used to determine geopotential numbers at the IHRF stations. Furthermore, the results obtained provide a preliminary analysis for the future development of a precise quasigeoid model for all of the Argentinean territory.

Keywords: International Height Reference Frame (IHRF), quasigeoid modelling, FFT-1D, remove-compute-restore (RCR), Argentina

Session 1: Reference systems and frames in Physical Geodesy

Presentation preference: Oral

A novel MatLab-based software library for the calculation of far–zone effects for spherical integral

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Integral transformations serve as a valuable mathematical tool for modeling gravitational fields, providing the foundation for developing integral estimators to determine gravity field values and propagate errors. While traditional integral transformations like Stokes's and Hotine's have been extensively studied for calculating geoid/quasi-geoid heights in geodesy, theoretical and practical concepts regarding other integral transformations, including non-isotropic (azimuth-dependent) transformations, have yet to be explored. A fundamental assumption of integral transformations is global data coverage, yet ground measurements are often constrained. To address this, the global integral is typically divided into near- and far-zones, with significant attention needed to accurately assess systematic effects in the far-zone. Consequently, a new MATLAB software library is under development to compute far-zone effects in integral transformations for gravitational potential gradients up to the third order. This library includes scripts for computing integral and error kernels, truncation error coefficients, and far-zone effects based on user-defined parameters. This contribution focuses on implementing theoretical equations defining far-zone effects and subsequently testing the library's functionality through numerical simulations. Closed-loop tests were conducted using gravitational potential functionals derived from a global Earth's gravitational field model.

Keywords: Far-zone effect, Gravity field modelling, Integral transformations, Truncation errors

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference: Oral

Spectral combination of vertical and horizontal spheroidal boundary-value problems: A theoretical study

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The spectral combination method or technique encompasses all procedures to combine heterogeneous datasets by spectral weights, which depend on spherical harmonic degree n. It was initially developed to combine terrestrial gravity data and a global geopotential model optimally to calculate the geoid or quasigeoid. Later on, this technique was extended to combine solutions of spherical geodetic boundary-value problems. It is well-known that the Earth is considerably flattened at the poles, and its shape is closer to a rotational ellipsoid rather than a sphere, which was already proved by arc measurements in South America and Lapland in the 18th century.

This contribution will apply the spectral combination method to solutions of vertical and horizontal spheroidal boundary-value problems. For this purpose, we will derive the corresponding spectral weights for each solution of vertical and horizontal spheroidal boundary-value problems, as well as for their combination. The numerical correctness of derived spectral weights will be tested in a closed-loop test with data from a global geopotential model.

Keywords: Gravity field modelling, Spheroidal boundary-value problem, Spectral combination, Spectral weights,

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference: Poster

MAGIC's ability to estimate the long-term trend in climate-related mass-transport signals

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GRACE and its successor, GRACE-FO, have successfully observed Earth's Gravity field changes for over two decades. For the continuous data collection, GRACE-C (NASA/DLR) is planned to launch in 2028 in a polar orbit as its predecessors, followed by ESA's Next Generation Gravity Mission (NGGM) with a similar architecture but an inclined orbit with an expected launch date in 2032. Together, these two missions form the Mass change And Geosciences International Constellation (MAGIC), expected to deliver the anticipated higher temporal and spatial resolution for temporal variable gravity solutions.

Already today, the data record of satellite gravity missions has improved our understanding of large-scale processes of the water cycle. Additional value will arise through the continuation of satellite gravity observations. A longer observation record will lead to significance concerning climate-related mass transport signals such as the essential climate variable Terrestrial Water Storage (TWS) as well as the mass component of the sea-level rise.

In multi-decadal numerical closed-loop simulations, this contribution evaluates different parameterisation schemes of current and future satellite gravity missions, showing their potential in resolving climate trends. The observed climate signal is based on ESA's Earth system model for gravity simulations over 12 years. For even longer time series simulations, components of the TWS are extracted from CMIP6 climate projections following the shared socio-economic path-way scenario 5-8.5. The linear trend and annual signal recoverability will be evaluated for global parameter models based on spherical harmonic synthesis.

Keywords: MAGIC, NGGM, Satellite Gravimetry, Climate change, TWS

Session 5 Gravity for climate, atmosphere, ocean and natural hazard research

Presentation preference: no preference

Intercomparison of Spherical Harmonics and Mascons for GRACE-based Mass Change Estimates

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Since 2002, GRACE and GRACE-FO have provided pioneering observations of temporal variable mass changes. Mass flux estimation for GRACE typically parameterizes as a spherical harmonic series, while an alternative approach is the use of mass concentration (mascon) blocks. This study comprehensively examines and compares the effectiveness of spherical harmonic solutions and point-mass mascon solutions in retrieving gravity field signal based on a noise-free numerical simulation approach. This evaluation focuses on their performance in both a single-pair GRACE-like mission and a double-pair Bender-type mission.

The results of this study are based on the difference between 3° global equal area mascons and standard spherical harmonic coefficients up to degree and order 60 in the recovery of gravity information from simulated GRACE inter-satellite K-band range rate data. The comparison is made in the spectral domain by decomposing mascons into their spherical harmonic coefficient representations. Additionally, a direct spatial comparison is made between these two solutions. The findings suggest that averaging within each mascon block for point-mass mascon solutions results in damping of signal at high degrees. This averaging process, however, effectively mitigates aliasing errors in the recovered gravity signal. Conversely, spherical harmonics demonstrate greater power at high degrees, yet they fail to adequately eliminate the aliasing errors.

To reduce signal leakage error in mascon solutions, the 3° global equal area mascon is densified along the coastline. The resultant coast densified mascon solution marginally reduces signal leakage errors when compared to the 3° global equal area mascon solution. However, it suffers from high uncertainty of estimated parameters along the coastline due to small areas. The double-pair mission demonstrates significant advantages due to its superior observation geometry, resulting in a substantial improvement in both spherical harmonics and mascons.

Keywords: GRACE, Time variable gravity, Mascons, Spherical harmonics

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral)

A new determination of the vertical gravity gradients at the absolute gravity stations of the Czech Republic

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The new remeasurement of the vertical gravity gradients (VGGs) at absolute stations of the Czech Republic is currently being conducted.

The stations are measured independently by two expert groups with different types of relative gravimeters – ZLS Burris, Scintrex CG-5 and CG-6. Each group uses slightly different approaches, but minimally four vertical levels are used. A special tripod for Scintrex gravimeters with adjustable height levels is employed.

All results are processed uniformly with scientific software developed by ourselves. An appropriate degree of polynomial for VGGs is chosen based on statistical testing. The final adjusted results are compared with previously published results.

Keywords: gravimeter, gravity, vertical gradient

Session 1 you submit your abstract to

Presentation preference - Poster

Least Squares Collocation for Continental Scale Analysis Ready Gravity Data

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Computing a geoid from gravity anomalies involves a series of "remove-predict-restore" operations, where global gravity and terrain effects are removed, a geoid is predicted, and then the effects are restored to obtain the final geoid model. Our study presents a methodology for geoid computation across Australia, employing least squares collocation (LSC) for prediction. The LSC method comprises two main stages: firstly, generating a grid of gravity anomalies covering the region, and subsequently utilizing these gridded anomalies to calculate grid-based geoid heights. Gravity anomalies in Australia originate from various sources, including terrestrial datasets, satellite altimetry, and airborne gravimetry and gradiometry campaigns. Our presentation focuses on the LSC computations for New South Wales and Victoria, emphasizing the integration of diverse gravity data types—terrestrial, altimetry, airborne gravimetry, and airborne gradiometry. We adopt a combined approach to produce a gridded quasi-geoid using LSC in a remove-predict-restore technique.

This work provides valuable insights into the robust application of LSC for geoid determination, demonstrating its efficacy in amalgamating different datasets to yield precise and comprehensive geoid models tailored to specific regions.

Keywords: Gravimetric Geoid, Least Squares Collocation, Airborne Gravimetry and Gradiometry

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference (Oral)

GravTools: An open source software for the analysis of relative gravity surveys

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GravTools is new open source analysis software for relative gravity surveys developed at Austria's Federal Office of Metrology and Surveying (BEV). It enables to adjust gravity surveys based on differential or nondifferential observations with weighted constraints being used for the datum definition. Furthermore, it provides options for the estimation of vertical gravity gradients, the modelling of tidal and atmospheric corrections, and statistical testing. The well-structured graphical user interface (GUI) is designed to improve the usability. The GUI provides extensive options to assess and clean the observation data, as well as to visualize and compare the estimation results. Since 2022 GravTools is operationally uses at BEV to analyze field surveys for geoid determination and to adjust the Austrian gravity reference network.

GravTools is developed as a Python 3 package and uses the Qt framework for the GUI. The object-oriented program design makes it easily expandable with additional modules and program features. The source code is published open source under the GNU GPLv3 license at https://github.com/ahellers/GravTools and the Python package is available at https://pypi.org/project/gravtoolbox/.

This contribution gives an overview of GravTools' features, with a focus on the software design, the adjustment methods and data visualization.

Keywords: gravity surveys, adjustment, open source software, python

Session: Poster Session 2

Presentation preference (Poster)

Repeated gravity observations at the AUT1 IHRF station as a means to monitor potential temporal variations

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The IHRF Coordination Center serves as the linchpin for maintaining and advancing the integrity of the International Height Reference Frame (IHRF) while is committed to delivering precise and reliable solutions for the International Height Reference System (IHRS), including accurate coordinates of reference stations and vertical datum parameters. In its current realization, the IHRF focuses only on determining the static part of the potential/geodynamic numbers at its sites, while a provision to also include temporal variations in the future is envisaged. The change of a station over time is composed by a geometric part, due to changes in the location of the point, and a dynamic part due to the change of the actual potential itself. AUT1 is one of the core sites of the IHRF where a rigorous determination of the potential has been caried out employing the Geodetic Boundary Value Problem (GBVP) approach utilizing available land and marine gravity data around the station. The achieved accuracy in potential determination is at the 0.1-0.2 m^2/s^2 (~1-2 cm) level, which is considered as optimal given the accuracy of the available gravity data. In this work, we focus on determining potential rates as a combined effects of both the geometric change of the station position and height, provided by the AUT1 CORS (being a EUREF station), and the dynamic part through respective temporal gravity variations. With that in mind, a protocol of repeated relative gravity measurements at monthly regular intervals, between the absolute station at the GravLab premisses, established with an A10 (#027) absolute gravity meter, and AUT1 has been prepared, in order to monitor the temporal gravity variations at the AUT1 station. The observations have been carried out employing the GravLab CG5 relative gravity meter and have been referred to GRS80/IGSN71, relative to the absolute gravity station. During the measurements, the height on all three sides of the gravimeter was measured with an accuracy of 1 mm and at each occupation the instrument was left for 10 minutes to stabilize the measuring system and allow the instruments to reach the ambient temperature. At each occupation, a total number of ten observations were made in order to keep the ones with a precision better than 10 μGal. We report one the first set of repeated measurements during the first four months of the observations and derive some early results on possible correlations with CORS, GRACE-FO and InSAR observations.

Keywords: IHRF, potential, temporal variations, repeated gravity observations, collocation.

Session 1

Presentation preference: Poster

Hybrid Geoid Modeling for the GeoNetGNSS CORS network

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In contemporary geodetic infrastructure, the creation of geoid models with high resolution and accuracy is increasingly recognized as a pivotal component. Considering this, in the frame of the GeoNetGNSS project, funded by the European Union and National Funds through the Region of Central Macedonia (RCM) in Northern Greece, a local gravimetric geoid was determined utilizing both historical and recently collected high-precision and density gravity data obtained from specialized gravity campaigns. The geoid prediction was carried out by the well-known remove-compute-restore technique evaluating Stokes' integral in the frequency domain via Fast Fourier Transform and the Wang-Gore modification for the kernel function. After several tests with the latest GOCE/GRACE-based and combined Global Geopotential Models, XGM2019e has been used as a reference, while the residual terrain model correction was employed for the treatment of the topography. The validation of the developed gravimetric geoid model was carried out using a set of 462 GNSS/Leveling benchmarks within or up to 50 km away from the area under study, achieving an improvement of 3.1 cm in the std, 9.3 cm in the mean and 14 cm in the range of the differences compared to the previous geoid model. A hybrid deterministic and stochastic approach has then been used to model the residuals of the gravimetric model relative to available GNSS/Levelling geoid heights. Various parametric models ranging from simple north-south bias and second- or third-degree polynomial ones for the deterministic part have been used, while the residuals have been treated with a Least Squares Collocation approach employing exponential, 2nd and 3rd order Gauss-Markov analytical covariance functions. After the parametric and stochastic modeling, 80.6% and 98.3% of the differences are lower than the 1 cm and 2 cm standard errors respectively, while the final std of the agreement with GNSS/Levelling geoid heights reaches the 6 cm level. Given the errors of GNSS (1-2 cm) and leveling (2-3 cm) data, the final hybrid geoid has an absolute accuracy of ~2 cm and a relative accuracy better than 8 ppm, providing confidence on the use of the hybrid geoid for everyday surveying purposes.

Keywords: Hybrid Geoid, GNSS/levelling validation, Parametric models, Stochastic modeling, Northern Greece

Session 1

Presentation preference: Poster

Long-wavelength variation in the Earth's shape from SLR and GRACE

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The earth's shape or geoid can be fit by the triaxial ellipsoid model, which is better than the biaxial rotational ellipsoid. The triaxial ellipsoid surface is uniquely defined by the Earth's total mass, the rotation rate, the dynamic factors of polar and equatorial flattening, and the east longitude of the equatorial major axis. The polar flattening or oblateness is characterized by the seconddegree zonal harmonic gravity coefficient, C20, and the equatorial ellipticity is uniquely determined by the degree 2 and order 2 gravitational coefficients, C22 and S22. For over four decades, satellite laser ranging (SLR) has recorded the global nature of the long-wavelength mass change within the Earth system. Significant quadratic variation (with a turning point in 2005) in the geopotential coefficients, C20 was observed from analysis of 48-year SLR data. This quadratic variation suggests the decrease caused by GIA turn to be increasing from 2005 caused by significant ice mass loss in Polar Capes. A significant decadal and secular variation in C22/S22 was determined from 32-year SLR data and 22-year GRACE/GRACE-FO data. This secular variation in C22/S22 reveals that the equatorial ellipticity of the Earth is linearly increasing and the Earth's equator is flattening by~0.16 mm/yr. This drift is the consequence of the long-term longitudinal mass redistribution that occurs in the "geophysical fluids" or within the Earth system, but unlikely to be due to the GIA effect. Detailed analysis will be presented.

Keywords: SLR, Geoid, Oblateness of Earth, Equatorial ellipticity, C20

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral)

Gravity reference frame realization and densification in the field

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Terrestrial gravimetry is used in various fields of geodesy and geophysics. Applications comprise, among others, modeling the fine structures of the gravity field, providing reference values for metrology and monitoring local crustal deformation and mass transport, e.g., in the hydrosphere, the cryosphere or the solid Earth. In order to guarantee compatibility of measured gravity values and the related long-term stability, realization and connection to a stable reference frame is required. Currently, IAG is under way to implement a new reference frame for gravity, the International Terrestrial Gravity Reference Frame (ITGRF). This frame will be represented by measurements of the acceleration of free-fall with absolute gravimeters traceable to the SI which provide instantaneously access to the absolute level of the frame. The frame will be realized at globally distributed reference stations with a relative accuracy of 10^-8 or better. In order to make this frame accessible to the user community, compatible second order gravity networks are envisaged which are connected to the ITGRF stations by absolute or relative field gravimeters. The present study shows results from a combined absolute-relative network of medium spatial extent. This gives an indication of the level of accuracy for the realization/densification of the ITGRF achievable with state-of-the-art field equipment. Thereby, we consider application of the conventional temporal gravity corrections as well as availability of additional information like the g-reference height of different instrumentation, the local vertical gravity gradient, scale uncertainties of relative gravimeters and the effect of temporal variations between observational epochs.

Keywords: ITGRF, gravity network, absolute gravimetry, relative gravimetry

Session: Poster Session 1

Presentation preference (Poster)

Separation of temporal gravity signals using standard statistical and neural network methods

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The global, temporal gravity data measured by the Gravity Recovery And Climate Experiment (GRACE) and GRACE-Follow on (GRACE-FO) missions reflect the sum of many mass change processes in the Earth's system. The separation of the individual sub-signals such as ice mass changes, hydrological mass changes or mass changes in the atmosphere, oceans and the solid Earth is crucial for interpreting and exploiting the data as good as possible towards the improvement of our understanding of a multitude of geophysical processes, including many climate processes.

We tackle the signal separation problem by exploiting prior knowledge on the typical space-time behavior of the individual signal components. For this, we consider two methods, one standard statistical method based on the Principal Component Analysis (PCA), and one neural network method using a multi-channel U-Net architecture. Both methods are tested in the same closed-loop simulation setup, using synthetic data derived from the Updated Earth System Model (ESM) of ESA. This allows us to compute the errors of our predictions and thereby evaluate and compare the performance of our methods. The ESM consists of separate datasets for temporal gravity variations caused by mass redistribution processes in the atmosphere, the oceans, the continental hydrosphere, the cryosphere and the solid Earth. The available model data are split in time to form a dataset used to introduce prior knowledge to the methods and a dataset used to test the found signal separation models.

Our results show a comparable performance of the neural network-based and the PCA-based method, both achieving relative prediction errors of about 20 to 40 %. Besides an analysis of the separation errors, we present possibilities to further improve our signal separation methods, e.g. by introducing additional prior knowledge as constraints. In order to develop our simulation setup towards real data products of GRACE type, realistic satellite noise needs to be included as an additional signal component.

Keywords: time-variable gravity, signal separation, neural networks

Session 5: Gravity for climate, atmosphere, ocean and natural hazard research

Presentation preference (Oral/Poster)

The Global Geodetic Observing System: Facilitating Opportunities for Strategic Outreach, Collaboration, and Engagement with External Stakeholders

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The vision of the International Association of Geodesy's Global Geodetic Observing System (GGOS) is "Advancing our understanding of the dynamic Earth system by quantifying our planet's changes in space and time." This mission, as well as work toward the goals and objectives of the GGOS Strategic Plan, is partly supported by targeted engagement with external stakeholders, managed as a component of the GGOS Coordinating Office. GGOS External Relations includes a work portfolio that focuses on advocacy, visibility, and collaboration to ensure geodesy is a visible, valued, and sustainable worldwide asset.

Working toward proactive engagement with the broader Earth observations community, GGOS external outreach and engagement centers on advocacy for interoperable, discoverable, and openly available geospatial data; promoting infrastructure development; identifying geodetic contributions to United Nations frameworks, as well as working with external partners to leverage the use of geodesy in broader Earth Observations campaigns.

We present an update on how GGOS participation in diverse stakeholder organizations works to identify synergies, making connections across organizations in the name of geodesy and mutual benefit. How GGOS participation and leadership – often on behalf of the IAG – works to ensure Earth observation organizations are aware of their dependency on geodetic infrastructure for applications such as climate change and disaster risk reduction will be discussed.

Opportunities for the physical geodesy community to engage with and benefit from GGOS external relations activities will be presented.

Keywords: stakeholder engagement, strategic partnerships, community engagement, technology policy, cross-functional collaborations

Session: Session 6: Data management, dissemination of results and networking of stakeholders

Presentation Preference: no preference

Height System Unification and Transformation in Switzerland

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The transformation of physical heights from one height system to another is a necessary task for many geodetic applications. For local works crossing national borders, the estimation of a simple offset may be accurate enough. However, for larger works or for the preparation of continental/global datasets, more elaborated transformation methods have to be applied. One option would be to just use the heights of common points along the border. But usually these are only very few points and the differences between national heights might not be easy to interpolate. Another method would be to use national geoid models or height transformation surfaces between ellipsoidal heights and the national height systems. Or – at least in Europe – we could use a transformation that involves a continental height system such as the EVRS.

In this presentation several methods are compared and the results are shown for Switzerland and all neighboring countries.

Keywords: Height System Unification, height transformations, local geoid models

Session 1: Reference systems and frames in Physical Geodesy

Poster

Western Mediterranean altimetry and gravity covariance study for DOT estimation through MIMOS

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The advent of SWOT mission data in combination with the recent altimetry satellites (CRYOSAT-2, SARAL-Altika, SENTINEL-3A, SENTINEL-3B) provide additional value in regional Dynamic Ocean Topography (DOT) estimation both in the resolution and the accuracy of the final product. The near-real-time records support the phase of the operational altimetry. Two study areas in the Western Mediterranean were chosen in order to study the signal and error covariance of each altimetric product from 2017 to 2024. The successive information of the satellite track led to the spectral estimation of the signal and error PSD and covariance. Various covariance models (exponential, gaussian, ARMA) were tested in order to fit the data-driven estimation. A similar computation scheme was tested in the sea gravity data using simulated repeated fields. The final analytic gravity covariance from the periodogram PSD approach was tested against the fitted empirical one. Finally, gravity and altimetry PSD information is used in the DOT estimation through an adequate Multiple-Input-Multiple-Output-System (MIMOS).

Keywords: DOT, covariance, satellite altimetry, sea gravity, MIMOS

Session: 4: Regional gravity field modelling and geophysical interpretation

Presentation preference: Poster

Estimation of gravimetric contributions to sea level change in the Baltic Sea and prediction with Deep learning method

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The two key factors to sea level changes are the mass (gravimetric) component from melting of ice sheets and glaciers, along with the steric component from the expansion of seawater. This study focuses on gravimetric sea level changes in the Baltic Sea, using satellite altimetry and tide gauge observations to record relative sea level changes from May 2002 to April 2023. The regional sea level changes are decomposed into the gravimetric contributions from Antarctic ice sheet melt, Greenland ice sheet melt, glacier melt, terrestrial water storage (TWS) change, glacial isostatic adjustment (GIA), and into the steric effects due to salinity and temperature changes. By solving the sea level equation and using GRACE observations, we obtained the sea level fingerprints for each contributor in the Baltic Sea. As GRACE observations in this study three mascon solutions from JPL, CSR, and GSFC are used and results are intercompared.

Based on the results using the JPL mascon solution, as an example, it was found that 16% of the sea level change in the Baltic Sea was contributed by GIA, 10% by steric effects, and 65% was due to mass changes. For the mass changes, the contributions from the Antarctic ice sheet, Greenland ice sheet, glaciers, and land were around 24%, 12%, 33%, and 16%, respectively. For sea level prediction, we will utilize deep learning methods. Applying the obtained sea level fingerprint signals, we use the Long Short-Term Memory (LSTM) method to predict the individual components, aiming to forecast future sea level changes in the Baltic Sea. We quantify the uncertainty of predictions, providing confidence intervals and probability distributions to help understand the reliability and risks of forecast results. The outcomes will show the contributions to the Baltic sea level change of all gravimetric components and the prediction of these signals will be ensembled for the total sea level forecast.

Keywords: Regional sea level change, Mass concentration, Sea level fingerprint, Sea level prediction, Long Short-Term Memory method

Session: Poster Session 5

Presentation preference (Oral/Poster)

On the application of the Atmospheric attraction computation service (Atmacs) in absolute gravimetry

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Classically, atmospheric corrections for terrestrial gravimetry are computed from the local air pressure record and an admittance factor of 3 nm/s^2/hPa is usually adopted to derive gravity effects. The reference level is based on a standard atmosphere in agreement with the Resolution N° 1 of the International Association of Geodesy (IAG) of 2023, which defines the International Terrestrial Gravity Reference System (ITGRS). Roughly 90% of the atmospheric contributions to gravity variations are covered by this approach. To account also for the spatial distribution of air masses around any given station, the Atmospheric attraction computation service (Atmacs) was established that relies on numerical weather models of the German Weather Service (DWD). However, while Atmacs provides accurate time-variations of atmospheric corrections, the long-term stability is currently limited by occasional model changes at DWD. Such model updates do not only include improvements in the spatial and/or vertical resolution but also modifications of the associated model orography, and may thus cause discontinuities in the time series of atmospheric corrections which may rise the µGal level and are typically altitude-dependent. In the present study, we aim to solve this problem by referring the time series to a common reference ensuring the compatibility with the conventions adopted for the ITGRS, and we explore the use of Atmacs for correcting absolute gravity observations.

Keywords: terrestrial gravimetry, atmospheric corrections, Atmacs, numerical weather models, ITGRS

Session 1 Reference systems and frames in Physical Geodesy

Presentation preference: Oral

Experiments with point mass model for estimating total water storage change from GRACE spherical harmonics

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This study estimates total water storage change over the Chambal catchment using GRACE level 2 spherical harmonic coefficients (SHC) data and the point mass model. The point mass model extracts mass anomalies from the SHC, Satellite orbit information and Mascon location. While modelling the mass anomalies, we deal with an inherently ill-posed and spectrally inconsistent problem. The design matrix of the observation geometry is rank deficient and ill-conditioned, and the truncation of SH coefficients results in a spectrally inconsistent model.
Gravity disturbances obtained from the synthesis of truncated SH coefficients can be used as observations of the Mascon model, where the parameters are point masses that induce gravity disturbances. The study investigates the impact of different factors on estimated mass anomalies, such as sampling methods, filtering of gravity data, spectral consistency, catchment grid size, and the effect of buffer zone grid size and buffer zone extension on signal leakage from the neighbouring catchments. Experiments are performed with equiangular, equidistance, random, and equal-area grids with different grid spacings. Singular value decomposition (SVD) analysis is carried out for the design matrix of each grid. GRACE level 2 SHC data is corrected for the C20 coefficient and GIA effect and filtered to remove noise and errors. The filtered SHCs are synthesised to generate gravity disturbance observations for the point mass model. The mass anomalies are estimated using the ordinary least squares method, and
Tikhonov regularisation is used to address the ill-posed nature of the inverse problem. The L-curve method is employed to find the optimal regularisation parameter. The estimates are validated against CSR RL06 global mascon solutions.
Initial observations of this work suggest that the mascons positioned at random grid points are preferred over the regular or equiangular grid points as they allow the design matrix to store unique information, which reduces its condition number and yields better estimates. Nash–Sutcliffe efficiency (NSE) coefficient value of 0.8837 with reference to the global solution is observed for the estimates from the random grid. The equidistance grid for mascons helps stabilise the design matrix. 1° catchment grid size with a Buffer zone extension of 10° and grid size of 2° are optimal. It is observed that both a destriping and a Gauss filter shall be employed to obtain reliable gravity disturbance measurements; 3° Gaussian and destriping filters for gravity data are optimal.

Keywords: GRACE, Mascons, Tikhonov regularisation.

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference: Oral

Reduction capabilities of ocean tide aliasing by coestimation of major zonstituents with future satellite constellations and formations

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Satellite gravity missions are an indispensable tool to monitor mass (re-)distribution processes on a global scale with high revisit times. With the current dualsatellite mission GRACE-FO based on the successful heritage of its predecessor GRACE, CHAMP and GOCE, monthly gravity-field products with a spatial resolution of about 300 km are generated routinely. High-frequency mass variation processes beyond temporal resolvability are under-sampled and cause temporal aliasing, which is the dominant error source of the achievable gravity field performance. These processes include non-tidal mass variations, mainly from atmospheric and oceanic contributions, as well as tidal mass variations. To encounter these limitations and simultaneously monitor high-frequency mass processes, the goal for future satellite gravity missions is to increase the spatiotemporal resolution, which can be achieved by enhanced satellite constellations.

We investigate the capabilities of extended constellations to encounter ocean tide-induced aliasing by simultaneously improving underlying ocean tide models in numerical simulations. This can be achieved by an enhanced parametrization strategy within the gravity field processing, where ocean tide constituents are coparametrized besides the spherical harmonic coefficients of the gravity field. Our study focuses on the eight major ocean tides (Q1, O1, P1, K1, M2, N2, S2, K2), which are co-parametrized in several retrieval periods, ranging from one month to a decade. Various constellations based on polar and inclined satellite pairs in in-line and cross-track formations are investigated in terms of performance for gravity field and ocean tide estimation.

The best results can be achieved with constellations of globally distributed polar satellites (varying in mean anomaly and right ascension of the ascending node), which provide optimal global coverage during the selected retrieval period. Since such extended constellations might be realized only with lower-cost satellites, we consider lower instrument performances for miniaturized instrument candidates for the accelerometer and the inter-satellite ranging sensor. However, even with these limitations the enhanced satellite constellations still can significantly reduce ocean tide aliasing effects.

Keywords: Temporal Gravity Field, Ocean Tides, Numerical Simulation, Satellite Constellations, Future Satellite Mission

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral)

Future satellite gravimetry with a network of miniaturized satellites

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Mass variations and redistributions in atmospheric, hydrological, glacial, and oceanic processes can only be monitored globally by satellite gravimetry missions. The up-to-date launched gravity missions consist of either a single satellite (CHAMP and GOCE) or a single in-line satellite pair (GRACE and GRACE-FO). Based on the provided observation geometry, they have spatiotemporal limitations leading to under-sampling of highfrequency mass variations caused by atmospheric and oceanic processes. Additionally, ocean tide models have high uncertainties and contribute to the aliasing phenomena as well. In several previous studies, future mission concepts were investigated to reduce the aliasing problem by improved satellite formations such as Pendulum or Cartwheel and by a satellite constellation with an additional inclined satellite pair. The latter configuration is currently being investigated within the Mass Change and Geoscience Constellation (MAGIC) study for the next satellite gravity mission. The size, weight, and power (SWaP) assumptions of the planned satellite buses and onboard instruments are in the same range as for the GRACE and GRACE-FO satellites.

As the possibilities for miniaturizing satellite buses and the required instruments continue to increase, realistic and costeffective concepts consisting of multiple satellites can be considered for future satellite gravimetry. Within our DFG project “Cube-satellite networks for geodetic Earth observation on the example of gravity field retrieval (CubeGrav)”, we investigate the potential and the capabilities of CubeSats for temporal gravity field determination. In this contribution, we present the scientific results and a preliminary mission concept. The scientific analysis focuses on the added value of a larger number of satellites distributed on one or several orbital planes in terms of different satellite formations and constellations for increasing the temporal resolution.

The improved ground coverage achieved with the satellite network enables the retrieval of short-term gravity field solutions down to 6 hours resolution. Additionally, we investigate the minimum performance requirements of miniaturized key sensors (accelerometers, inter-satellite ranging instrument). For a realistic mission concept, we identify an appropriate miniaturized set of these key sensors besides the other instruments supporting the observation system. Our preliminary system design consists of a constellation of satellite pairs where each satellite pair is flying in in-line formation and each satellite being a 6U CubeSat. Finally, we provide rough estimations on system budgets involving power consumptions and mission lifetime. Based on the above-mentioned results, we conclude by assessing our mission concept regarding feasibility and future implementation.

Keywords: Gravity Field, Satellite Constellations, Future Satellite Mission, Technological Demonstrator, Numerical Simulation

Session: Poster Session 2

Presentation preference (Poster)

Height datum: Definition, New Concepts, and Standardization

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Geometric heights above an adopted reference ellipsoid, estimated from GNSS-based geocentric Cartesian coordinates, must be converted into physical heights for practical applications. Such applications include among others levelling, sea-level monitoring, flood risk assessment, ground deformation monitoring, and construction engineering. Based on the type of physical height, the conversion is possible when geoid height (for orthometric heights) or height anomaly (for normal heights) is known with the sufficient precision (1 cm or better). The height conversion is necessary because 1- geometric heights do not reflect physics of processes at, above or even below the Earth's surface, and 2- reference ellipsoid only approximates the geoid, a reference equipotential surface of the Earth's gravity field, which serves as the height reference surface for physical heights. Significant challenges are encountered when estimating values of the geoid height or height anomaly in practice. Geoid heights computed by various groups may show differences of up to several decimeters, even when using the same theoretical and methodological procedures.

Additionally, the definition of height anomalies may result in nonuniqueness of the normal heights. In this contribution, we report on recent activities of the joint study group "Height datum: Definition, New Concepts, and Standardization" within the IAG's Inter-Commission Committee on Theory. The group aims to 1-establish new or extend existing cooperation within the international geodetic community, 2- provide clear, rigorous, and manageable guidelines for the precise

estimation of geoid heights and height anomalies, and 3- formulate recommendations to the IAG. Updated or new concepts will consider data from various observation systems, including modern technologies such as precise optical clocks. Furthermore, we will explore methods to seamlessly and accurately integrate geoid/quasi-geoid models with local high-resolution and precise spirit levelling observations. This integration is crucial as the concept and realization of height datums must effectively support real-world applications of physical heights.

Keywords: Gravity Field, Satellite Constellations, Future Satellite Mission, Technological Demonstrator, Numerical Simulation

Session 1: Height Datum, Geoid, Quasi-geoid

Presentation preference (Oral)

Airborne Gravity Vector for Geoid Determination; Insights from a Real Dataset

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We investigate the advantages of using airborne gravity observations in vector form (3D) compared to scalar form (1D or vertical component only) for geoid modelling. Our study utilizes vector gravity data from a real test survey over the Colorado 1-cm geoid experiment region in the USA, covering a one degree by 1 degree area. The survey's average flight line spacing is 5 km, with a terrain clearance of 300-500 meters, derived from a gentle drape surface. We employ the onestep integration method for geoid determination in Helmert and No-Topography spaces and compute regional geoid models based on various input characteristics. The external accuracy of models are then computed by comparing to geoid heights from GSVS17 and historical GPS-on-BMs data.

Our findings demonstrate that:

- Using vector-form airborne gravity observations, which include deflections of the vertical at the flight level, can improve the external accuracy of the geoid by up to 50%.

- The flight line spacing can be increased without compromising the external accuracy of the geoid when using gravity vector observations, compared to using gravity scalar observations.

- Airborne gravity vector data alone, without any terrestrial gravity data, can achieve centimetre-level accuracy even in regions with medium topography.

- It is unnecessary to interpolate the airborne gravity observations into grid points at a constant flight height (a commonly used approach) when they are used in vector form. Scattered airborne gravity vector data can provide better or equivalent geoid accuracy.

In this contribution, we show details of our computations and provide recommendations for future airborne gravity surveys.

Keywords: Airborne gravity, geoid, least squares, downward continuation

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference (Oral)

Evaluation and homogenisation of a marine gravity database from shipborne and satellite altimetry-derived gravity data over the Nigeria Sea

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Abstract

Combining gravity data from various sources, including shipborne gravimetric observations, global geopotential models, and satellite altimetry, is crucial for creating an accurate geoid model for marine areas. This study aims to develop homogenised gravity data for the Nigeria Sea region. We began by comparing the shipborne gravity data available at the Bureau Gravimétrique International (BGI) with the gravity data predicted from the DTU21GRA, SSv29.1, SGG-UGM-2, XGM2019e_2159, GECO, EIGEN-6C4, and EGM2008 models. Our findings showed that the altimetry models exhibited similar characteristics in the Nigeria Sea, with DTU21GRA demonstrating superior performance in standard deviation (STD), Root Mean Square (RMS) and mean offset values compared to shipborne data. To ensure data accuracy, we addressed residual linear drifts inherent within the shipborne gravity dataset using cross-over adjustment for each leg of the surveys. Concurrently, we identify and eliminate gross errors within each survey leg by employing the 2-sigma method as the rejection criterion and implemented a stringent pre-refinement process for ship marine surveys using the DTU2GRA model as a reference. Furthermore, we applied leave-one-out cross-validation techniques to detect and eliminate outliers across the entirety of the shipborne gravity data, resulting in a refined shipborne gravity dataset with improved consistency and accuracy. This refined dataset was merged with the DTU21GRA gravity data via Least-Squares Collocation (LSC) to create a combined dataset. We independently validated the combined datasets by evaluating them at randomly selected 100 shipborne gravity stations not included in the LSC process. The comparison showed significant enhancements in fit, with a 47% decrease in STD. In addition, we comprehensively compared the complete refined shipborne gravity data and the combined dataset. The comparison showed significant improvements in fit, with a 62% decrease in STD. Finally, we have generated marine geoid models for the study area: one utilising the refined shipborne data exclusively and the other incorporating a combination of refined shipborne and DTU21GRA gravity datasets. We derived the Mean Dynamic Topography (MDT) using DTU21MSS and validated it against CLS22 MDT. Our findings indicate the superior performance of the geoid model constructed with the combined gravity data compared to the gravity data derived solely from refined shipborne gravity data, with a 30.4% decrease in STD when evaluated against the CLS22 MDT. We show the relevance of integrating historical shipborne data after careful processing, even in the era of modern high-resolution altimetry gravity anomaly determination.

Keywords: Shipborne gravity, Marine gravity, Satellite altimetry, Combined GGMs, Nigeria Sea

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation: Oral Presentation

Estimating the new geoid and establishing the IHRS/IHRF in Italy

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The last estimate of the Italian geoid was computed in 2005. In recent years, new gravity observations were added to the Italian gravity database, new Global Geopotential models were estimated, and Digital Terrain Models were improved. Furthermore, new GNSS/levelling data were measured in the Italian area so that a more accurate estimate of the precision of the gravity geoid undulation can be assessed. Also, some improvements in the geoid computation methods have been devised to be profitably applied in estimating the undulation. Taking advantage of these improvements in data and methodology, the geoid undulation in Italy has been newly computed. Comparisons with the GNSS/leveling data prove that the precision of this estimate is of the order one centimeter. Following this computation, the estimate of the orthometric heights according to the IHRS/IHRF scheme has been performed in several points over Italy, including the most relevant tide gauge sites and the GGOS Core Station of Matera. In this way, the Italian height reference network has been linked to the International Height Reference System defined in the IAG resolution n°1 of 2015 established during the IAG/IUGG Assembly in Prague.

Keywords: Italian geoid, collocation, IHRS/IHRF
Session: Session 4: Regional gravity field modelling and geophysical interpretation
Presentation preference: no preferences

An Investigation of the Spatial and Temporal Characteristics of Extreme Dry and Wet Events across NLDAS-2 Models

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ABSTRACT: Extreme hydrological events (including droughts and floods) produce severe social and economic impacts. Monitoring hydrological processes from remote sensing is necessary to improve understanding and preparedness for these events, with current missions focusing on a range of hydrological variables (i.e., SWOT, SMAP, and GRACE). This study uses output from three state-of-the-art land surface assimilation models and an event clustering algorithm to identify the characteristic spatial and temporal scales of large-scale extreme dry and wet events in the contiguous United States for three major hydrological processes: precipitation, runoff, and soil moisture. We also examine the sensitivity of extreme event characteristics to model resolution and assess intermodel differences. We find that models generally agree in terms of the mean characteristics of events: precipitation dry events are of shorter duration in comparison with soil moisture and runoff events, and more intense events tend to be smaller in area. We also find that mean spatial and temporal characteristics are highly dependent on model resolution—important in the context of detecting and monitoring these events. Results from this study can be used to inform land surface model development, extreme hydrology event detection, and sampling requirements of upcoming remote sensing missions in hydrology.

SIGNIFICANCE STATEMENT: Understanding the fundamental characteristics of dry and wet extreme events (droughts and floods) is of importance for improving our preparedness and response to events, as well as for designing satellite observing systems that can adequately monitor them. Here we use output from land surface models to determine the average size and duration of large-scale extreme events for the contiguous United States using fine temporal data. We find that events that are most extreme—the most severe floods and droughts—tend to be shorter in duration and smaller in size. We also present an assessment of how three commonly used land surface models detect extreme hydrological events, which is important for assessments based on models. These findings are important for understanding the proportion of events that may be not adequately resolved by current hydrology remote sensing missions.

KEYWORDS: Drought; Extreme events; Flood events; Hydrology; Satellite observations

1. Introduction

Extreme hydrological events, including droughts and floods, are of significant societal consequence, with implications in water resource management, agriculture, and hazard management (Wilhite 2000). Water insecurity is estimated to cost $500 billion per year to the global economy, with urban flood damage alone responsible for $120 billion per year (Sadoff et al. 2015). The social consequences of hydrological extremes are also significant: between 1998 and 2017 approximately 2 billion people were affected by floods worldwide, while 55 million people are affected by droughts every year (source: https://www.who.int/health-topics/). An estimated 280 000 deaths globally attributed to drought between 1991 and 2000 (Logar and van den Bergh 2011). Indirect consequences of hydrological extremes also include poverty, sanitation issues, civil unrest, and migration, which is expected to increase in upcoming decades (Gerber and Mirzabaev 2017).

Wet and dry extremes manifest in a number of different hydrological processes, including precipitation, runoff, and soil moisture, which produce a cascade of variability across space and time scales (Changnon 1987; Farahmand et al. 2021). For example, short-term localized precipitation events may produce more persistent signals in soil moisture, which persist longer and extend to greater regions than the initial rain event. There is also evidence that extreme events are influenced by anthropogenic climate change (Herring et al. 2014; Trenberth et al. 2015) and may increase in frequency in future (Lenderink and van Meijgaard 2008; Berg et al. 2013). Characterizing the spatiotemporal dynamics of extreme events across different hydrological processes can improve our understanding of climate extremes.

To investigate the spatial and temporal characteristics of hydrological extremes, previous studies have examined relationships between severity, duration, and intensity among various hydrological variables including precipitation, runoff, and soil moisture. Andreadis et al. (2005), used the severity–area–duration (SAD) methodology to examine drought events for the United States using LSM soil moisture and runoff focusing on events ranging in duration from 3 to 72 months, and areas starting at 25 000 km^2 for 1903–2000. They found that most severe hydrologic droughts (as measured by runoff) coincided with most severe agricultural droughts (as measured by soil moisture). Building on this study, Sheffield et al. (2009), extended the SAD methodology using soil

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moisture to look at droughts with an area of at least 500 000 km^2, and 3 months or longer for the period 1950–2000 using LSM output from Variable Infiltration Capacity (VIC). They found that maximum soil moisture droughts ranged from 4 to 11 million km^2, persisting for 12–49 months. This framework was also expanded to produce a global catalog of drought and pluvial events in soil moisture, runoff, precipitation, and evapotranspiration, using VIC and river-routing models, again focusing on events in excess of 500 000 km^2 and monthly or longer intervals (He et al. 2020). Wang et al. (2009) also extended these studies to examine the multimodel representation of drought for the United States, using soil moisture to characterize drought events, and found good agreement among models.

Knowledge of the characteristic scales of hydrological events is important for understanding climate variations, designing observing systems, and responding to extreme events. Satellite remote sensing is an effective tool for monitoring drought and flood events at global scales, and understanding hydrological processes, and is increasingly used in water resource decision making (Sheffield et al. 2018). Using soil moisture data from the Soil Moisture Active Passive (SMAP) satellite, the variability in soil moisture was investigated globally, and arid locations were found to have a slower turnover of the water cycle (i.e., greater persistence in soil moisture anomalies following a precipitation event) (McColl et al. 2017). SMAP data were also used in a novel drought detection tool for predicting food security with prediction lead times of 3–6 months (Krishnamurthy R et al. 2022). Deviations in total water storage measured from the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) can also be used to identify regions globally experiencing water deficits (Thomas et al. 2014; Rodell and Reager 2023). SMAP is important for characterizing agricultural dry and wet extremes by providing estimates of soil moisture, while GRACE/GRACE-FO can provide information relevant for both agricultural and hydrologic drought by observing changes in fluxes of total water storage (constituting both water stored in lakes, rivers and reservoirs, as well as soil moisture and groundwater). The Surface Water and Ocean Topography (SWOT) mission will provide information on river discharge for rivers of 100 m width or greater at a 21-day revisit (Biancamaria et al. 2016).

Here, we build on previous studies (Andreadis et al. 2005; Sheffield et al. 2009; He et al. 2020; McCabe and Wolock 2021) to examine dry and wet extremes in the contiguous United States (CONUS) starting at 5-day intervals and greater. We look at events that are 5 days or longer in order to ensure they are meaningful climatic events, and also to remove the "noise" produced by shorter-term fluctuations. We also examine scales relevant to the time scales of sampling intervals of current and future hydrological remote sensing missions. For example, GRACE/GRACE-FO measure at monthly intervals with a spatial resolution of ~400 km × 400 km (~160 000 km^2), SMAP obtains soil moisture at a resolution of ~36 km × 36 km (~1300 km^2) every 3–5 days, and the SWOT mission measures river discharge every 21 days for river reaches of 100 m or greater (Biancamaria et al. 2016). Information on hydrology sampling requirements is relevant for informing satellite remote sensing mission development.

We use output from three LSMs from the North American Land Data Assimilation System 2 (NLDAS-2; Xia et al. 2012), a state-of-the-art land surface assimilation system for the United States. NLDAS-2 provides high spatial and temporal resolution information from 1979 to present, which is needed for examining the characteristics of hydrological extreme events overlarge scales but is not readily available from observations. This is especially true for soil moisture, which was not easily observable over large areas before SMAP in 2015, and for runoff, which is also not directly measurable. By contrast, precipitation is one of the best observed variables of the hydrological cycle, though it too can suffer from uncertainty in complex terrain and sparse regions (Sheffield et al. 2004). By using an ensemble of three LSMs we also sample across different model physics and examine sensitivity of results to the different models used. This extends other studies (i.e., Wang et al. 2009) to look at both dry and wet extremes across a range of LSMs.

We address the following questions:

- How do extreme dry and wet events manifest across the NLDAS-2 models? What are the average spatial and temporal scales (in terms of precipitation, total runoff, and soil moisture)?
- What is the sensitivity of our results to changes in model (i) spatial and (ii) temporal resolution of datasets used?

We investigate these questions, and their implications for hydrology missions (especially SMAP, GRACE/GRACE-FO, and SWOT) by identifying whether current sampling frequency and scale is adequate to observe most wet and dry extremes. The results of this study will supplement our knowledge of how extreme events unfold in space and time.

2. Methods

a. Datasets

We use hourly data at 1/8° spatial resolution from NLDAS-2 Noah, Mosaic, and VIC for surface runoff, subsurface runoff, and 0–100-cm depth soil moisture (Xia et al. 2012; available to download at https://disc.gsfc.nasa.gov/datasets?keywords=NLDAS). This depth is chosen as it is the deepest common depth of the three LSMs. For precipitation, we use the NLDAS-2 forcing data, which are the same for each of the three LSMs. The output from NLDAS-2 is among the best quality and highest resolution that currently exists for CONUS. By using output from the three different NLDAS-2 LSMs, we also constrain the results across three different model configurations.

We use ~30 years of NLDAS-2 model output and create 5-day means (pentads) for each of the datasets, and the rest of the analysis is carried out on the pentad data. Since we are interested in regionally significant events, in this analysis we also sample the 1/8° spatial resolution to produce 0.5° output. We therefore focus on capturing large spatial events. We choose to focus on 5-day means, as we are interested in considering shorter duration events than observed in previous studies [i.e., 3 months (Sheffield et al. 2009; Andreadis et al. 2005) and 1 month and greater (He et al. 2020)].

Analysis with 1-day data [see section 2c(3) and Figs. A3 and A4 and Table A6 in the appendix)] indicated that the

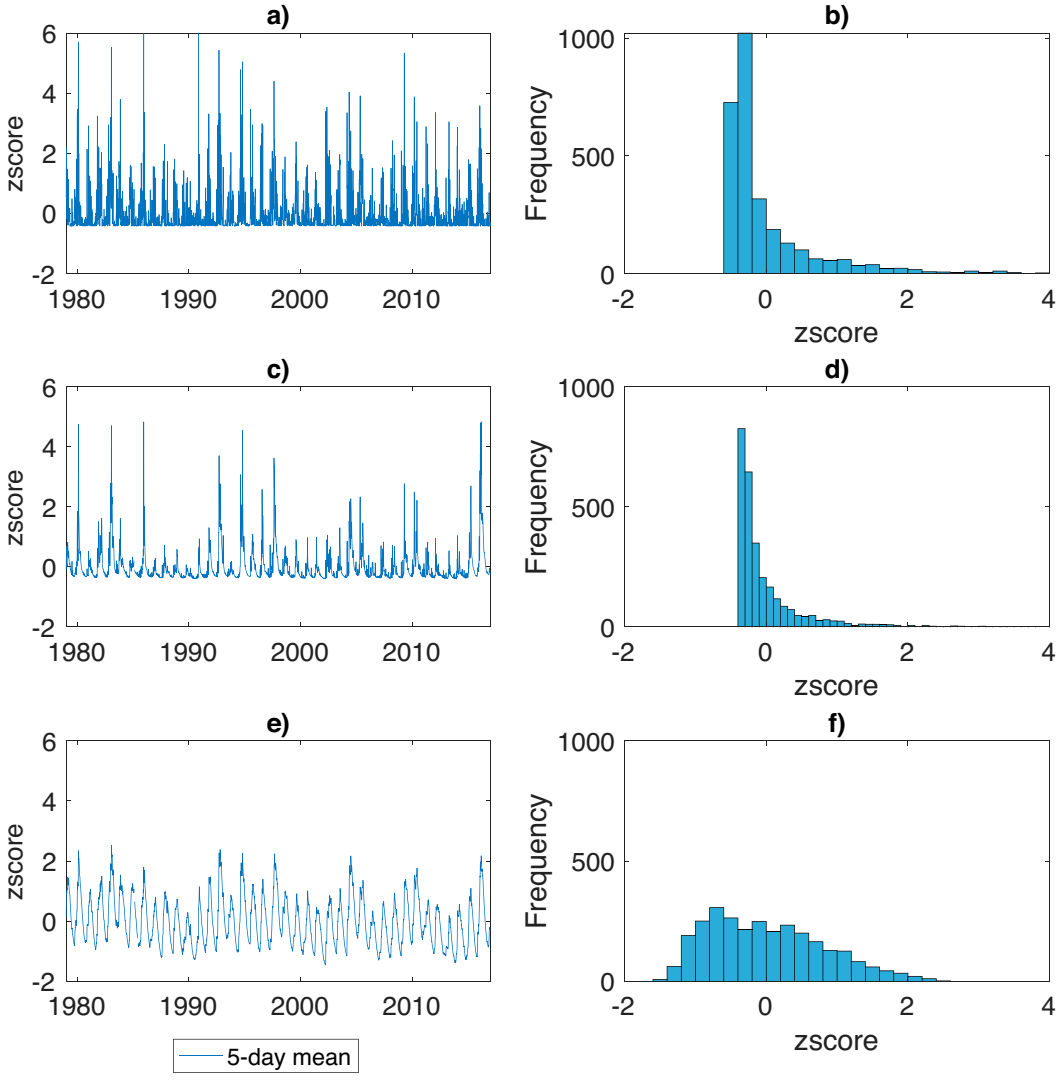

FIG. 1. Example for California for the standardized anomaly (z score) over the period 1979–2017 for the time series of (a) precipitation, (c) runoff, and (e) soil moisture (0–100 cm) plotted as 5-day means. Also shown are histograms of the distribution of (b) precipitation, (d) runoff, and (f) soil moisture.

tracking algorithm captured transient short-term 1-day events, which may not be very significant (especially for drought, where drought on the order of days is not particularly meaningful). We therefore use the 5-day and 0.5° information to fill the need for considering both regionally ($>\sim$30 000 km^2) and temporally significant events, and in particular to supplement previous works that looked at longer durations. Sensitivity to these choices is presented in section 2c(3) and in the appendix (Figs. A1–A4; Tables A5 and A6).

b. *Hydrological extremes definition*

For each dataset, at each grid point we calculate the standard score by subtracting the long-term mean of that grid point and dividing by the standard deviation (over 1979–2017). This permits us to normalize the drought conditions in space. Other studies have evaluated the use of using standard scores on precipitation data to detect hydrological extremes and found similar results when compared with use of other indices [e.g., the standardized precipitation index (SPI)] (Wu et al. 2001; Salehnia et al. 2017). An example of the standardized data for precipitation, runoff and 0–100-cm soil moisture for the state of California is shown in Fig. 1. Precipitation and runoff are both characterized by positively skewed distributions (Figs. 1b,d) while soil moisture is more normally distributed (Fig. 1f).

We define a dry (wet) hydrological extreme as when a particular grid cell enters the bottom (top) 10th percentile of the time series. This method to identify extreme events follows Sheffield et al. (2009) (where the top and bottom 20th percentile was used instead of the 10th percentile to define extreme events). Here, percentiles, which range from 0 to 100, are appropriate for the data rather than absolute thresholds, as it

permits us to characterize events across the domain [also described in Sheffield et al. (2009)].

Extreme events are considered to begin when at least 10 contiguous pixels (which corresponding to an area of ~30 000 km^2) are below or above the determined threshold based on percentiles. This is a subjective decision and is used to limit smaller-scale events in the data and to focus on regionally significant events. This is also a smaller area threshold than that used by previous studies that used similar severity–area–duration frameworks (Sheffield et al. 2009). To make sure we are not detecting spurious events that shrink in size or have limited spatial connectivity [i.e., as noted in Sheffield et al. (2009)], at each time step, we require that drought events maintain an area of at least ~30 000 km^2.

c. *Tracking algorithm*

We design an algorithm that tracks the duration and area of each extreme hydrological event. This methodology is conceptually similar to the feature tracking algorithm used to identify drought events in other studies (Sheffield and Wood 2007; Sheffield et al. 2009; Herrera-Estrada et al. 2017). For the majority of the analysis, we consider the 10th percentile as constituting extremely dry or wet conditions. We also set different thresholds (5th and 2.5th percentile) to examine the sensitivity of our results to different severities [see section 2c(3)]. The algorithm used to identify and track events is described below. Our methodology is designed to be simple and to determine the characteristic spatial and temporal scales of extreme events for each of the different processes.

1) Data preprocessing

For each time step, the standardized data are converted into percentiles and is then processed to remove events that are either above or below a given threshold (i.e., top 10th percentile of dry events) (see, e.g., Fig. 2a). The remaining data then contain the pixels classified as an extreme event.

At each time step, the data contain larger adjoining regions classified extremes, as well as single pixels (Fig. 2a). We use mathematical morphology to erode and dilate the pixels, in order to merge areas under drought or flood into more coherent regions (see, e.g., Fig. 2b). This step is equivalent to the filtering of the data to remove spatial noise used in previous studies (Herrera-Estrada et al. 2017).

2) Event tracking algorithm

1) An event is considered to begin when at least ~30 000 km^2 (10 contiguous pixels) are identified as a dry or wet extreme. For each time step, the centroids of these events are found (see Fig. 2c). For each event identified, the area (in pixels) of the initial event t_1 is recorded.
2) The extreme events are then tracked individually. An event is considered to persist in the next time step t_2 if at least 30 000 km^2 (10 contiguous pixels) are identified as an extreme event in a box of 7 × 7 pixels (~150 000 km^2) centered over the location of the centroid identified in t_1. The reason for choosing this larger area is to account for shifts in space between different time steps, and the larger area is there to give a buffer around the event. The size choice is arbitrary but was found to reasonably capture events of irregular spatial dimensions and was selected on testing of these parameters. In each time step, the centroid moves to the new center of the event, in a box of ~150 000 km^2. This allows us to track events that move in space. At each time step, the area of contiguous pixels corresponding to an extreme event are recorded.
3) The event is considered to end when the area under extreme conditions shrinks to less than 30 000 km^2 (10 contiguous pixels) (see Fig. 3 for tracking of event centroid and

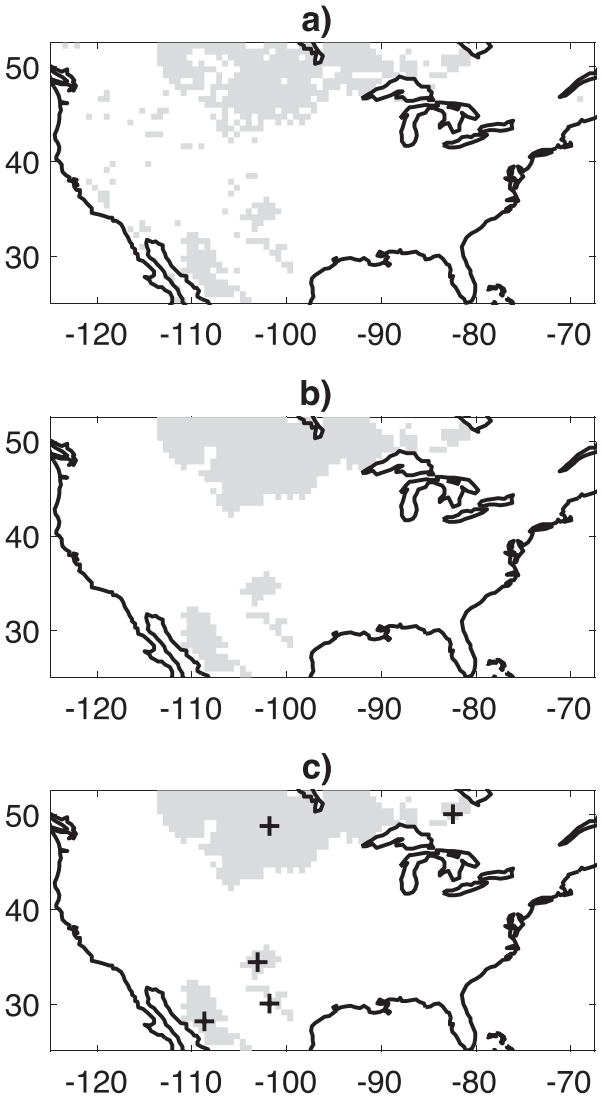

FIG. 2. An example of the steps taken by the algorithm to identify extreme hydrological events for 10th-percentile dry runoff events using NLDAS-2 runoff. (a) First, regions in the upper 10th percentile of dry extremes are identified. (b) The area then undergoes dilation and erosion of the pixels to remove single pixels and to smooth irregular areas. (c) Centroids of contiguous drought clusters that are at least 10 pixels (30 000 km^2) are then identified (indicated by black crosses).

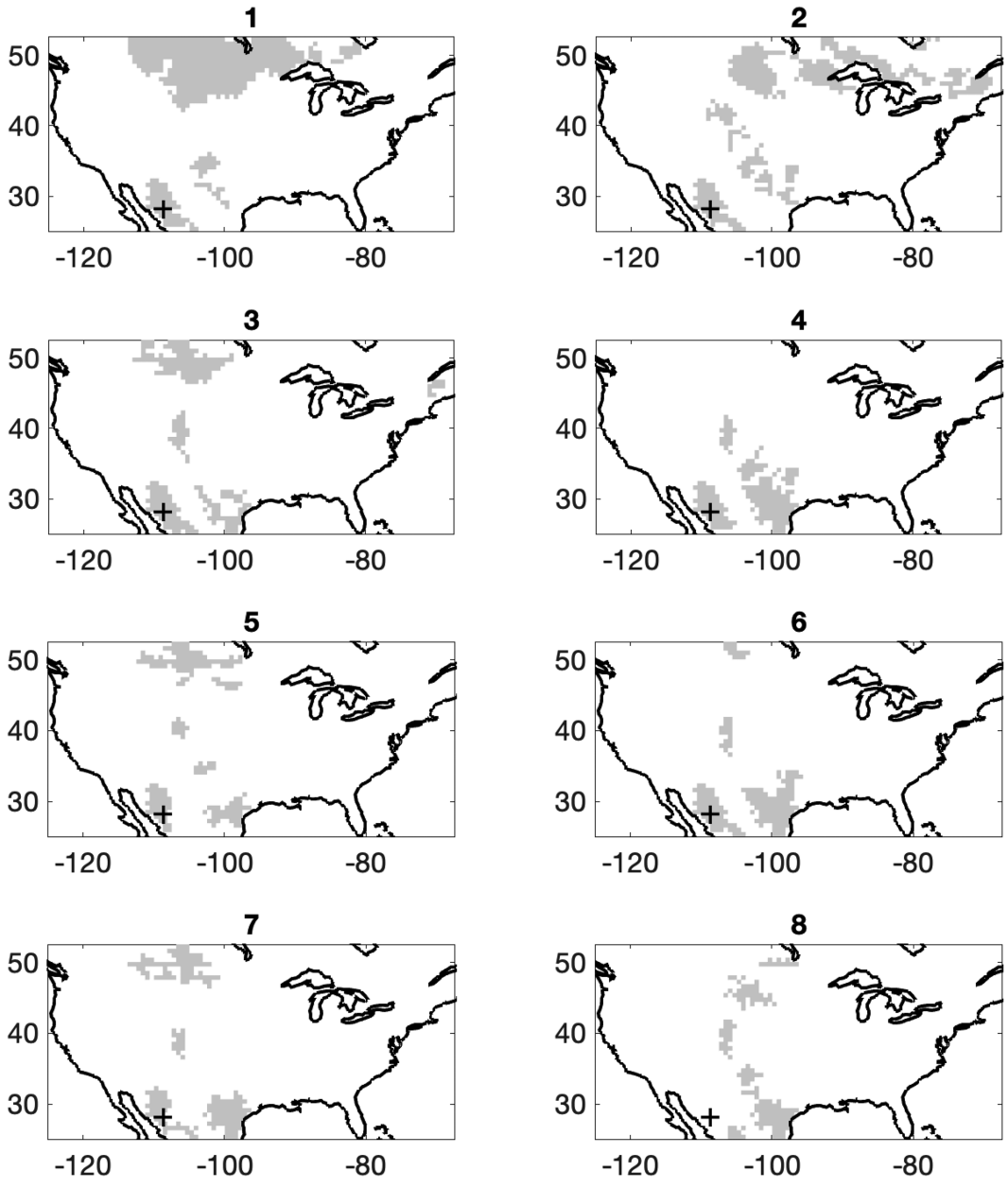

FIG. 3. Example evolution of drought duration pentads = 7 (i.e., 35 days). The drought tracker is following the event in the southwest, indicated by the cross marker. The event subsides at pentad 8, once drought is no longer detected in the southwest region.

termination). The duration of the event is then recorded, and the average area of the event is also recorded.

4) Steps 2 and 3 are repeated for each of the individual events identified at the initial time step t_1 before proceeding to the next time step. The locations of centroids are recorded so that events are not double counted. By tracking the location of centroids in each time step, this prevents double-counting of events that split, but will instead continue tracking the larger event. This requirement may also help to prevent double counting of events that merge if close in space.

The methodology is successful for picking out contiguous regions of wet and dry extremes and tracking their evolution in space and time. The use of the mathematical dilation and erosion is useful for removing noise or single pixels from the events, similar to filtering. The method is simple but uses a number of subjective parameters (minimum drought area, enclosing area, data resolution, etc.), which could impact results were selected based on testing of the algorithm, with the area of 30 000 km^2 to capture larger-scale events. The data resolution (0.5° and pentad data) impacts results in various ways; rerunning the algorithm with finer data captures smaller-area

TABLE 1. Mean statistics of dry and wet event duration and size averaged over the three LSMs used in the study (Noah, Mosaic, and VIC).

		Area ($\times$100 000 km^2)			Duration (days)		
		10th percentile	5th percentile	2.5th percentile	10th percentile	5th percentile	2.5th percentile
Dry events	Precipitation	9.7	9.7	9.7	18	19	19
	Runoff	5.2	4.6	4.4	22	28	28
	Soil moisture	6.9	4.7	3.8	51	41	38
Wet events	Precipitation	3.2	2.3	1.9	12	11	11
	Runoff	3.3	2.9	2.4	20	16	14
	Soil moisture	5.6	3.8	2.9	40	30	24

events that persist longer in duration. Rerunning the algorithm with daily data instead of pentads captures more short-duration events with a larger area, suggesting that more transient large-scale 1-day events are picked up. The sensitivity of our algorithm to these choices is explored in detail below [section 2c(3)(iii)].

3) UNCERTAINTY AND SENSITIVITY ANALYSIS

(i) Model ensemble

To account for potential model structural errors, we use output from three different NLDAS-2 LSMs to produce an ensemble of results for runoff and soil moisture. Precipitation forcing is the same for each of the three NLDAS-2 models. The precipitation forcing in NLDAS-2 is observationally derived from the Center for Climate Prediction (CPC) CONUS daily gauge data (Higgins et al. 2000; Chen et al. 2008) with topographic adjustment using the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) (Daly et al. 1994). Details of the NLDAS-2 precipitation forcing are described online (appendix C of this website: https://ldas.gsfc.nasa.gov/nldas/v2/forcing#AppendixC). The precipitation forcing is downloaded (as for the other variables) online at GES DISC (https://disc.gsfc.nasa.gov/datasets?keywords=NLDAS). By using output from three different models, we are able to determine how the modeled hydrological characteristics of runoff and soil moisture are impacted by choice of LSM, and our results are therefore more robust than they would be using a single model as we sample across different model physics.

(ii) Sensitivity to extreme threshold

We also assess the sensitivity of the results to the choice of threshold for the extreme events by exploring 10th-, 5th-, and 2.5th-percentile events. We assess the spatial and temporal characteristics for each of the three hydrological processes (precipitation, runoff, and soil moisture) examining 10th-, 5th-, and 2.5th-percentile dry and wet events to assess sensitivity of choice of threshold. We present statistics for each of the three different thresholds and LSMs.

(iii) Sensitivity to spatial and temporal resolution

We test the sensitivity of the results to both spatial and temporal resolution using output from the NLDAS-2 Noah LSM. To examine the impact of spatial resolution on results, we run the tracking algorithm on 0.25°, 5-day data (Table A5 and Figs. A1 and A2 in the appendix). To examine the impact of temporal resolution, we run the tracking algorithm on 0.5°, 1-day data (Table A6; Figs. A3 and A4). This is compared with the main results using 0.5° and 5-day mean data (Table 1). We choose to focus on 0.5° and 5-day duration to remove some of the effects of transient single-day events on the data.

3. Results

a. Spatial patterns of extreme event duration

For each grid point in CONUS we find the average duration of dry and wet 10th-percentile extreme events from 1979 to 2017 (Fig. 4). The average duration is shortest for precipitation in both dry and wet events (extending up to ~30 days) (Figs. 4a,b). The longest persistent extreme events occur in soil moisture, with many regions exceeding 100-day-long events for both dry and wet extremes (Figs. 4e,f). Runoff event duration falls between the other processes, attaining average maximum event duration of approximately 45 days (Figs. 4c,d).

Dry extreme events generally persist longer than wet events across all processes (Figs. 4a,c,e). The southwestern United States tends to have a concentration of the most persistent extreme events. The eastern United States generally has shorter-duration events.

b. Temporal characteristics

We find the mean duration of dry and wet events for precipitation, runoff, and soil moisture (Table 1). Precipitation 10th-percentile dry extreme events are the shortest duration (average of 18 days), followed by runoff (22 days) and soil moisture (51 days). For wet extreme events, wet precipitation extremes are also shortest (12 days), followed by runoff (20 days) and soil moisture (40 days). The dry extremes tend to have longer duration than wet extremes, consistent with the findings in Fig. 4.

We create probability density functions (PDFs) for the Noah model only (Fig. 5) and cumulative distribution functions (CDFs) for all three LSMs (Fig. 6). Most precipitation events are short, while runoff and soil moisture events have longer tails in in their distribution (Fig. 5). In general, there is good agreement between Noah and VIC models for runoff and soil moisture, with the largest divergences between LSMs existing for 0–100-cm soil moisture (Fig. 6). The Mosaic results also tend to produce longer-duration events for runoff and soil moisture than do the other two LSMs (Figs. 5b,c). The more extreme events (top 5th and 2.5th of extremes) tend to also produce longer-duration events for dry extremes

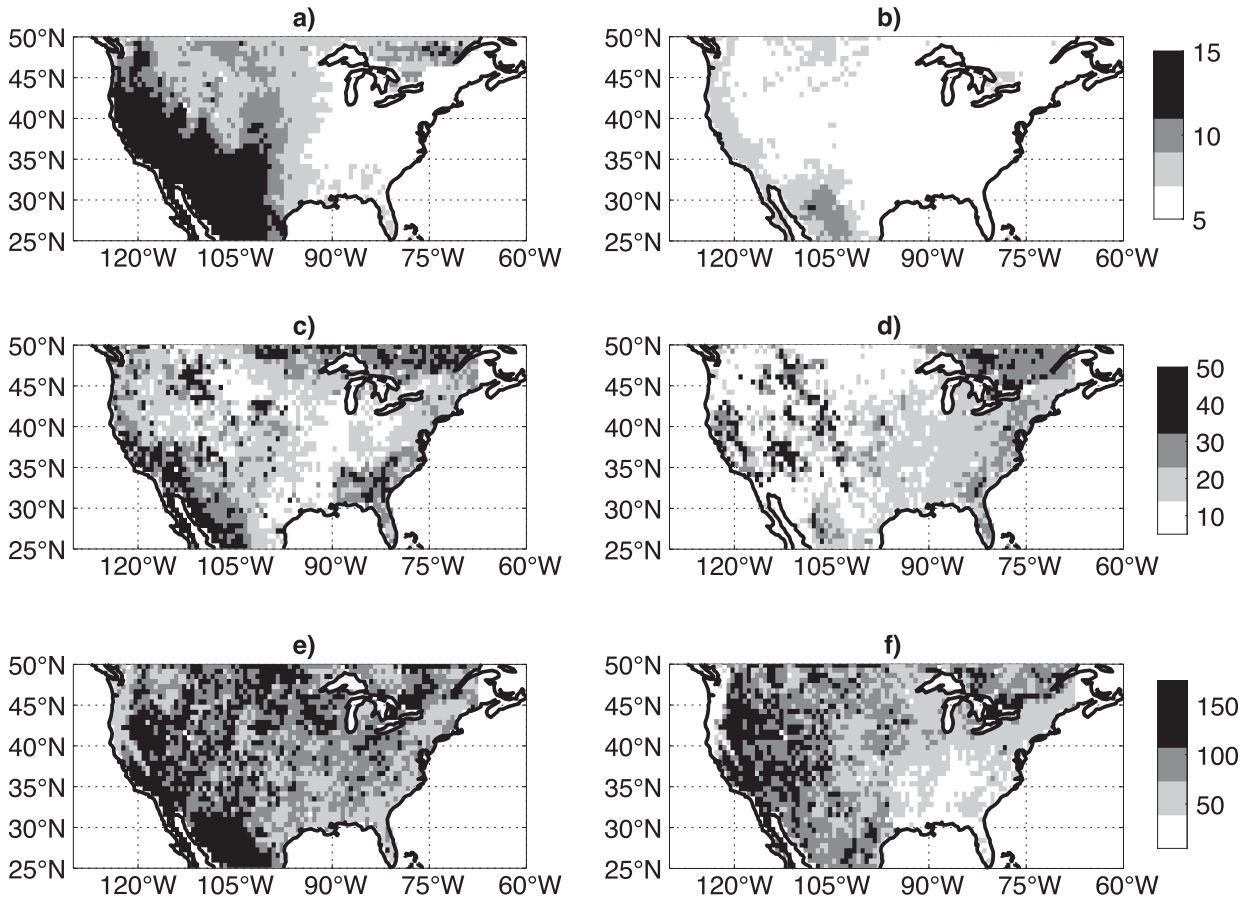

FIG. 4. Duration in days of anomalous (left) dry and (right) wet conditions (exceeding the top or bottom 10th percentile) for (a),(b) precipitation; (c),(d) runoff; and (e),(f) 0–100-cm soil moisture. Note that the shading bars use different scales.

in precipitation and runoff, and shorter-duration dry extremes for soil moisture (Figs. 5 and 6; Table 1). More extreme events (top 5th and 2.5th extremes) also produce longer-duration runoff and shorter-duration soil moisture wet event extremes, with no change for precipitation.

The average statistics based on the CDFs of event duration across the three LSMs are also calculated for 15 days, 1 month (30 days), and 2 months (60 days) (Tables A1 and A2 in the appendix). Again this shows that dry extreme events are shortest for precipitation and longest for soil moisture: After 15 days 66% of precipitation events have occurred, followed by 60% of runoff events and 26% of soil moisture events (Table A1). After one month, the cumulative percentage of dry events increases to 89% for precipitation, 83% for runoff, and approximately half (49%) for soil moisture. This indicates that almost all precipitation and runoff events have occurred, but only about half of all soil moisture events since they are characterized by a long tail in their distribution. The top 5th and 2.5th percentile of dry extremes tend to be shorter duration, and the majority of events occur at shorter time scales.

The results show similar patterns for 2.5th-percentile wet extremes: at 15 days 94% of precipitation events have occurred, followed by 65% of runoff events and 41% of soil moisture events (Table A2). The wet extremes also persist shorter than the dry events for all three hydrological processes.

Using finer-resolution data (0.25°, 5 days) we also find that for 2.5th-percentile dry extremes, over 53%, 53%, and 31% of precipitation, runoff, and soil moisture are 15 days or shorter (not shown). For 2.5th-percentile wet extremes, these numbers increase to 96%, 77%, and 54% for precipitation, runoff, and soil moisture, respectively. This indicates that even using finer-resolution data, the most extreme events are also found to occur in the sub-15-day range, showing some consistency with differing spatial resolutions. Because of the detection of 1-day transient events with the 1-day data, we expect these proportions to be even higher when using 1-day data.

c. *Spatial characteristics*

We find the mean area of dry and wet events for precipitation, runoff, and soil moisture (Table 1). For dry extreme events, precipitation events are on average the largest (~970 000 km^2), followed by soil moisture (~690 000 km^2) and runoff (~520 000 km^2). In contrast, for wet extremes, precipitation events are found to be the smallest (320 000 km^2), followed by runoff (330 000 km^2) and soil moisture (560 000 km^2). Wet extremes are also smaller in area for all processes when compared with dry extremes.

In turning to the PDFs (Fig. 7) and CDFs (Fig. 8) for average spatial scales, we find that dry extreme precipitation events

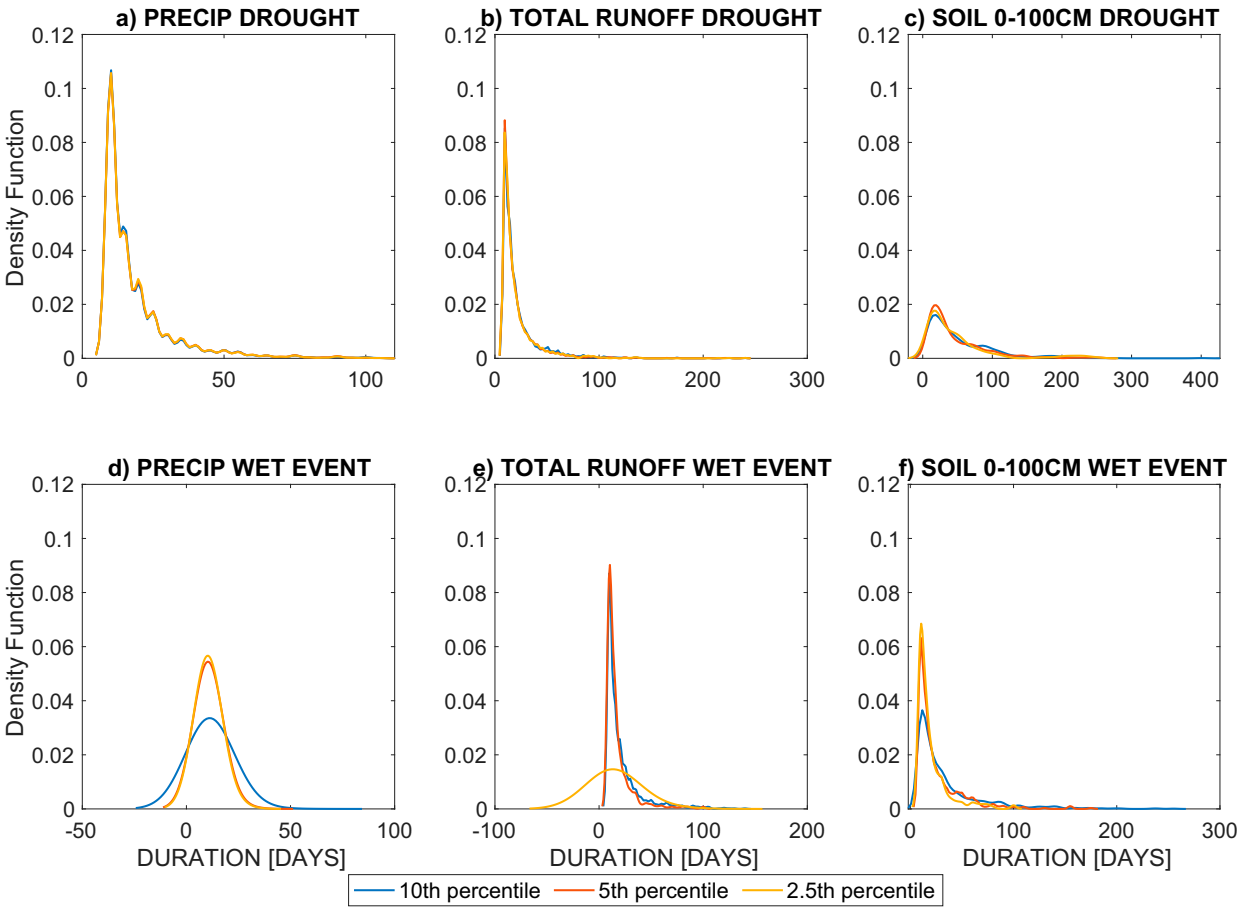

FIG. 5. Density function for drought/wet event duration for NLDAS-2 Noah produced using kernel density estimation. The *y* axis represents the density function of events, and the *x* axis is the duration in days of the anomalous drought or wetting event.

(Fig. 7a) tend to occur over larger areas than runoff (Fig. 7b) and soil moisture events (Fig. 7c). The opposite occurs for wet events, with precipitation wet events occurring over smaller areas than runoff and soil moisture (Figs. 7d–f). There is generally good agreement between the three LSMs in the CDFs for runoff and soil moisture spatial area statistics (Fig. 8).

We also calculate mean statistics from the CDFs plotted in Fig. 8 (Tables A3 and A4 in the appendix). We consider three spatial scales in our analysis: 100 000, 500 000, and 1 000 000 km^2. For dry extremes, events occur over larger areas for precipitation in comparison with runoff and soil moisture events: 64% of precipitation dry extremes are 1 000 000 km^2 or smaller, as compared with 85% of runoff events and 80% of soil moisture events. For wet events, we instead find that precipitation and runoff events are smaller than soil moisture events: 94% of precipitation and runoff events are 1 000 000 km^2 or smaller, as compared with 85% of soil moisture events. The area of events is also smaller for the more extreme 5th- and 2.5th-percentile events.

d. Sensitivity to spatial and temporal resolution

Increasing the spatial resolution (from 0.5° to 0.25°) captures more smaller-area events (Table A5 and Fig. A2 in the appendix). This has the effect of reducing the overall mean size of dry and wet extreme events when compared with using 0.5° and 5-day resolution. For example, the mean size of 10th-percentile dry extreme events precipitation area decreased from 970 000 to 700 000 km^2, for runoff area decreased from 520 000 to 370 000 km^2, and for soil moisture area decreased from 690 000 to 370 000 km^2. These decreases also are present for more extreme 5th- and 2.5th-percentile events, for example, with 2.5th-percentile dry soil moisture extremes decreasing in area from 380 000 to 200 000 km^2. The area of extreme wet events also decreased; for example, 10th-percentile precipitation events area decreased from 320 000 to 240 000 km^2, runoff events area decreased from 330 000 to 260 000 km^2, and soil moisture events area decreased from 560 000 to 370 000 km^2. The smaller area used to classify events also tends to capture longer-duration events (appendix Table A5 and Fig. A1), which could be due to smaller-size events tending to persist longer as smaller area events, than when only considering larger regional-scale events, which are considered to end when falling below 30 000 km^2.

The effect of increasing the temporal resolution (from 5- to 1-day) captures more shorter-duration events (Table A6; Fig. A3), which is expected as more single-day events are being detected by the tracking algorithm. For example, the mean

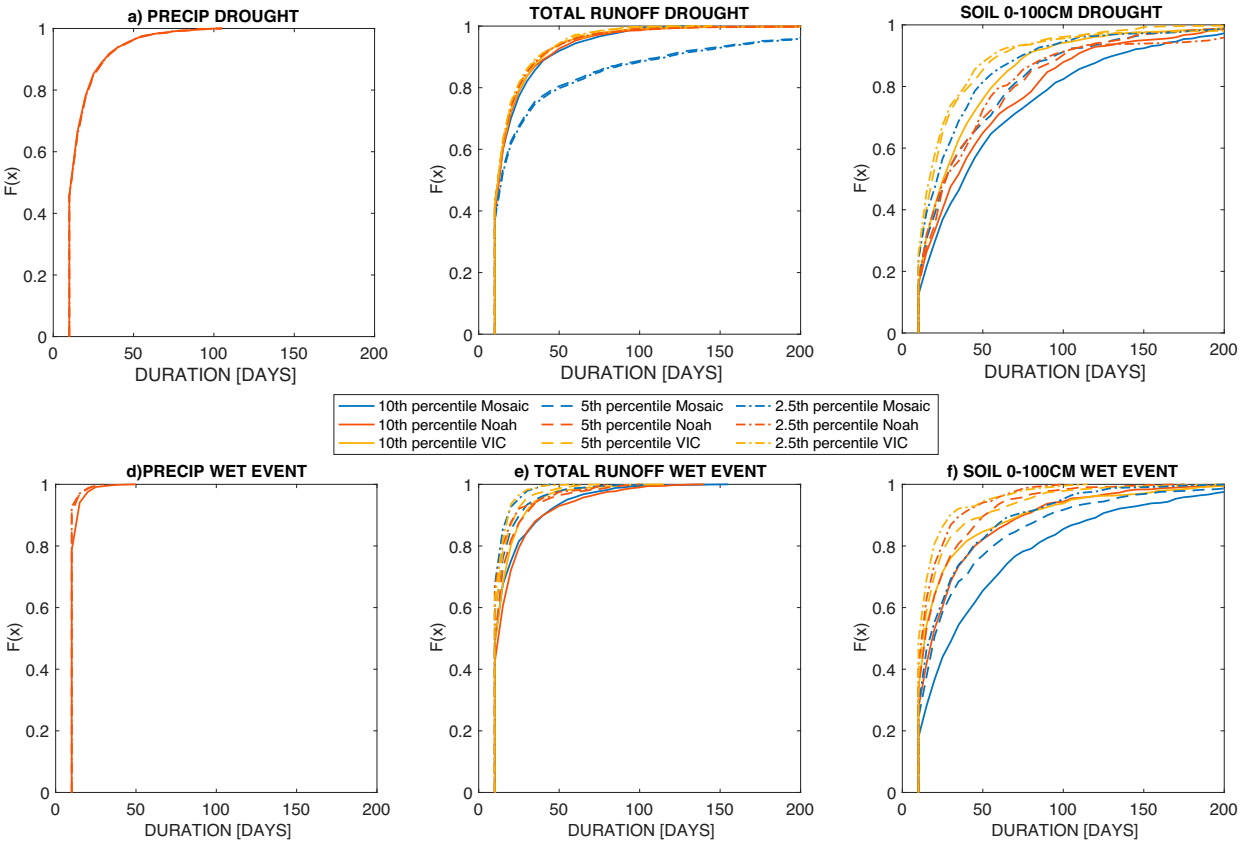

FIG. 6. Cumulative distribution function for drought/wet event duration. The *y* axis represents the fraction of events, and the *x* axis is the duration in days of the anomalous drought or wetting event.

duration of 10th-percentile extreme precipitation events decreased from 18-days dry extremes to 8.6-days dry extremes and from 12-days wet extremes to 2.5-days wet extremes (Table A6). Similar patterns were found for runoff (from 22-days dry extremes to 11-days dry extremes and from 20-days wet extremes to 13-days wet extremes) and for soil moisture (from 51-days dry extremes to 38-days dry extremes and from 40-days wet extremes to 21-days wet extremes). Increasing to 1-day resolution also leads to overall larger mean wet and dry events relative to using 0.5°, 5-day data. This was found to be the result of large-scale single-day continental-scale transient events being included in the dry and wet event means.

4. Discussion

In agreement with past studies, our results show hydrological extremes persist longest in soil moisture, and shortest for precipitation for both dry and wet events. This is well documented in the literate, and our findings support hydrological theory illustrating the cascade of hydrological processes in time and space (Changnon 1987; Farahmand et al. 2021). A number of studies have also examined the cascade of hydrological processes in time and space: a spectral analysis of precipitation fluctuations in the United States found that the synoptic scale (from 16 h to 22 days) explained most of the variability in precipitation (Joseph et al. 2000). An analysis of in situ networks of soil moisture was used to characterize the spatial and temporal variability of soil moisture, and how these variations are related to both small-scale variations in land cover, topography and local features, and also large-scale atmospheric patterns resulting from precipitation and evaporation (Entin et al. 2000). These larger-scale patterns were found to produce average variations in soil moisture of 500 km and 2 months.

We also find more persistence in soil moisture and runoff extreme events, in comparison with precipitation: periods of above or below normal precipitation have the shortest duration (lasting days to weeks), which are translated into much more persistent soil moisture events (lasting weeks to months; consistent with the findings based on SMAP observations; McColl et al. 2017). Spatially, we also observe a cascade of processes—during excessively dry conditions, deficits in precipitation tend to occur over larger areas when compared with the spatial scale of runoff and soil moisture dry events. Conceptually this can be understood as the input (precipitation) falling over a large area and subsequently influencing runoff and soil moisture systems on more local scales.

Our results also find that event duration (for both dry and wet extremes) is longest in the arid and semiarid southwestern United States for all three processes. This finding is consistent with previous studies that found that the storage of precipitation

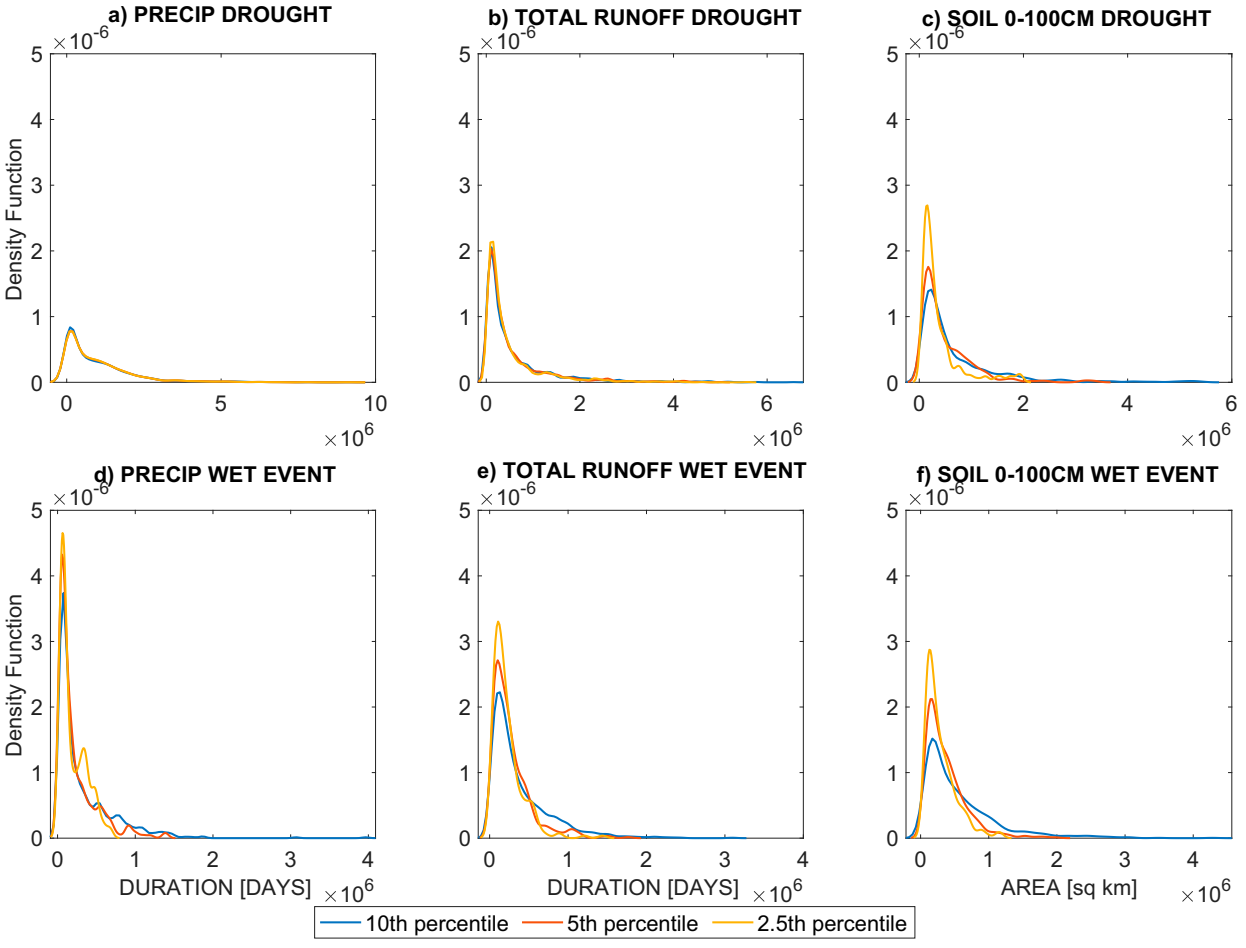

FIG. 7. Density function for drought/wet event area for NLDAS-2 Noah produced using kernel density estimation. The *y* axis represents the density function of events, and the *x* axis is the area (km^2) of the anomalous drought or wetting event.

in the land surface (e.g., in soil moisture) persists longer in arid environments due to the slower turnover rate of the water cycle (McColl et al. 2017; Ge et al. 2016).

5. Conclusions

This study provides a view of the characteristic spatiotemporal scales of dry and wet extremes over CONUS using NLDAS-2 models and presents a sensitivity analysis of both dry and wet extremes based on LSM. The results can be used to inform monitoring of both dry and wet extremes, assess LSM performance, and inform future hydrological mission architectures. The summary of the main findings of this study are below:

The LSMs investigated (Noah, VIC, Mosaic) agree in the mean characteristics of extreme dry and wet hydrological events. We extend previous work that used multimodel experiments to examine the characteristics of drought (Wang et al. 2009) to look at both wet and dry extremes and present comprehensive statistics. Across the NLDAS-2 models, we find that models share common mean characteristics of dry and wet extremes. This includes 1) larger-area precipitation dry extremes relative to runoff and soil moisture extremes, 2) shorter-duration extreme precipitation events relative to runoff and soil moisture for both dry and wet extremes, and 3) more intense 2.5th-percentile extremes tending to be smaller in area for runoff and soil moisture for both dry and wet extremes. In general, the VIC and Noah models also tended to produce similar statistics for duration and spatial area, with Mosaic differing more from the other models with longer-duration events.

Dry and wet extreme characteristics are sensitive to model resolution used in the extreme event tracking algorithm, and considerations should be made for detection and monitoring of these events. We investigated the impacts of adjusting spatial (from 0.5° to 0.25°) and temporal (from 5 days to daily) resolution. Adjusting the spatial scale from 0.5° to 0.25° led to a decrease in the mean areas of extreme dry and wet 10th-, 5th-, and 2.5th-percentile events. For example, the mean size of the most extreme 2.5th-percentile soil moisture dry events decreased from 380 000 to 200 000 km^2. This can be understood as the smaller grid size permitting more small-scale variability to be detected that would otherwise not be resolved. Changing the temporal resolution from 5 days to daily, also changed the mean duration of dry and wet extremes. As anticipated,

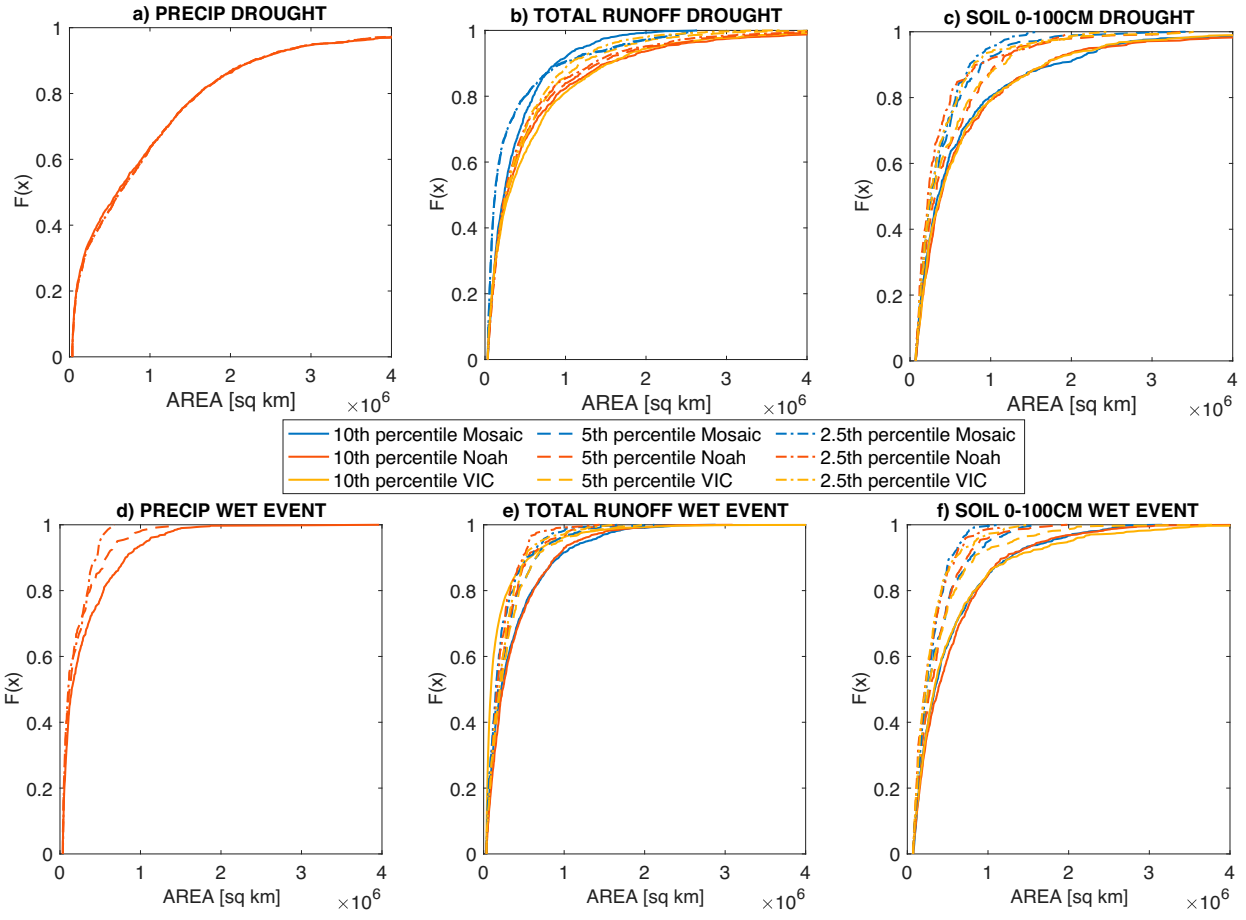

FIG. 8. Cumulative distribution function for drought/wet event area. The *y* axis represents the fraction of events, and the *x* axis is the area (km^2) of the anomalous drought or wetting event.

using daily data detected on average shorter-duration wet and dry extremes for precipitation, runoff, and soil moisture. These results indicate the sensitivity of extreme event detection to the model used and are relevant for informing understanding of hydrological processes and monitoring of these events.

High spatial and temporal resolution monitoring is necessary to capture the most extreme events. The more extreme events (5th and 2.5th percentile) are typically shorter duration and smaller in area than 10th-percentile events. For example, our findings indicate that for 2.5th-percentile dry extremes, 65%, 59%, and 39% of precipitation, runoff, and soil moisture, respectively, are 15 days or shorter. For 2.5th-percentile wet extremes, the percentage of events that are 15 days or shorter increases to 97%, 83%, and 59% for precipitation, runoff, and soil moisture, respectively. The area of soil moisture and runoff extremes also is smaller for 2.5th-percentile events when compared with 10th-percentile events. This indicates the importance of having adequate resolution to detect and monitor these hydrological extremes. As a caveat, these results are contingent on the parameters used in the tracking algorithm, as well as input dataset resolution. Our findings suggest a significant portion of events, in particular soil moisture and runoff, could be missed from monthly revisits (e.g., GRACE/GRACE-FO, SWOT). Wet events also occur over smaller spatial scales, and for precipitation 50% of all events are 100 000 km^2 or smaller, which is smaller than the current resolution of gravity missions (i.e., GRACE ~160 000 km^2).

Monitoring the hydrological cycle is critical and a key objective of the NASA Decadal Survey (https://science.nasa.gov/earth-science/decadal-accp). Satellite missions have specific design characteristics enabling their observation of particular aspects of the hydrological cycle (McCabe et al. 2017). Satellite data latency ranges from daily monitoring [such as the Global Precipitation Mission (GPM)] to monthly measurements (such as the measurement of total water storage from GRACE/GRACE-FO; Tapley et al. 2004). The nature of the hydrological process being observed is also an important guide for mission design; precipitation events generally occur at shorter time scales than longer-term variations in soil moisture and therefore require different temporal resolutions (McCabe et al. 2017). Given the critical importance of hydrological extremes for society, capturing these events with satellite observing systems is necessary, but challenging (Gaona et al. 2016).

Prior to GRACE, subsurface water transfers at global scales were difficult to resolve, including soil moisture and

groundwater. However, accurate knowledge of the variability of subsurface processes is also important for forecasting extremes. Another major challenge is obtaining reliable snow water equivalent, which is an important water storage term but as yet is not captured by satellite remote sensing (McCabe et al. 2017). Sampling frequency also poses a challenge to accurately capturing extremes; for example, infrequent sampling could miss critical hydrological extreme events. Therefore, identifying the spatial and temporal scales at which large-scale extreme hydrological events operate across different processes is needed to guide the observing requirements for future satellite missions.

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Data availability statement. All NLDAS-2 data used in this study are publicly available from National Aeronautics and Space Administration (NASA) Goddard Earth Sciences and Data Information Services Center (GES DISC) online (https://disc.gsfc.nasa.gov/).

APPENDIX

Additional Tables and Figures

Tables A1–A6 and Figs. A1–A4 present statistical results and the results of sensitivity testing.

TABLE A1. Dry events (cumulative % for average duration of 15, 30, and 60 days).

	Top 10th percentile			Top 5th percentile			Top 2.5th percentile		
Variable	15	30	60	15	30	60	15	30	60
Precipitation	66	89	98	65	88	98	65	89	98
Mean runoff	60	83	95	59	81	92	59	81	92
Mean 0–100-cm soil	26	49	73	33	60	79	39	63	86

TABLE A2. Wet events (cumulative % for average duration of 15, 30, and 60 days).

	Top 10th percentile			Top 5th percentile				Top 2.5th percentile	
Variable	15	30	60	Variable	15	30	60	Variable	15
Precipitation	94	99	—	97	100	—	97	—	—
Mean runoff	65	87	96	76	93	99	83	96	99
Mean 0–100-cm soil	41	64	81	50	75	89	59	82	93

TABLE A3. Dry events [cumulative % for average area of 1, 5, and 10 ($\times$100 000 km^2)].

	Top 10th percentile			Top 5th percentile			Top 2.5th percentile		
Variable	1	5	10	1	5	10	1	5	10
Precipitation	23	46	64	22	45	64	22	45	63
Mean runoff	23	68	85	29	72	87	29	74	88
Mean 0–100-cm soil	8	61	80	10	68	89	10	76	94

TABLE A4. Wet events [cumulative % for average area of 1, 5, and 10 ($\times$100 000 km^2)].

	Top 10th percentile			Top 5th percentile			Top 2.5th percentile		
Variable	1	5	10	1	5	10	1	5	10
Precipitation	39	77	94	46	86	98	49	96	—
Mean runoff	34	79	94	29	84	96	30	90	98
Mean 0–100-cm soil	8	62	85	12	76	94	13	87	98

TABLE A5. Sensitivity analysis using 0.25°, 5-day data on mean statistics of dry and wet event duration and size.

		Area (×100 000 km^2)			Duration (days)		
		10th percentile	5th percentile	2.5th percentile	10th percentile	5th percentile	2.5th percentile
Dry events	Precipitation	7.0	7.1	3.1	19.9	20.1	27.9
	Runoff	3.7	3.2	3.0	27.4	27.5	28.0
	Soil moisture	3.7	2.6	2.0	66.9	50.4	44.6
Wet events	Precipitation	2.4	1.7	1.4	12.1	11.2	10.9
	Runoff	2.6	1.8	1.4	26.7	19.9	16.1
	Soil moisture	3.7	2.5	1.8	42.2	30.8	23.8

TABLE A6. Sensitivity analysis using 0.5°, 1-day data on mean statistics of dry and wet event duration and size.

		Area (×100 000 km^2)			Duration (days)		
		10th percentile	5th percentile	2.5th percentile	10th percentile	5th percentile	2.5th percentile
Dry events	Precipitation	29.6	29.6	29.6	8.6	8.6	8.6
	Runoff	10.5	9.7	9.3	11.0	10.7	10.7
	Soil moisture	7.0	5.1	4.2	37.8	35.3	34.9
Wet events	Precipitation	3.8	2.6	1.9	2.5	2.2	2.1
	Runoff	4.3	3.0	2.5	13.3	7.4	6.0
	Soil moisture	5.5	3.7	2.8	20.7	13.4	9.5

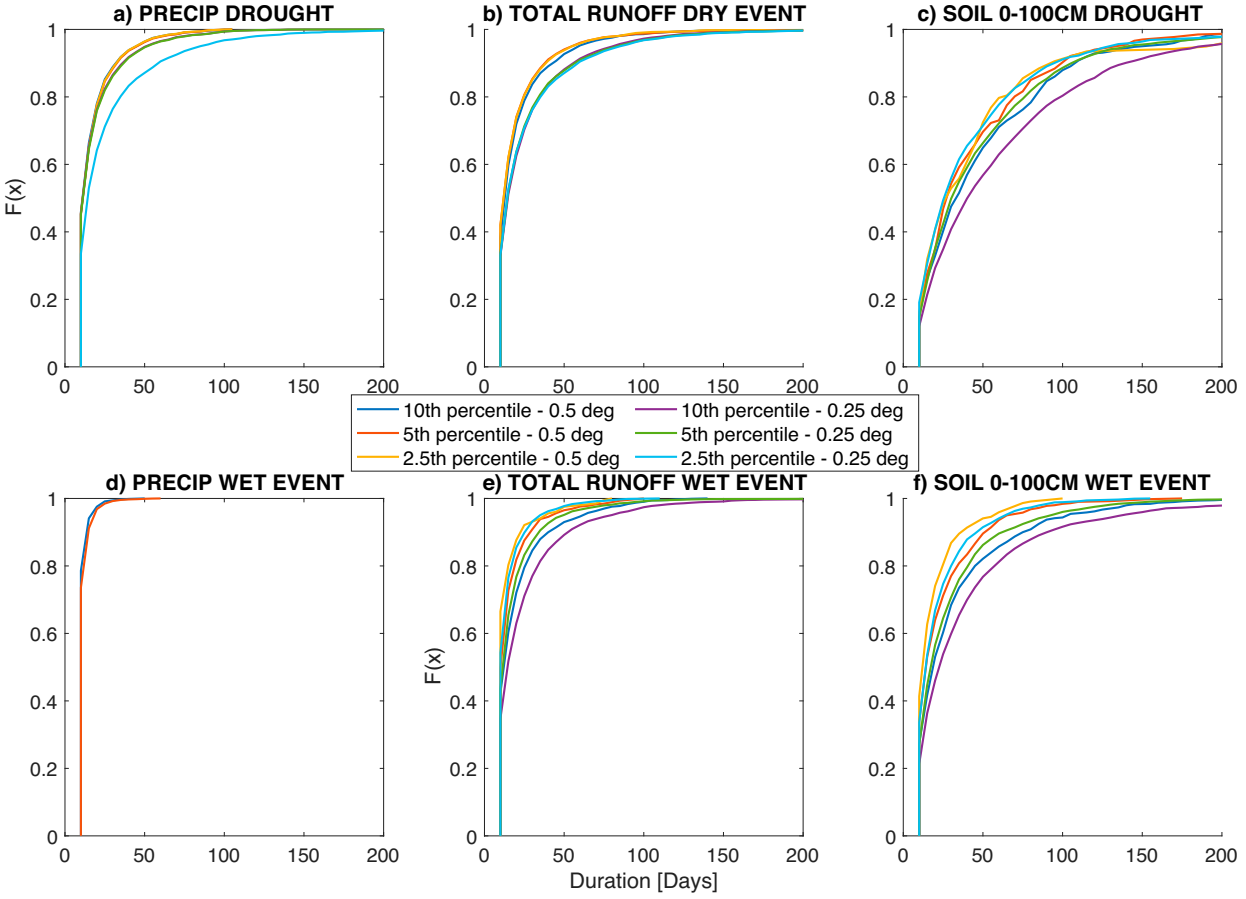

FIG. A1. Sensitivity of drought/wet event duration using 0.25°, 5-day data on cumulative distribution function. The *y* axis represents the fraction of events, and the *x* axis is the duration in days of the anomalous drought or wetting event.

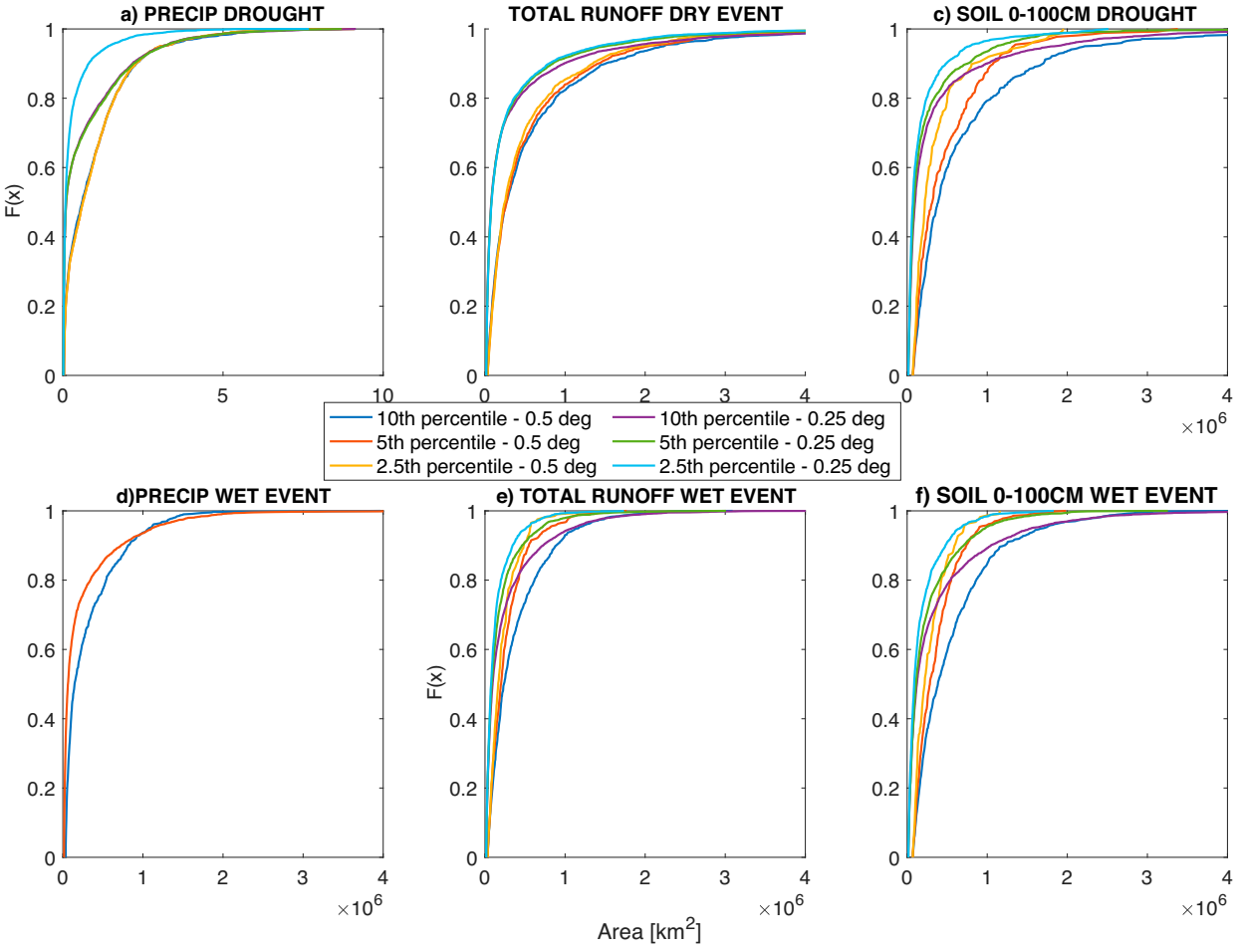

FIG. A2. Sensitivity of drought/wet event area using 0.25°, 5-day data on cumulative distribution function. The *y* axis represents the fraction of events and the *x* axis is the area (km^2) of the anomalous drought or wetting event.

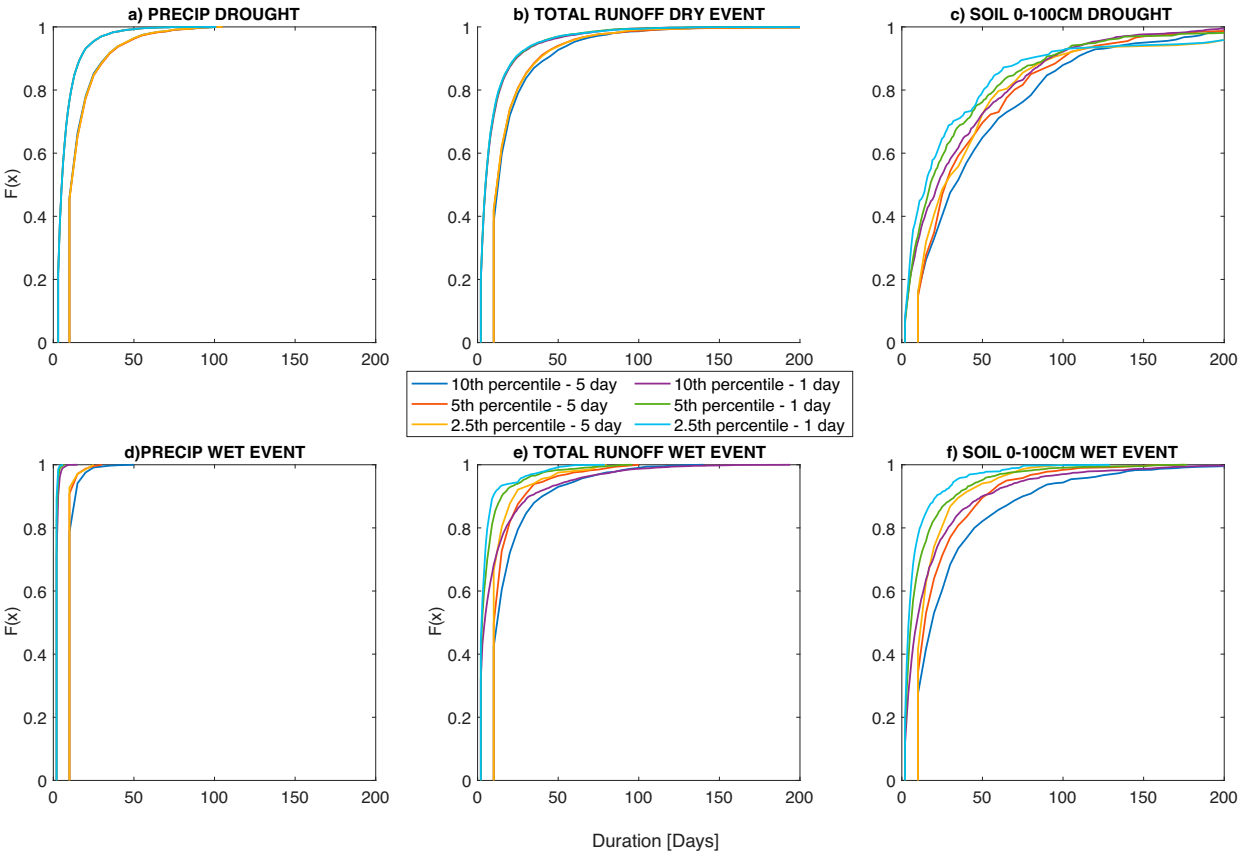

FIG. A3. Sensitivity for drought/wet event duration of using 0.5°, 1-day data on cumulative distribution function. The *y* axis represents the fraction of events and the *x* axis is the area in square kilometers of the anomalous drought or wetting event.

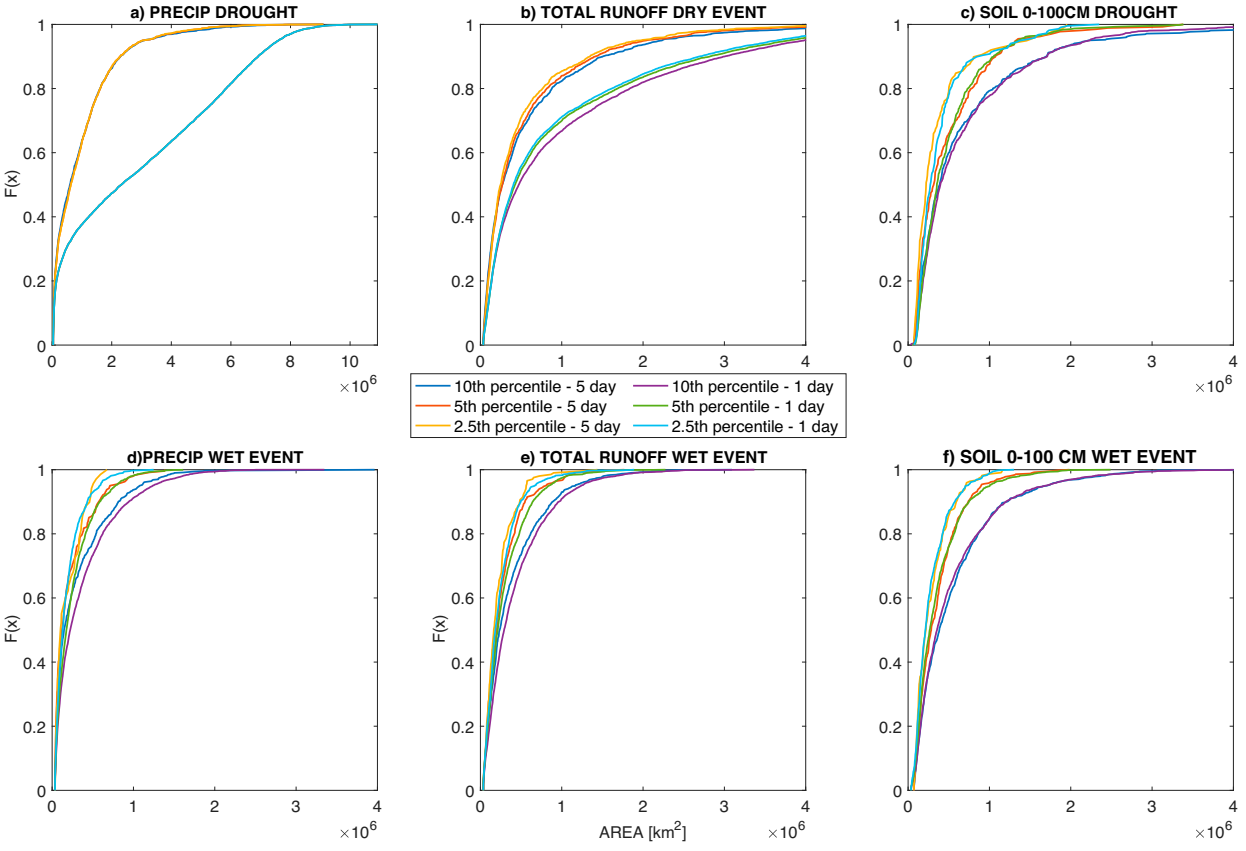

FIG. A4. Sensitivity for drought/wet event area of using 0.5°, 1-day data on cumulative distribution function. The *y* axis represents the fraction of events and the *x* axis is the area (km^2) of the anomalous drought or wetting event.

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The future potential of satellite gravity constellations for hydrologic extreme events

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The GRACE-FO mission has been pivotal in hydrological research, particularly in understanding groundwater dynamics, drought, and flood potential, estimating changes in terrestrial water storage to aid in groundwater assessment, drought severity, and flood risk identification. Despite its contributions, GRACE-FO has limitations like coarse spatial resolution and limited temporal coverage, hindering the capture of small-scale hydrological processes. Additionally, reliance on satellite observations introduces uncertainties due to atmospheric and oceanic variations.

Looking forward, future gravity constellations like The Mass-Change and Geosciences International Constellation (MAGIC) offer hope for overcoming these limitations. This constellation aims to enhance spatial and temporal resolution by deploying multiple pairs of satellites to improve monitoring of hydrological processes with greater detail and accuracy. This presents new opportunities for supporting sustainable water management practices.

In this presentation, we will offer a list of hydrology-user need assessment attributes for future gravity missions in order to contextualize the potential of a future gravity constellation, as well as present results on forward modeling of flood and drought extremes and how the population distribution of global historic flood and drought events would be better sampled with a constellation architecture instead of a single pair mission. We find that an additional 20-30% of global flood and drought events could be observed as a benefit of enhanced temporal resolution, while an additional 10% gain in the number of events observed due to proposed enhancements in spatial resolution.

Keywords: Satellite gravity constellations, Hydrology, Flood and drought

Session:

Presentation preference (Oral)

Modelling gravity and geoid by Least Squares Collocation with planar covariance models

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Least Squares Collocation (LSC) is currently used to estimate or filter a signal. This is based on a proper covariance model that is usually fitted to empirically estimated covariance values. In Geodesy, the collocation method is applied to gravity filed and geoid modelling. In these computations, standard covariance models such as Tscherning-Rapp (1974) for the spherical approach and Forsberg (1987) for the planar approach are used in fitting the empirical covariance values. In this study, we propose a method for gravity field estimation based on new planar covariance models.
Numerical implementation and necessary tests are carried out by using the gravity data of the Colorado area. Comparisons of the obtained results with the standard LSC collocation approach are discussed. Comments on future applications of planar collocation are finally given.

Keywords: Collocation, planar covariance models, Colorado test
Session: Session 4: Regional gravity field modelling and geophysical interpretation
Presentation preference: oral

JGEOID2024: the Japanese gravimetric geoid model incorporating nationwide airborne gravity data

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This study presents a Japanese gravimetric geoid model JGEOID2024 that incorporates nationwide airborne gravity data. First, we show the results of the accuracy assessment of the collected airborne gravity data. We here used two approaches for the assessment: cross-over validation and comparison with terrestrial/GGM gravity data. The former represents data repeatability, and the latter represents absolute certainty. The cross-over validation was performed by evaluating gravity differences at cross-over points between survey lines and validation lines. The comparison with terrestrial/GGM gravity data was performed using the three-dimensional least-squares collocation method with surface gravity data and EGM2008 over a land area. As a result, we confirmed that our airborne gravity data have a repeatability of 0.8 mGal and an absolute certainty of 1.4 mGal. Then, we show the results of the geoid computation and the accuracy assessment. The computation method was the remove-compute-restore Stokes-Helmert scheme with the hybrid Meissl-Molodensky modified spheroidal kernel. We found that the impact of introducing the airborne gravity data on the geoid computation ranged from -25 cm to +23 cm, with the impact being especially large in coastal areas around the inland sea and bay. We confirmed that our new gravimetric geoid model has an accuracy of approximately 3 cm by comparison with GNSS/leveling geoid height data. The new gravimetric geoid model will be used for the modernization of the height reference system in Japan.

Keywords: Regional geoid modelling, Airborne gravimetry, Height modernization

Physics-Informed Neural Networks for local geoid modeling: preliminary results in Colorado

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Although machine learning has become increasingly important in geodesy related fields such as geophysics, seismology and remote sensing, its applications in geodesy, especially in physical geodesy, are still in its early stages. The main reason for this can be attributed to the black box nature of pure data-driven machine learning, which lacks physical interpretability and credibility, making it difficult for machine learning approaches to be used in physical geodesy that takes reliability and accuracy as its core criteria.

Physics-Informed Neural Networks (PINNs) is a class of deep learning algorithms aims to seamlessly integrate data and physical prior knowledge including ordinary or partial differential equations, it can yield more physically interpretable machine learning models that provide robust and accurate predictions. We present the PINN approach for gravimetric geoid modeling from Earth gravity model, terrestrial and airborne gravity datasets. A deep learning architecture with five fully connected layers is used, gravity measurements and physical laws are integrated by embedding the Laplace's equation of disturbing potential and two fundamental equations of gravity anomaly and gravity disturbance into the loss function of the neural network using automatic differentiation. The PINN based geoid computation approach is tested in the area of the Colorado 1-cm geoid experiment using the terrestrial and airborne gravity observations, GPS leveling measured geoid heights provided by NGS/NOAA. The gravimetric geoid model computed using the PINN approach agrees with the GSVS17 GPS leveling data at 194 marks in 2.1 cm in terms of the standard deviation of discrepancies, while the standard deviation of the mean model of 13 quasigeoid models based on traditional methods in Colorado experiment is 2.6 cm. In addition, the PINN, the pure data-driven neural network (physics un-informed) and the traditional methods are compared and discussed.

Keywords: Geoid, Machine learning, Physics-Informed Neural Networks, Colorado experiment

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference (Oral)

Error tree analysis of geopotential field models

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For the realisation of geopotential-based height systems with the target accuracy of $0.1 m^2 s^{-2}$ (resp. 1cm on the geoid), a detailed error budget analysis of current gravity field models and modelling techniques is necessary. The Colorado 1-cm geoid experiment showed a strong correlation of the model discrepancies with the topography. This implies that current methods to model the topographic gravity effect are not sufficient in areas with strong topographic gradients. Thus, for better performance in mountainous regions, it is necessary to further study the high-frequency topography effects and the impact on geopotential field models. In addition, a realistic error assessment is required to identify and reduce the main error sources in regional gravity field modelling.

In this study, multiple regional models are computed to evaluate different topographic gravity field models for an exemplary area in the European Alps. The resulting gravity field models are compared with each other and tested against independent data. By combining different validation techniques, the model accuracies over different wavelengths can be evaluated. It can also help to distinguish between model errors and systematic errors in the validation data. This study aims to derive realistic uncertainty estimates for the different models and to identify possible errors in regional gravity field modelling, with a focus on mountainous regions.

Keywords: geopotential-based height systems, regional gravity field modelling, topographic gravity effect

Session: Session 1: Reference systems and frames in Physical Geodesy

Presentation preference: oral presentation

Computation and validation of gravitational, tidal and non tidal accelerations.

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The evolution of geodesy has introduced a new era in which satellite-based data dominate the field, providing information for a wide range of geodesy-related applications. Satellite-based observations are closely related to the complex problem of orbit determination. Our goal is to design an open-source software capable of estimating precise orbits . In order to determine the precise trajectory of a satellite, it is mandatory to estimate the accelerations it experiences. Comparatively for the case of Low Earth Orbiters, the acceleration caused by the Earth's gravity field is the largest in magnitude and therefore the most important. Next in order, is the acceleration caused by third body attractions namely the Sun and the Moon. Other disturbing forces that a spacecraft experiences include effects of solid Earth tides, ocean tides, , pole tides, atmospheric tides, and the ocean pole tide. To validate the computations performed by our software the benchmark provided by the Combination Service for Time-variable Gravity Field (Cost-G), was used. More specifically, the Cost-G benchmark implements high quality and robust models for the computation of the aforementioned accelerations, using one day of GRACE orbit. Extended testing was carried out with based on the results of the benchmark. The validation tests showed that the software is highly compliant with the benchmark results.

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Keywords: Orbit Determination, Gravitational Accelerations, Software Validation.

Session 3: Static and time-variable global gravity field modelling

Presentation preference: Poster

Cold Atom Interferometry Accelerometers for Future Satellite Gravity Missions

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Satellite gravity missions like GOCE, GRACE and GRACE-FO successfully recovered the global Earth's gravity field and thus reveal valuable insights for geosciences and other disciplines. The accelerometers onboard of these satellite missions are one of the limiting factors and consequently the new concept of Cold Atom Interferometry (CAI) is studied for improved future satellite gravity missions.

The simulated measurements of classical electrostatic and CAI accelerometers are combined by a Kalman filter in order to benefit from their complementary characteristics in sampling rate and long-term stability. The effect on the recovered gravity field solution is evaluated by closed-loop simulations for low-low Satellite-to-Satellite Tracking (ll-SST) and satellite gravity gradiometry. Additionally, a combination of these two measurement concepts, i.e. one satellite of an ll-SST mission is equipped with a cross-track gradiometer, is presented. The simulation results show the benefit of an additional CAI accelerometer, but also reveal critical factors as the time-variable background modelling, the rotation-induced phase shift and the required accuracy for the angular velocity determination. The concepts are examined for different orbital altitudes and constellations.

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Keywords: Future Satellite Gravity Missions, Cold Atom Interferometry, Accelerometer, Closed-loop Simulation

Session 2 (Co-organized with the IAG QuGe Proect): Novel technologies in terrestrial, airborne and satellite gravity field determination

Presentation preference: Oral

Strapdown airborne gravimetry with focus on geophysical applications

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In 2020-2023, Navigation and Control Laboratory at Lomonosov MSU has been developing postprocessing algorithms and software for airborne gravimeters based on navigation-grade strapdown inertial sensors. In the presentation we will briefly outline the development of data processing methodology focusing on the potential of strapdown gravimeters to be used in aerogeophysical surveys under harsh dynamic conditions (e.g., drape flights in mountainous regions). The methodology of laboratory and in-flight calibration of a gravimeter will also be briefly described. This will be followed by recent results, especially using a novel strapdown gravimetry system from a domestic manufacturer (the other gravimeter considered in the presentation is the iMAR unit). The results were obtained from several aerogeophysical campaigns carried out in 2023-2024 in Russia using a multi-instrumented helicopter and fixed-wing aircrafts. We also report how the new gravimetry system can achieve the 1-2 mGal accuracy under various dynamic conditions.

Keywords: airborne gravimetry, strapdown IMU, GNSS, postprocessing, Kalman filtering

Session 2: Novel technologies in terrestrial, airborne and satellite gravity field determination

Presentation preference: Oral

The design of the cors geodetic network "Geo-Net" in Albania.

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The establishment of a Continuously Operating Reference Station (CORS) geodetic network, termed "Geo-Net," marks a significant milestone in Albania's spatial infrastructure development. This paper outlines the meticulous design process undertaken to create a robust and reliable network tailored to the geographical and geodetic requirements of Albania. Beginning with a comprehensive review of existing geodetic networks and international standards, the design of Geo-Net prioritized national coverage, accessibility, and precision positioning capabilities.Geo-Net's design encompasses strategically located reference stations equipped with state-of-the-art GNSS receivers, antennas, and communication systems. Emphasis was placed on achieving optimal geometric distribution to minimize errors and ensure consistent accuracy across the country. Advanced algorithms were employed for network adjustment and quality control, ensuring data integrity and reliability. Moreover, integration with existing geodetic frameworks and interoperability with global navigation systems were key considerations in Geo-Net's design.The implementation of Geo-Net promises manifold benefits for Albania, including enhanced capabilities in surveying, mapping, geodesy, and geosciences. It facilitates precise positioning for various applications such as land management, infrastructure development, disaster monitoring, and scientific research. Moreover, Geo-Net fosters collaboration between governmental agencies, academia, and private sectors, driving innovation and sustainable growth.In conclusion, the design of Geo-Net represents a significant leap forward in Albania's geospatial infrastructure, laying the foundation for a more accurate, reliable, and accessible positioning system. The successful deployment and utilization of Geo-Net are poised to propel Albania towards greater socioeconomic development and technological advancement in the realm of geospatial sciences.

Keywords: Geonet, GNSS, CORS, accuracy, geospatial infrastructure, design.

Session 1: Reference systems and frames in Physical Geodesy

Presentation preference (Poster)

Realization of Gravimetric Measurements in the Local Datum of Tide Gauges in Albania.

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This paper presents the methodology and results of a study focused on the realization of gravimetric measurements within the local datum of tide gauges in Albania. Tide gauges are essential instruments for monitoring sea level variations, but their accuracy is heavily influenced by the local geodetic datum. Gravimetric measurements provide valuable data for understanding the gravitational field variations, which in turn affect sea level measurements. In this study, we employed precise gravimetric techniques to establish a reliable connection between tide gauges and the local geodetic datum. We utilized advanced gravimetric instruments and methodologies to collect and analyze gravity data at multiple locations along the Albanian coastline. The collected data were processed using state-of-the-art geodetic software to compute accurate gravity anomalies. Through a rigorous adjustment process, we determined the transformation parameters necessary to link the gravimetric measurements to the local datum of tide gauges. The results highlight the significance of incorporating gravimetric data into the calibration and maintenance of tide gauge networks, especially in regions prone to sea level changes. This research contributes to enhancing the accuracy and reliability of sea level monitoring systems in Albania, with implications for coastal management, climate change adaptation, and disaster preparedness.

Keywords: Tide gauges, leveling, sea level, tides, Gravimetric measurements.

Session 1: Reference systems and frames in Physical Geodesy

Presentation preference (Poster)

A New Reference Equipotential Surface of the Earth

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A new reference equipotential surface which best fits to the shape of the Earth in least squares sense is determined. Using the ETOPO global relief model and the EGM2008 gravitational field model of the Earth, both expressed in terms of spherical harmonics, we compute the reference surface based on the technique conventionally known as an adjustment by conditions. Also, we provide a detailed explanation of the methodology and computational technique used to estimate the gravity potential value of the equipotential surface as well as its uncertainty. Since the gravity models are valid for the outer space of the Earth, to evaluate the gravity model inside the topographic masses, the topographic bias effect needs to be considered. In this regard, we investigate the effects of topographic bias on the reference surface and on the gravity potential value. After estimating the gravity potential, we estimate the two semi-axes of the biaxial reference ellipsoid of Somigliana-Pizzetti type and their standard deviations. Finally, we show the computed reference surface with respect to the determined reference ellipsoid.

Keywords: least-squares adjustment, reference ellipsoid, topographic bias

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference (Poster)

Towards a first solution for the International Height Reference Frame (IHRF)

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The International Height Reference System (IHRS) was introduced by the International Association of Geodesy (IAG) in 2015 to provide a global standard for the accurate determination of physical heights. The IHRS is based on the combination of a geometric component, given by coordinates $\mathbf{X}$ referring to the International Terrestrial Reference Frame (ITRF), and a physical component, given by the determination of potential values W at the positions P defined by the ITRF coordinates. The primary vertical coordinate is the geopotential number ($C_P = W_0 - W_P$), which can be converted to a metric (orthometric or normal) height. The IHRS vertical datum is given by the equipotential surface of the Earth's gravity field, defined by the conventional value W_0 = 62 636 853.4 m^2s^{-2}. The realisation of the IHRS is the International Height Reference Frame (IHRF). The IHRF realises the IHRS in two ways: physically, through a set of globally distributed reference stations, and mathematically, through the precise determination of potential values at the reference stations. Thanks to a strong international collaboration hosted by the IAG, the station selection for the IHRF reference network is complete and current efforts are focused on the determination of potential values at the global IHRF reference stations. This presentation summarises the challenges and achievements in computing a first solution for the IHRF.

Keywords: IHRS realisation, IHRF, geopotential-based height system

Session 1: Reference systems and frames in Physical Geodesy

Presentation preference: oral

Roadmap for geopotential-based height systems

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The establishment of any geopotential-based height system, such as the International Height Reference System (IHRS), relies on the precise determination and combination of a geometric component given by coordinates in the International Terrestrial Reference Frame – ITRF (determined for example, by GNSS positioning) and a physical component given by the geopotential values determined at these ITRF coordinates using gravity field modelling methods. The reliability of this type of height systems therefore depends on the available geodetic infrastructure, not only in terms of the existing GNSS networks, but also in terms of surface (terrestrial, airborne, marine) gravity data. Considering that the basic approach is the optimal combination of Global Gravity Models of High Resolution – GGM-HR (enhanced with synthetic gravity signals derived from topography models) with surface gravity data, we present a generalised scientific concept for the establishment, maintenance and long-term sustainability of geopotential-based height systems based on various scenarios with different distribution and quality of surface gravity data. We focus on baselines for data collection, data processing, data combination and data validation; on standardisation issues to reduce inconsistencies between potential coordinates caused by the use of different constants or reduction models in gravity data processing and in the computation of ITRF coordinates; on methods for the computation of globally consistent geopotential values considering a global realisation of the IHRS, regional geopotential (geoid) models, and GGM-HR if no local gravity data is available; and on a general definition of the requirements for a consistent combination of ITRF and IHRS coordinates and the integration/connection of existing local height systems into the global IHRS. The ultimate goal is to determine a height value everywhere in the world, together with realistic accuracy estimates depending on the gravity data availability and quality.

Keywords: geopotential-based height systems, IHRS, height system unification

Session 1: Reference systems and frames in Physical Geodesy

Presentation preference: no preference

Clock-based unification for the realization of a global height system

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Regional or local height systems differ from each other due to various error sources like systematic tilts and offsets associated with the classical leveling approach, sea surface topography, etc. A global physical system where elevations are referenced to the global geoid is of paramount importance for various applications. Establishing an International Height Reference System (IHRS) with geopotential numbers as the vertical coordinate is a key objective of the geodesy community.

This goal can be achieved through the unification of all existing height reference systems worldwide using clock networks. The fractional frequency change between two atomic clocks gives the combined effect of geoid height difference and vertical land motion as geopotential difference. High-performance clocks with 10-18 uncertainty are sensitive to one-centimeter physical height difference. Unifying one height system to another involves the estimation of the discrepancies to a selected reference system. To demonstrate the benefit of using clock networks, our approach is to first split an a-priori system into local systems with artificial errors and carry out the reunification process to finally generate unified heights through a clock-based adjustment assuming realistic conditions.

Initially, the unification to a predefined datum is carried out separately for the European (EUVN2000) and the Brazilian systems. The unifying datum for Europe is chosen to be NAP (Normaal Amsterdam Peil) and Imbituba for the Brazilian system. Later, the European system will be unified with the Brazilian system of which the Imbituba datum is related to the global geoid.

Thereby, all height values will be referenced to the global geoid. The accuracy of the reunification is determined by comparing it with the a-priori height values. Clock observations are simulated by including tidal effects and link uncertainties creating a more realistic scenario. An optimal number of clocks with sufficient spatial distribution and appropriate link configuration is crucial for a good unification. We will present the clock-based method and achievable accuracies for the unified global height system.

Acknowledgement:

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Keywords: Chronometric levelling, Atomic clock, Global height system, Geopotential number

Session 2: (Co-organized with the IAG QuGe Proect): Novel technologies in terrestrial, airborne and satellite gravity field determination

Presentation preference (Oral)

GGOS: The Global Observing System of the International Association of Geodesy

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The Global Geodetic Observing System (GGOS) is the response of the international geodetic community, organised under the umbrella of the International Association of Geodesy (IAG), to the need to monitor changes in the Earth system continuously. GGOS is Geodesy's contribution to the Global Earth Observation System of Systems (GEOSS) by providing the reference frames needed for all position-dependent observations, thus the foundation for most Earth observations, and measuring changes in the Earth's shape, size, gravity field and rotation over time and space. GGOS is built on the Scientific Services of the IAG (IGS, IVS, ILRS, IDS, IERS, IGFS, ISG, PSMSL, IGETS, IDEMS, ICGEM, BGI) and the products they derive on an operational basis for Earth monitoring using space- and ground-based geodetic techniques. A key objective of GGOS is to realise an integrating framework that moves from the provision of technique-specific products to a level of combined, integrated products as the basis for a consistent modelling and interpretation of Earth system processes and interactions. This is necessary to ensure a coherent Earth monitoring system that contributes significantly to a better understanding of global change and its impacts on the environment and society. This is being achieved through strong international and multidisciplinary cooperation, focusing on (1) bringing together different geodetic observing techniques, services and analysis methods to guarantee that the same standards, conventions, models and parameters are used in all data analysis and modelling of Earth system processes; (2) combining geometric, gravimetric, and Earth rotation observations in data analysis and data assimilation to jointly estimate and model all necessary parameters representing the different elements of the Earth system; (3) identifying science and societal needs that can be addressed by (new) geodetic products and define the requirements for accuracy, time resolution, and consistency of these products; (4) identifying service gaps and developing strategies to fill them; and (5) promoting and enhancing the visibility of Geodesy by improving the accessibility of geodetic observations, information and products to the widest range of users. This contribution summarises recent achievements, ongoing activities, and main challenges for the near future.

Keywords: GGOS, geodetic Earth observation, integrated geodetic products

Session 6: Data management, dissemination of results and networking of stakeholders

Presentation preference: oral

Clock-based unification for the realization of a global height system

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An update on the development of the next pair of satellites, GRACE-Continuity (GRACE-C), to track Earth system mass change will be presented. The satellites are being developed in partnership between the United States and Germany, continuing the successful collaborations established on GRACE and GRACE-FO. Heritage elements are leveraged considerably in the design with some notable changes: the primary ranging instrument will be a higher precision laser ranging interferometer, capitalizing on the successful demonstration of this technology on GRACE-FO. With a planned launch date in 2028, the GRACE-C architecture is designed to meet the primary science goal of maintaining continuity in the essential record of mass change data that currently spans over 22 years. Milestones over the last year will be highlighted, including a transition into Phase C development after successfully completing a Preliminary Design Review.

Keywords: GRACE, gravity, mass change

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral)

LUH-JAQGM2024 Joint Measurements with Absolute Quantum Gravimeters at Leibnitz University Hannover

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Absolute Quantum Gravimeters (AQG) are commercially available, from Exail (France), since 2014. Up to now 16 units of the AQG have been distributed worldwide, most of them in Europe. Organized by the GFZ Section 4.4 “Hydrology” and under the umbrella of the Collaborative Research Centre “TerraQ” (SFB 1464), the world's first AQG comparison took place from 22nd to 26th of January 2024 at Leibniz University Hanover (Germany) in the gravimetric laboratory of the HiTec building.

Five AQG units of the same type (version B – temperature stabilized) participated in the comparison. The following teams participated in the measurements: instrumental park of Action Spécifique Gravimétrie of Epos-France (AQG-B01), the German Research Center for Geosciences in Potsdam, Germany (AQG-B02), the Institute of Geodesy and Cartography, Poland (AQG-B07), the Leibniz Institute of Applied Geophysics in Hanover, Germany (AQG-B09), and the German Federal Agency for Geodesy and Cartography in Leipzig (AQG-B10). The measurement activities lasted 5 days (day and night, 11-12h tracking series) and included a series of test measurements aimed at deepening the knowledge on the operation principle of AQG gravimeters produced by Exail.

The following work will present the initial results from the comparison. This non-official comparison did not have its focus on obtaining the most precise absolute gravity station values but the joint measurements were carried out with the intention of testing certain device characteristics and behaviours, with the focus on comparing the performance of the devices. Among other things, this involved the noise behaviour of the devices and their stability during longer measurements. Repeatability, i.e. how accurately a result can be measured again at the same point, was also an important point of the comparison.

The comparison was independently supported by absolute gravity measurements with CG6 and FG5 gravimeters from the Leibniz University Hannover and the German Federal Agency for Geodesy and Cartography.

Keywords: quantum gravimeter, gravity reference, intercomparison

Session 2 (Co-organized with the IAG QuGe Proect): Novel technologies in terrestrial, airborne and satellite gravity field determination

Presentation preference (Oral/~~Poster/no preference~~)

JPL Level-2A products: GRACE/GRACE-FO Dynamic Orbits

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Dynamic orbits are computed for both GRACE-FO spacecraft through integrating and solving the equations of motion. They include accelerations observed by the spacecraft and modeled using background models. These orbits are used as a Taylor point xo for the estimation of the gravity field. Reduced observations can be obtained by differencing the observations measured by the respective ranging instrument (MWI or LRI) with those derived from the spacecrafts' dynamic orbits. Such reduced observations have been used to study geophysical signals mapped along the track of the spacecraft, providing superior signal localization in space and time. Reduced observations, also termed "along track" observations, have been used for detection and monitoring of mass variations in different reservoirs like the ocean, hydrosphere and cryosphere. JPL will be delivering a new product, which will provide the users with the dynamic orbits used as the Taylor point in our Level-2 gravity field estimation process. This product would be intended to provide the scientific community with the flexibility to derive reduced observations using an orbit incorporating JPL's choices in background models, data processing, and parametrization, and enable study and exploration of new science applications.

Keywords: GRACE-FO, Dynamic Orbits, Along Track, Laser Ranging Instrument

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral)

Evaluation of the retrieved gravity fields and their ocean tide aliasing errors by small satellite constellations

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With the fast development of space technology, satellite business is booming. Many small satellite constellations are on the schedule. It is worthy to explore the capability of retrieving the Earth gravity field using non-gravity-dedicated small satellite constellation, and the influence of different errors, especially among which, the ocean tide aliasing error. In this report, a number of scenarios of different small satellite constellations will be investigated in closed-loop simulations, given both with and without accelerometer on board. The spatiotemporal resolution as well as the anti-aliasing effect with respect to ocean tides will be evaluated. Feasibility of non-gravity-dedicated small satellite constellation for gravity field recovery will be analyzed.

Keywords: small satellite constellation, gravity field recovery, aliasing, ocean tides

Submit to Session 3

Presentation preference: Oral

Quantum Gravimetry in Space: How space debris will affect the gravity field recovery

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In the project CARIOQA-PMP, we are investigating how using a Cold Atom Interferometer (CAI) as an accelerometer on board a satellite impacts the gravity field recovery. Current simulation studies are often limited by the temporal resolution of the drag models and a lack of short time scale events. Our study addresses these limitations by simulating thruster firings and hits on the spacecraft, such as meteorite or space debris collisions, based on real data. The artificial accelerometer data is generated using GRACE-FO and MICROSCOPE data. We are studying the effect of these phenomena on the CAI measurement using a four second cycle time of the CAI instrument in a closed-loop simulation. We are working with a preparation time of 2s, where there are no measurements, and an integration time 2T of 2s. We also look at how working with a hybrid accelerometer changes the picture.

Keywords: Satellite Gravimetry, Quantum Gravimetry, Gravity Field, Cold Atom Interferometry

Session 2: (Co-organized with the IAG QuGe Proect): Novel technologies in terrestrial, airborne and satellite gravity field determination

Presentation preference (Oral)

Detailed gravity field modelling in high mountains treated in spatial domain: a case study in Tatra Mountains (Slovakia/Poland)

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This study presents local gravity field modelling in high mountains using the finite element method (FEM). This numerical approach is applied to solve the fixed gravimetric boundary value problem in spatial domain on the discretized Earth's surface. The FEM numerical scheme is based on pentahedron finite elements with linear basis functions. The oblique derivative problem, whose impact increases in such extremely rugged mountainous terrain, is treated by a decomposition of the oblique derivative into its normal and tangential components. The FEM numerical solution is fixed on an artificial upper boundary at altitude of 230 km by disturbing potential generated from the GRACE/GOCE-based satellite-only global geopotential models.

The case study presents detailed gravity field modelling in the area of Tatra Mountains (Slovakia/Poland). Gravity disturbances as input data in a computational grid of the uniform horizontal resolution 20 x 20 m have been generated from terrestrial gravimetric measurements through evaluating complete Bouguer anomalies. Large-scale parallel computations have resulted in the disturbing potential obtained in the whole 3D computational domain. On the discretized Earth's surface, it is transformed into the local quasigeoid model of Tatra Mountains with the high-resolution 20 x 20 m. The GNSS-levelling test indicates its accuracy of several cm.

Keywords: local gravity field modelling, fixed gravimetric boundary value problem, finite element method, numerical solution, large-scale parallel computations

Session 4

Presentation preference: Oral

Experimental geoid model for Greece and evaluation using a velocity field model

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In the frame of the ModernGravNet project a new experimental gravimetric quasi-geoid model for the broader Greek region has been developed. The computations were based on the remove-computerestore approach, the 1D spherical Fast Fourier Transform method with the Wong-Gore modification, XGM2019 as the reference geopotential model and the Residual Terrain Modeling scheme. The model's evaluation was conducted using GNSS/leveling data across the Greek mainland, taking into account the geoid separation term. Furthermore, a velocity field model, derived from 16 years of continuous observations at 227 GNSS permanent stations in Greece and the adjacent areas, was incorporated into the evaluation process to assess temporal horizontal and vertical changes. This model reflects the dynamic geometrical properties associated with the crust's geophysical processes. As the gravimetric geoid was computed using gravity data from various time periods, the velocity field has been utilized to examine temporal changes in the GNSS/leveling data relative to the gravimetric geoid heights, aiming for more precise comparisons. The study highlights the importance of adopting a dynamic geoid model and emphasizes the need for its thorough evaluation.

Keywords: geoid, Greece, velocity field model, GNSS/leveling

Session: Poster Session 1

Presentation preference (Poster)

A 30 Arc-second Global Digital Elevation Merged Model GDEMM2024 for Geodesy and Geophysics

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Various study topics in Earth sciences such as gravity field modelling, terrain correction and ocean circulation, require high resolution and accuracy digital land topography, bathymetry, and ice thickness grids that refer to a consistent vertical datum. Unfortunately, most of the available elevation grids do not provide such solutions for Earth relief layers with the same accuracy and resolution globally. We have analysed the digital elevation models (DEMs) published in the recent years. To overcome their shortcomings, we merged selected DEMs to create an up-to-date composite and global elevation grid together with complementary Earth's relief layers, bedrock, surface, bathymetry, and ice thickness.

Despite the unique features of each DEM, the merged grid provides improved and seamless elevation information globally based on a common vertical and horizontal reference surface. The improvements are due to the higher accuracy and coverage of the original input data, updated land-type masks and merging methodology developed. The DEMs and associated auxiliary files included in the merged product are: TanDEM-X 90m over all dry land and ice-covered regions, ETOPO2022, GEBCO-2022 and GEBCO-2023 over land and ocean, BedMachineGreenland-v5 over Greenland, BedMachineAntarctica-v3 over Antarctica, GLOBathy (the Global Lakes Bathymetry Dataset) over lakes globally. Masks for ocean, dry land, lakes, ice-covered land, and ice-covered shelves, and the ice-covered lake Vostok (Antarctica) were taken into account in the merging.

We provide high resolution 30 arcsecond grid suite for relief layers and a land-type mask which have been substantially improved w.r.t. the global grids in literature. The quality of the merged surface elevation is assessed by comparing against the heights determined at about globally distributed 5000 ITRF stations. The merged surface model shows a reduction in standard deviation of a factor of three compared to other commonly used DEMs. The impact of such improvement in the DEM is investigated in terms of gravity field functionals which reach up to several cms in the geoid globally.

Our aim is to disseminate the use of a homogeneous and a consistent elevation model that is essentially suitable for geodetic applications in all parts of the world, including global and regional geoid calculations. This complete model is anticipated to provide a standardized DEM for various applications in geodesy and geophysics. Our future plans include high resolution topographic gravity field modelling using this consolidated 30 arc-second digital elevation model and laterally varying global density data. Moreover, new DEM datasets will be incorporated to update the GDEMM2024 in spatial and spectral content.

Keywords: Earth relief model, digital elevation model, merged DEM, high resolution DEM, GDEMM2024
Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference (Oral)

Future Role of the ICGEM Service in the use and archiving of global gravity field data and related products via the SAMDAT project

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The International Center for Global Earth Models (ICGEM), as one of the five services coordinated by the International Gravity Field Service (IGFS) of the International Association of Geodesy (IAG), has been actively responding to the needs of the geoscientific community since its establishment in 2004. The service provides an archive of static, temporal, and topographic global gravity field models of the Earth represented in a standardized format with the possibility of assigning DOIs. Furthermore, ICGEM supports its users by interactive calculation and visualisation services of gravity field functionals. Maintenance of such a service and development of new “demand-based” tools are of utmost importance to keep the service ready for use in up to date geoscientific research.

In the era of abundant and diverse scientific research data and products, such a service has a direct role in shaping the relevant research topics via bringing FAIR (Findable, Accessible, Interoperable, Reusable) data standards and quality measures to the gravity field models and related products. Gravity data are widely used in geodesy, geophysics, oceanography and hydrology, among others. With the new developments in sensors and future satellite mission concepts, the use of gravity field models that represent even higher spatial and temporal variations will become available and utilized for understanding the system Earth. However, this data should be documented and archived, made available on freely accessible portals, linked to other geoscientific services and data archives, and made more visible in interdisciplinary research topics and for society.

Our SAMDAT (Service and Archive for Mass Distribution And mass Transport data) project, funded by the German Research Foundation (project #: 527258067) aims to expand and enhance the ICGEM service via collaborative work between Earth, data and computer scientists. Starting with a comprehensive user survey, the project components will be implemented during the next three years which includes promoting the global gravitational field models and related products to increase their visibility through contributions from GFZ Potsdam, TU Munich, model developers with the participation of the ICGEM user community.

Keywords: Global gravity field models, ICGEM, SAMDAT, FAIR data, gravity data

Session 6: Data management, dissemination of results and networking of stakeholders

Presentation preference (Oral)

Global gravitational field modelling for spheroidal planetary bodies: theory and numerical aspects

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The standard theoretical framework for the gravitational field determination often relies on spherical approximation. However, Earth's shape is much closer to a rotational ellipsoid flattened at the poles, as proved by the legendary expeditions of the French Academy of Sciences to South America and Lapland already in the 18th century. Contemporary investigations of solar system planetary bodies have revealed that many resemble prolate or oblate ellipsoids, whereas a high amount of them is flattened more significantly than the Earth. Four such spheroidal bodies have recently been subject to immense research interest: 1) Mars being explored by satellite and lander missions as it represents a potential target for future colonisation, 2) the asteroid Bennu explored by the sample-return satellite mission OSIRIS-REx, 3) the dwarf planet Ceres, and 4) the asteroid Vesta, both explored by the satellite mission Dawn. Moreover, several comets and asteroids with spheroidal (ellipsoidal) shapes have been subjected to intense small-body research. Consequently, there is an urgent need to formulate a modern theoretical framework for the gravitational field determination.

In this contribution, we formulate a mathematical theory for gravitational fields generated by ellipsoidal bodies. Four quantities are parametrised by a set of ellipsoidal harmonic functions inside the minimum Brillouin ellipsoid: 1) the gravitational potential, 2) the components of the gravitational gradient, 3) the components of the second order gravitational tensor, and 4) the components of the third order gravitational tensor. The internal part of these expansions is represented by multiplications of the Legendre functions of the first kind with spherical harmonics. The external part is formed by the products of the Legendre functions of the second kind with spherical harmonics. The applicability of the presented formulas is examined in numerical experiments. In particular, we systematically investigate selected numerical aspects of the Legendre functions of the first and second kind.

Keywords: Gravity field modelling, Boundary value problems, Integral transformations, Ellipsoidal harmonic synthesis

Regional gravity field modelling and geophysical interpretation

Poster

On uncertainties associated with regional gravity field modelling

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The regional gravity field modelling is based on the recovery of the unobservable geopotential from its noisy gradients measured discretely in space and time by surface or airborne sensors. Transformation of the measured gradients, i.e., components of the geopotential gradient tensor of different orders, is solved in geodesy by various methods. Green's functions appear in surface integrals solving geodetic boundary-values problems. For example, the Hotine surface integral can be used to transform first-order vertical gradients of the geopotential (its slightly modified version known as Stokes's integral is then even more popular in geodesy). In recent years, second-order gradients of the geopotential have been collected locally by airborne and globally by satellite sensors. Moreover, the theory for application of higher order geopotential gradients, although operationally unobservable so far, have been also developed extending the theory of physical geodesy. These solutions represent deterministic models that have been developed, studied, and implemented for either currently available or synthetic gradient data. This contribution discusses stochastic methods that allow for noise propagation through deterministic models based on surface integrals modified for regional gravity field modelling. Implementation and approximation errors as well as the external accuracy of the recovered geopotential are also discussed.

Keywords: geopotential gradients; noise; stochastic modelling; surface integrals

Session 6 you submit your abstract to

Presentation preference (Oral/Poster/no preference): no preference

Numerical evaluation of variations in gravitational potential derivatives up to second order implied by polyhedral shape changes for high resolution Digital Terrain Models

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The dynamic evaluation of a time variable gravity field can be performed by a stochastic consideration of the source geometry. This allows the modelling of mass changes and quantifying the influence of shape changes on the obtained gravity signal. According to the algorithm, coordinate changes of the corresponding polyhedral shape are transformed into spherical harmonic coefficient variations. The estimation procedure eventually computes variations in gravitational potential first and second order derivatives. Two approaches are used to define the involved spherical harmonic synthesis formulas. The first includes the expressions of associated Legendre functions (ALF) and their derivatives up to second order, the second uses an alternative of ALF, namely the derivatives of Legendre polynomials, denoted as derived Legendre functions (DLF). The evaluated variations of first and second order potential derivatives using both approaches, are compared with gravity signal differences induced by various polyhedra that represent the modelled shape changes, using the line integral analytical approach. The numerical tests are applied to the real shape data of several asteroid models that differ in terms of their oblateness. Concerning the first order derivatives, the ALF approach provides results closer to the analytical method, while both methods converge equally fast for the second order derivatives. The dynamic modelling is also applied to real mass changes, in particular deformation analysis and subsurface mass modelling scenarios. For this purpose, various synthetic test cases are created based on a digital terrain model covering a 6.25 km × 6 km area of the Austrian Alps with a resolution of 1 m. The obtained stochastic results are compared with the analytical determination of the same gravity changes in order to explore the computational limits of the stochastic approach.

Keywords: Stochastic modelling, variable gravity field, first and second order potential derivatives, spherical harmonic coefficients, analytical approach

Session 4

Presentation preference: Oral

Implementation of different stochastic models in dynamic modelling of polyhedral gravity signal variations

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The stochastic modelling of an uncertain mass distribution provides useful insights into the induced gravity field variability. The examined algorithm computes variations of spherical harmonic coefficients implied by respective shape changes, that can then be propagated to the sought gravitational functionals. A crucial parameter of this procedure is the selection of a stochastic model to represent the shape model's variability. Most commonly a Gaussian model is used for this purpose. In the present contribution three additional covariance functions are implemented, namely an exponential, an inverse quadratic and an inverse multiquadric. Thereby, the effect of specific parameters such as correlation length and coordinate variances is examined. The estimated uncertainties are compared with gravity signal differences between various polyhedra that represent the modelled shape changes, using the line integral analytical approach. The numerical tests were carried out using real data of several asteroid shape models. The inverse multiquadric model does not depend as much on the correlation length and defines uncertainties that vary inside a smaller range compared to the other models by 2 %. Eventually, the Gaussian, inverse quadratic and inverse multiquadric model tend converge to the same value as the correlation length increases and diverge from the exponential by 0.3 – 1.2 % depending on the shape model's oblateness. The dynamic modelling is extended to evaluate variations of first and second order potential derivatives, while additional numerical tests are implemented for investigating realistic mass changes using a digital terrain model that covers a 37.5 km^2 area of the Austrian Alps with a resolution of 1 m.

Keywords: Gravity field variations, stochastic models, spherical harmonic coefficients, analytical approach

Session 4

Presentation preference: Poster

Signatures of residual ocean tides in GRACE(-FO) ranging post-fits

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Imperfections of global ocean tide models used for orbit modeling during gravity field recovery from GRACE and GRACE-FO inter-satellite ranging measurements are considered as one of the most crucial factors limiting the quality of the derived gravity field solutions. In this contribution, we analyze 21.5 years of range-rate post-fit residuals for remaining ocean tide signal using spectral analysis tools. We could identify over 30 individual ocean tide frequencies of different origin (e.g. astronomical tides, minor degree-3 tides, non-linear tides) as a distinguishable part of the post-fit residuals. We present amplitude maps of selected constituents and compare them to satellite altimetry measurements and data-unconstrained ocean tide solutions.

Keywords: GRACE, ocean tides, range-rate post-fit residuals

Session: Poster Session 3

Presentation preference (Poster)

Purely geodetic estimation of the Mean Dynamic Topography and Geostrophic Currents in the Tyrrhenian and Adriatic Seas (Italy)

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The estimation of the Mean Dynamic Topography (MDT) and geostrophic currents using satellite geodetic observations has provided important results in the oceans, where the MDT values are on the order of 1 m and more, which is greater than the precision of the geodetic satellite models involved in the computation, such as the Mean Sea Surface (MSS) and the geoid undulation. In basins like the Mediterranean Sea, characterized by small dimensions, alternation of sea and land, and values of MDT around 20 cm, a pure geodetic approach is challenging. However, the use of local geoid models improves the geodetic estimation of the MDT for the Italian sea basins (Tyrrhenian and Adriatic Sea). The derived geostrophic currents have been validated using independent observations. In particular, a dataset of satellite-tracked surface drifting buoys trajectories has been used.

Keywords: MDT, geoid, drifters, geostrophic currents, Mediterranean

Session xx you submit your abstract to 4

Presentation preference (Oral/Poster/no preference) no preference

Review and Revision of Normal Gravity Field Models

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In geodesy, a level ellipsoid is traditionally used to define the normal gravity field which is uniquely determined by four fundamental geodetic parameters: GM, ω, J_2, and W_0 (or a). The model is based on the Pizzetti-Somigliana theory, which was developed at the beginning of the 20th century. At that time, geodesy focused solely on terrestrial measurements and did not consider time variations in the physical surface, gravitational field, or rotation of the Earth. Additionally, consistency across different types of geodetic reference systems and reference frames (coordinates, heights and gravity) was not a major concern.

With the advancement of space geodesy techniques and increased accuracy and resolution in both measurements and models of geophysical phenomena, some limitations of using the level ellipsoid have become apparent. These include implicit accounting for the atmosphere and the permanent component of tides, lack of information about the Earth's internal structure, and failure to account for relativistic effects and changes in fundamental geodetic parameters over time. Considering these factors, it is clear that the traditional ellipsoidal model, despite its simplicity and historical importance, is not suitable for meeting the demands of modern geodesy or its s role will be limited to only specific applications. Additionally, a mere update of the fundamental constants is unlikely to yield significant benefits from introducing a new geodetic reference system (GRS). On the other hand, considering these effects necessitates changes to the theory and well-known formulas.

We consider and discuss various normal field models that could eliminate the above disadvantages and limitations and become a new GRS for present and future geodetic applications.

Keywords: geodetic reference system, normal gravity field, level ellipsoid, potential theory

Session 1 Reference systems and frames in Physical Geodesy

Presentation preference: Oral

Advancing space geodesy techniques: insights from GRACE / GRACE-FO

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Along with providing fundamental gravity information and essential climate variables, satellite-to-satellite tracking (SST) with GRACE and GRACE-FO allows exploring the limits how accurately we can track the motion of test masses in space. This includes orbital motion as well as angular motion, both for the satellites (as "outer" test masses) and for the inner test masses inside the electrostatic accelerometers. Any deviation in the sense of systematic errors can show ways to evaluate and improve the understanding of the nature of the tracking process. GRACE / GRACE-FO Level 1 and Level 2 analysis reveal a range of such systematics that have not yet been addressed in detail but could provide valuable insight. A re-assessment and refinement of the measurement models is also the basis for a more complete calibration. The SST measurement system involves calibration of many quantities at different levels, and some interesting and possibly very relevant options for calibration procedures have not been explored so far.

As an example, the frequent attitude control manoeuvers should be analyzed as an integral part of the regular science measurement signals and offer additional calibration options. In our view, addressing these topics may not only improve the quality of derived data products and support mission operation but is also important for significantly advancing the understanding of fundamental measurement techniques and procedures for space geodesy.

Keywords: Satellite-to-Satellite Tracking, GRACE, calibration, space geodesy

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral)

Status and development of high-resolution strapdown gravimetry at DTU Space

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The gravity group at DTU Space is currently part of an EIT Raw Material funded project DroneSOM (Drone Geophysics and Self-Organizing Maps). Within this project, we aim to develop the world's first drone-based gravity observing system. Based on the experience of conducting airborne gravity surveys over the last 30 years, and from the first ever test of drone gravity in the Irish Sea in 2020, existing sensor technology and processing techniques are adapted to fulfil the specific requirements of a drone-based observation system. The observing system uses modern strapdown gravimetry applying an iMAR navigation-grade inertial measurement unit and a geodetic GNSS receiver.

The software under development applies the so-called direct method. This technique has a clear resolution for the along-track filtering in contrast to the traditional Kalman filtering based technique. A clear resolution is a desired property in the data combination used for geophysical inversion in the scope of DroneSOM.

We show the present status and development of the drone-based observing system towards the target accuracy of 1 mGal accuracy on a spatial resolution of 1 km. In addition, results showing mGal-accuracy of the most recent airborne gravity campaigns in the coastal zones of Norway and Antarctica are presented. The airborne surveys are used for validation of satellite altimetry and older marine gravity observations which in the future will be used to determine high-resolution geoid models.

Keywords: strapdown gravimetry, drone-based observing system, airborne gravimetry, gravity validation

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference (Oral)

Analysis of LRI Gravity Field Products from GRACE-FO

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The Gravity Recovery and Climate Experiment (GRACE) and its Follow-On mission (GRACE-FO) have been providing invaluable month-to-month global mass change observations since 2002.

These observations are essential to track and understand Earth's changing climate system and water cycle. A successor mission, GRACE-Continuity (GRACE-C), is also planned to launch in 2028, to continue these vital global observations into the next decade. For GRACE-FO, the primary observable enabling these scientific applications is the inter-satellite rangerate, provided by both a K-band ranging system (KBR) and a laser ranging interferometer (LRI) as a technology demonstration. While the KBR is the primary instrument for GRACE-FO, the technology demonstration of the LRI has been widely successful and GRACE-C will replace the KBR, in favor of the LRI as its prime instrument. From this perspective, this presentation will analyze gravity fields computed with the LRI instrument and compare them with KBR solutions. Additionally, analysis of signal and noise content will be explored; as well as experimentation designed to optimize the quality of the LRI gravity field solutions.

The research presented in this abstract has been carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Keywords: GRACE-FO, Time variable gravity, Laser Ranging Interferometer (LRI)

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral)

On the role of regional comparisons of absolute gravimeters within the International Terrestrial Gravity Reference Frame (ITGRF)

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Comparisons of absolute gravimeters are an essential component of the future International Terrestrial Gravity Reference Frame (ITGRF) of IAG to guarantee the compatibility of observations. Since no independent reference for gravity exists, it is the only way to ensure a common level. Comparisons have been conducted at the Geodetic Observatory Wettzell since 2010. Besides the geodetic comparisons, the EURAMET comparisons of 2018 and 2024 have the importance to provide links to the respective CIPM comparisons in 2017 and 2023. The consistency of these links is discussed as well as the stability of the reference function from continuous records of superconducting gravimeters, including preliminary results from the most recent comparison in 2024.

Keywords: Absolute Gravimeter, Comparison, ITGRF

Session 1: Reference systems and frames in Physical Geodesy

Presentation preference (Oral)

Canada 1 Water: Towards integrated gravity – water storage change models for regional and national scale monitoring

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Large scale changes in water storage produce changes in gravity that can be measured and used for monitoring. However, the cause-and-effect relationship is not unidirectional. Large changes in gravity also impact hydrology, water flow, and water surface topography. The new vertical datum (mean sea level) for North America, the North American Pacific Geopotential Datum (NAPGD2022), will for the first time contain a time dependent component. While much of the large-scale temporal changes are driven by tectonic processes such as glacial isostatic rebound, changes in water and ice are significant contributors as well. Details on water storage changes through time are often required to explain the complex non-linear gravity signals observed and to produce meaningful gravity (or vertical datum) change models. As such, studying changes in gravity and water storage in parallel helps us refine our approaches and improve our estimates of both. A good example of this is the Canada1Water (C1W) project which aims to develop a national scale coupled surface water - groundwater model to provide decision support tools to inform on surface water - groundwater quantity and related impacts such as droughts, floods, carbon sequestration availability, wildfire risk, permafrost changes, and ecosystem service value. Satellite gravity observations from the GRACE and GRACE-FO missions are helping to provide important large scale water balance constraints for basins within the C1W project. These constraints are critical for validating and calibrating the surface and subsurface flow domains within the C1W fully-integrated groundwater – surface water models. Once hydrological models have been validated at a large scale, they can then be used to help interpret gravity change signals at a much finer resolution than is currently possible with satellite gravity.

We will discuss a case study for southern Ontario that demonstrates our ability to accurately capture changes in regional water storage using satellite gravity data. We focus on southern Ontario as there are abundant hydrological observations and sophisticated models, such as the regional scale HydroGeoSphere model, that can be used to validate the GRACE estimates. We show that GRACE/GRACE-FO effectively captures and quantifies both extreme events and regular seasonal behavior. Furthermore, the GRACE results demonstrate that the large and recent changes in the Great Lakes water levels have little correlation with seasonal changes in total water storage for southern Ontario, which have remained relatively consistent over the same period. We conclude with a brief discussion of how our method is being applied at the national scale to identify areas of interest and to further help with C1W model validation and calibration.

Keywords: GRACE, satellite gravity, hydrology, climate change

Session xx you submit your abstract to: Session 5: Gravity for climate, atmosphere, ocean and natural hazard research

Presentation preference (Oral/Poster/no preference): Oral please

AN EXPERIMENTAL STUDY ON COMPUTATION AND VALIDATION OF LOCAL GEOID MODEL

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ASBTRACT

National leveling networks, the backbone of height systems, are susceptible to deformations caused by crustal movements, construction, and roadworks etc. Therefore, there is a necessity to renew these damaged networks. In parallel with advancements in satellite technology, the traditional leveling method, which is labor-intensive, time-consuming, and limited by weather conditions, has begun to be replaced by an approach that combines the use of geoid models and Global Navigation Satellite System (GNSS). Gravity based orthometric heights are required in many engineering and mapping applications, and they can be obtained by subtracting geoid undulations derived from regional gravimetric geoids from GNSS based ellipsoidal heights. In this transformation, the accuracy of geoid model is crucial. Various aspects regarding the input datasets and computation algorithms influence the geoid modeling accuracy. Terrestrial gravity data measured on the Earth's surface are not on the same equipotential surface and cannot be directly gridded as they are under effects of topographic masses. Instead, Bouguer anomalies, calculated on the geoid and less affected by topographic masses, are gridded. This study examines the role of interpolation methods used in this gridding process on geoid undulation. To this end, geoid models were produced from complete Bouguer anomalies gridded using Inverse Distance to a Power (IDP), Kriging, and Artificial Neural Networks (ANN) methods in the study area of Auvergne. The experimental geoid models were calculated using each datasets obtained from the gridding algorithms and they were compared in the area and validated at GPS/leveling control benchmarks. Absolute validation results at the benchmarks are nearly identical for all three geoids. However, due to the installation of GPS/Leveling points in plain areas, rugged terrains may not be well represented in the validation. Therefore, in addition to absolute validation, spatial differences between the geoids were also examined. When assessing the computed geoids, absolute validation results revealed that the Kriging geoid exhibited the smallest difference (0.38 cm) from the IDP geoid, while the ANN geoid displayed the largest difference (1.58 cm). This result highlights the significance of the interpolation method used in gridding and demonstrates the impact of the distribution of GPS/Leveling points used in validation on the results. To further investigate the influence of spatial distribution of control data, a second study was conducted by dividing the topography into plain and rugged areas and the generated geoids were validated against GPS/Leveling points within each region. This analysis revealed a significant difference in standard deviations up to two times between the plain and rugged terrain regions.

Enhancing the spatial resolution of TWS estimates by combining GRACE(-FO) and InSAR data

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Terrestrial Water Storage (TWS) changes obtained from the Gravity Recovery and Climate Experiment (GRACE) and its Follow-On mission (GRACE-FO) have been extensively used for studying large-scale hydrological processes. However, due to the low spatial resolution of the GRACE(-FO) products, spatially localized water storage changes such as those of small lakes, reservoirs and regional aquifers are difficult to be isolated. This study introduces a novel approach that leverages Differential Interferometric Synthetic Aperture Radar (DInSAR) observations to detect small-scale anomalies.

This method enhances our understanding of regional water mass variations by enhancing GRACE(-FO) TWS estimates using high-resolution DInSAR analysis. We can infer the seasonal water level changes from measured ground displacement due to aquifer response to fluidpressure changes. Our approach follows a co-estimation of the land motion and TWS from all available data sets using a Blind Source Separation Technique.

Our research focuses on various case studies, where diverse hydrological characteristics exist, and where altimetry and auxiliary data are available.

Through the analysis of various data sets, we estimate the leakage effects of GRACE-FO data is selected regions, where the results can help to better separate TWS signals to relevant storage compartments.

Key Points:

1. Demonstrated the utility of synthetic aperture radar interferometry for tracking water level changes in small lakes and reservoirs.

2. Introduced a novel approach to InSAR processing from a semantic segmentation perspective, enhancing phase unwrapping and spatial accuracy for better water level measurement.

3. Enhanced understanding of regional water mass variations by integrating high-resolution DInSAR data with GRACE-FO TWS estimates.

4. Employed Blind Source Separation techniques to coestimate land motion and TWS changes from all available data sets.

5. InSAR technology can be applied to downscale the groundwater storage anomalies retrieved by GRACE-FO data.

6. A New Weighted Combination method is used to generate high-resolution Groundwater Storage Anomalies, indicating the synergy of two remote sensing tools to monitor the sustainable development of groundwater.

Keywords: Terrestrial Water Storage, GRACE/GRACE-FO, Interferometric Synthetic Aperture Radar, DINSAR, Bayesian Three-Cornered Hat, Blind Source Separation Technique, Semantic Segmentation

Session 5: Gravity for climate, atmosphere, ocean and natural hazard research

Presentation preference (Oral)

Exact Ekman formulas for gravity and height conversion among permanent tide systems and the impact of varying load Love numbers

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In 1989, the geodesist Martin Ekman published a suite of formulas for the conversion of geoid, orthometric, and ellipsoidal heights and gravitational accelerations among the three permanent tide systems: zero-tide, tide-free, and mean-tide. Ihde et al. (2008) and Mäkinen (2021) updated and provided the formulas to include higher than second-degree terms in conversion formulas of gravity and orthometric heights. The building block of these updated formulas was the revised expression of permanent tide-generating potential in geodetic coordinates. The formulas from 1989 and 2008 studies have been used extensively in the literature. However, sometimes different load Love numbers are used in these conversion formulas (i.e., k_2 and h_2, describing additional potential due to deformation and vertical tidal displacement of the crust relative to ellipsoid, respectively). This arises due to the availability of varying load numbers in the literature, e.g., k_2=0.3 and h_2=0.62 in Ekman (1989), and k_2=0.30190 and h_2=0.60780 in Petit and Luzum (2010). It further causes differences also in the derived load numbers δ_2 and γ_2. Hence, this study has twofold motivation: i) rederiving Ekman's conversion formulas using a more exact expression of permanent tide-generating potential in geodetic coordinates, and ii) quantifying the impact of available varying values of the load Love numbers. It is shown that although the difference between Ekman (1989) and rederived formulas for gravity conversion is within one μGal, the differences between the two formulas for geoid, orthometric, and ellipsoidal height sometimes vary more than one mm.

Keywords: permanent tide system, load Love number, exact Ekman conversion formula

Session: Reference systems and frames in Physical Geodesy

Presentation preference: Poster

Development towards consistently precise Indian gravimetric geoid model: Results from Haryana region

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The availability of various geoid modelling methods necessitates testing them to decide on a suitable methodology for developing a country-wide consistently-precise geoid model. Given the diversity of Indian landforms, it becomes difficult to confidently claim the precision of geoid for the entire country using one method if others are not tested. The difference between a precise geoid and a consistently-precise geoid is that the precision, in the latter, should be preserved when a geoid model is validated region-wise in addition to the validation with the complete ground truth. Otherwise, cm-precise geoid may have limited meaning. Hence, following the Indian National Geospatial Policy, with one of the milestones being developing a precise gravimetric geoid model, the Survey of India and the National Centre for Geodesy collaborate to test four geoid modelling methods in three regions of India having varying topographical features. The methods tested are: Curtin University's approach, Stokes-Helmert, Least Squares Modification of Stokes formula with Additive Corrections, and Remove-Compute-Restore with Residual Terrain Modelling. While recapitulating the experimental setup and results from the first case study region, this presentation will discuss the results from the second case study region, i.e., around Haryana state of India.

Keywords: Geoid modelling, India, consistently-precise, geoid method comparison

Session 1: Reference systems and frames in Physical Geodesy

Presentation preference: Poster

Evaluation and validation of the geodetic data for the project GARUDA over Gangetic plains in India

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This study has two objectives: (i.) to introduce our project on Geoid Analysis using Rigorously Unique Methods for DEM and its Applications (GARUDA), and (ii.) to present initial results of geodetic data assessment over the regions of Gangetic plains in India, especially in the state of Uttar Pradesh (case-study region for the project GARUDA). The assessment includes evaluating Global Geopotential Models (GGMs) using terrestrial point free-air gravity anomalies, and geometric geoid undulations from co-located GNSS and levelling data. Since the project involves testing various geoid modeling methods, both combined and satellite-alone GGMs are evaluated. It is essential because a few methods suggest using only satellite-alone GGMs. Another important dataset used in geoid modelling is Digital Elevation Model (DEM). A DEM is used mainly in topographic, atmospheric, and downward continuation effects in geoid modelling. Further, DEM is also required in calculating the geoid-quasigeoid separation term to convert the computed quasigeoid to the required geoid, in the methods that provide quasigeoid as the primary output. Hence, due to the availability of numerous DEMs, this study also presents the results of DEM validation with the GNSS-levelling data. The results of this study help identify the most suitable GGMs and DEM in our study region for the project GARUDA.

Keywords: Global Geopotential Models, gravity anomalies, India, geoid, GARUDA

Session 04: Regional gravity field modelling and geophysical interpretation

Presentation preference: Poster

Field and laboratory investigations of the A10-020 portable absolute gravimeter for the Finnish First Order Gravity Net

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The A10 portable absolute gravimeter has found widespread use in the establishment of reference stations for national gravity networks and relative-gravity surveys, and for monitoring variation in surface gravity. During 2009-2011 the First Order Gravity Net (FOGN) of Finland was renovated in cooperation with the Institute of Geodesy and Cartography (IGiK), using the A10-020 of the IGiK. Altogether 51 FOGN stations were occupied. The FOGN stations are outdoors, mostly attached to monumental buildings.

The FOGN is tied to the International Terrestrial Gravity Reference Frame ITGRF through the absolute-gravity (AG) network of the FGI. In this “zero-order” network, time series of AG measurements are maintained at 19 locations with the FG5(X)-221 absolute gravimeter, which is the national standard of free-fall acceleration in Finland. The stations are co-located with stations of the permanent GNSS network FinnRef. During the FOGN campaign, 6 stations of the AG network were occupied altogether 25 times by the A10-020.

The standard deviation of the offset of the A10-020 with respect to the time series of the FG5(X)-221 is 3 µGal only. To what extent does this high accuracy of the A10-020 indicated at AG stations carry over to the FOGN stations? The AG stations are in buildings, with stable piers and protection against temperature variation, wind etc. A typical FOGN station is outdoors on church stairs, less stable and more influenced by weather conditions.

To better understand the issues, we looked at the multiple instrument parameters recorded by the “g” acquisition program of the A10 and by additional standalone thermometers installed by us. They were analyzed together with features of the gravity output. We also performed a controlled laboratory experiment at the National Metrology Institute MIKES to test the relationship between ambient temperature (16 °C to 25 °C) and the frequency of the two-mode laser that provides the length standard of the A10-020. In another experiment, gravity was measured quasi-continuously for two days at the Metsähovi gravity laboratory, at temperatures 15 °C to 31 °C. We describe our findings and discuss their implications for the FOGN and for other A10 networks and campaigns.

Keywords: absolute gravity, A10 gravimeter, ITGRF, uncertainty, gravity networks

Session 2

Poster

The absolute gravity network of Italy in the framework of the ITGRS/ITGRF

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The activities for establishing the Italian Reference Gravity Network started in 2022. This is in line with the actions promoted by the International Association of Geodesy that during its 2015 General Assembly approved a resolution on the establishment of the new global gravity network the so-called International Terrestrial Gravity Reference System/Frame that will replace IGSN71.
An initial set of 30 stations has been defined over the peninsular part of Italy and the two main islands of Sicily and Sardinia. Particularly, the GGOS core station of Matera (the Agenzia Spaziale Italiana Center for Space Geodesy "Bepi" Colombo) is one of the network points as required in the documents of the GGOS-Bureau of Networks and Observations. Thus, this station will provide one link between the Italian national absolute gravity network and the GGOS observation system of IAG. In order to ensure the measurements traceability, as required by the international standards on gravity measurements, the absolute gravimeters used in the measurements participated in international comparison campaigns. Absolute gravity measurements have been supplemented with direct measurements of the local value of the vertical gravity gradient, in order to reduce the absolute values, measured by different instruments at different heights, to an intermediate and common reference height and to the ground reference level to transport it to an external associated station. The gravity field campaigns have been assisted by topographic survey campaigns, allowing a centimetric georeferencing of the gravity stations to the current ITRF.
The collected data will be then validated and reduced following the internationally accepted standards and finally published through a dedicate web page of the project. These data will also be submitted to the absolute gravity database maintained by the Bureau Gravimétrique International/Bundesamt fuer Kartographie und Geodaesie where the absolute gravity data that will contribute to the new global absolute gravity reference system are collected.

Keywords: Absolute gravity, ITGRS, Italian Absolute Gravity Network
Session: Session 1: Reference systems and frames in Physical Geodesy
Presentation preference: oral/poster

Recent geoid and MDT computation over the Mediterranean Sea in the framework of the Geomed 2 project

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The main aim of the Geomed2 project is the estimation of the best possible geoid approximation, given all the available marine- and ground-based gravity data, for the wider Mediterranean area, i.e. in the area bounded between $30 < \varphi < 48$ $-10 < \lambda < 40$. Particularly, all available shipborne gravity data have been collected, edited, homogenized and used to derive the most homogeneous possible dataset in order to devise a gravimetric only geoid model. In that respect, special attention has been paid to the data debiasing, where both area-wise and track-wise methods have been employed. Then, all the available gravity data have been gridded on a regular $2' \times 2'$ grid in the computation area using different methods
The geoid estimation was based on the well-known remove-compute-restore method, employing different approaches for the actual geoid modeling, like least squares collocation, 1dFFT and 2dFFT employing the original Wong&Gore modified Stokes kernel. The estimated geoids have been then compared with altimeter data over the Mediterranean area to obtain different estimates of the Mean Dynamic Topography (MDT), which in turn allowed the definition of the currents pattern in the Mediterranean Sea. Discussion on the obtained results and on the possible sources of noise and errors is provided in view of future and possibly more refined computations.

Keywords: Geomed2, geoid computation, Mean Dynamic Topography
Session: Session 4: Regional gravity field modelling and geophysical interpretation
Presentation preference: poster

Contribution of Very-High Degree Spherical Harmonic Coefficients to Selective Gravity Field Functionals at Known Benchmarks in Greece

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Over the past decade, spherical harmonic models, representing the Earth's gravitational field, have been evaluated to very high resolutions, reaching maximum expansion degrees of several thousands. However, at this degree range, the computation of the Associated Legendre Functions becomes challenging due to arithmetic underflow or overflow issues stemming from the limitations of standard floating-point arithmetic used in modern computer programming environments. To tackle this numerical problem, various methods emerged following different strategies, such as Extended Range Arithmetic, approximation techniques and computational approaches. All aforementioned techniques enable the computation of Legendre Functions at very-high degrees. In this study, we perform a comprehensive evaluation of the precision of these methods by evaluating selective gravity functionals and comparing them with real field data at known observation sites. At the same time, our objective is to adapt the aforementioned methods, so that they can be included into standard Spherical Harmonic Synthesis and Analysis algorithms. The calculation of various gravity field functionals is carried out over a network of control geodetic benchmarks in Greece, where GPS, levelling and gravity data is available.

Keywords: Spherical Harmonics, Legendre, Gravity Models, High Degree, Synthesis, Analysis

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral)

Effect of the differences between available DEMs on high-precision geoid modelling in the region of CERN

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For the realization of the Future Circular Collider (FCC), the planned next-generation particle collider at CERN, a quasigeoid with sub-cm accuracy is needed for the construction of the tunnel. In the (pre-)alignment phase of the components of the accelerator in the tunnel, a local geoid with a precision of 30-100 µm over a distance of 225 m must be computed.

In geoid modelling, digital elevation models (DEMs) are used to determine the topographic and downward continuation correction for the gravity observations performed on the surface. Therefore, an error in the DEM will have a direct impact on the geoid solution. In addition, DEMs are also used to determine the height of gravity data that was collected before GNSS was available to geolocalize the measurements. Furthermore, in the analysis for the calculation of a local geoid along the tunnel trajectory with a precision at the sub-mm level, a substantial amount of gravity measurements must be simulated by interpolation or prediction, utilizing again the DEM information.

In the region of CERN, several DEMs are available, which vary in geographical extent, grid size, precision, and accuracy. The characteristics are mainly driven by the acquisition method, which ranges from national elevation data, optical stereo reconstruction, LiDAR, to InSAR, or a combination of these methods.

In this study, firstly, differences between the available DEMs and relative differences between neighboring points of these DEMs are examined. Secondly, the vertical accuracy of the DEMs in the region of CERN is analyzed using GNSS levelling points. Thirdly, the effect of these differences on the terrain and downward continuation correction, on the interpolation of surface gravity measurements and on the resulting geoid height are assessed and compared to the requirements.

Keywords: regional geoid model, digital elevation model, gravity, CERN

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference: Oral presentation

Investigations of height system combination towards the evaluation of the Hellenic Vertical Datum

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The Hellenic Vertical Reference Frame (VRF) is a classic vertical datum tied to the zero-level of the Piraeus tide gauge mean sea level (MSL) (MSL from 1933-1978 with no data between 1948-1951) and delivers Helmert-type orthometric heights. It relies on leveling and geodetic benchmarks (BMs) which were connected with sprit and trigonometric levelling during several campaigns spanning from 1963 to 2004, while the latest nationwide adjustment by the Hellenic Military Geographic Service (HMGS) has been conducted in 1989. Moreover, Greece comprises of ~6000 islands and isles of which ~2000 are inhabitant, with each one realizing practically its own VRF, through either a TG station or by setting a conventional zero at some reference geodetic BM. Given that the geodetic BMs in Greece belong to so-called Map Leaflets (MLs) (387 for both mainland and the islands), that also realize the old Hellenic horizontal reference frame, and in order to guarantee consistency both horizontally and vertically within the same ML, local adjustments of the vertical network, per ML, have been performed. Given the above, it is apparent that the Hellenic VRF does not realize a single and consistent surface, as local realizations within each ML exist and the VRFs of the islands do not conform to the VRF of the mainland. With the above in mind, the present work focuses on an evaluation of the Hellenic VRF per ML, and the identification and minimization via parametric fit of the possible biases and tilts within neighboring and regional MLs. Geodetic and levelling BMs per ML have been identified, where both GNSS and levelling data are available, selecting for each at least four to six BMs. For those BMs, the latest combined global geopotential models form GOCE, GRACE, GRACE-FO have been employed to deliver geoid heights and investigate the fit between the triplet of heights, finally employing XGM2019e to d/o 2160. This work has been carried out for all MLs, investigating the height fit with various parametric models, ranging from simple north-south tilt to polynomial ones. The investigation was also done regionally, following the regional levelling traverses carried out by HMGS in the last ~50 years for the realization of the Hellenic VRF. As a result, local parametric fits are investigated and conclusions are drawn on both the biases and tilts between neighboring MLs, regional parametric corrections to be implemented as corrector values for the minimization of errors and recommendations for the Hellenic VRF realization through a modern geoid-based vertical reference system.

Keywords: Physical heights, Hellenic Vertical Datum, Height Reference Frame, homogenization, parametric models

Session: Poster Session 1

Presentation preference (Poster)

Comprehensive In-orbit Performance Evaluation of Quantum Sensors Onboard Future Satellite Gravity Missions

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Recent advances in cold atom interferometry (CAI) have paved the way for space applications of quantum accelerometers, a type of sensor that utilizes the principles of quantum mechanics to measure acceleration. These quantum accelerometers, whose level of stability is expected to increase dramatically with the longer interrogation times accessible in space, are proposed for future satellite gravity missions. They are particularly strong in providing long-term stable and precise measurements of non-gravitational accelerations. However, their limitations due to the low measurement rate and ambiguities in the raw sensor measurements demand the hybridization of quantum sensors with classical ones (e.g. electrostatic) with higher bandwidth.

In this study, a comprehensive in-orbit model is developed for a Mach-Zehnder-type cold-atom accelerometer. Performance tests are realized under different assumptions, and the impact of various sources of errors on instrument stability is evaluated. A roadmap for improvements in atom interferometry is provided that would maximize the performance of future CAI accelerometers, considering their technical capabilities. Moreover, we perform a Kalman-filter-based hybridization simulation by considering the full impact of rotation, gravity gradient, and self-gravity on the instrument. Finally, we investigate the impact of implementing a hybrid accelerometer onboard a future gravity mission on the gravity solution and the produced global gravity field maps.

This work is supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) Collaborative Research Center 1464 "TerraQ" – 434617780 and Germany's Excellence Strategy – EXC-2123 "QuantumFrontiers" – 390837967, and by the European Union's Horizon Europe research and innovation programme under grant agreement No 101081775 (CARIOQA-PMP project). This study is also partially supported by the SpaceQNav project funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK), Project 50NA2310A. QB and FP acknowledge the support of a government grant managed by the Agence Nationale de la Recherche under the Plan France 2030, with the reference "ANR-22-PETQ-0005." B.T. acknowledges support from the Federal Ministry for Economic Affairs and Climate Action (BMWK), Project 50NA2106. J.M. and A.K. acknowledge support by Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) for the project Q-BAGS (Project-ID 50WM2181).

Keywords: Cold Atom Interferometry, Quantum Accelerometers, Hybrid Accelerometers, Future Satellite Gravity Missions

Session 2 (Co-organized with the IAG QuGe Proect): Novel technologies in terrestrial, airborne and satellite gravity field determination

Presentation preference: Oral

What is a DOI and why should I bother to use them?

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With the ongoing digitalization and the development of new methods for data-driven science, together with increasing demands for open science, the availability of well documented data in machine-readable formats is increasingly required. The wide range of application areas of gravity field and related mass distribution and mass transport data in geodesy, geophysics, hydrology, oceanography, glaciology and climatology indicates their relevance and in the same time the necessity to provide them in citable form to allow the provision of proper credit and attribution for the data producers and their institutions.

The assignment of digital object identifier (DOI) can provide such credit and additionally support data discovery in the internet. The registration of a DOI requires the provision of at least a minimum set of descriptive metadata in machine-readable form (following international standards) that complements disciplinary, contextual metadata and documentation. The objects assigned with DOIs are persistently archived at the respective data repository, and data and software publications with DOI are fully citable in scholarly literature.

Since 2019, the GGOS Committee on DOIs for geodetic data is developing recommendations and guidance for the consistent use of DOIs for geodetic data across all services of the International Association for Geodesy (IAG). DOI services for gravity field data related to the IAG Services ICGEM, IGETS and ISG were among the first to be developed and are now widely used by the community. This presentation will provide an overview on existing DOI minting activities for gravitational data, address challenges and benefits. It will also look deeper into the metadata properties that can and should be used for data assigned with digital object identifiers and especially how these can digitally make the connection between data, software and scholarly literature.

Keywords: digital object identifier (DOI), metadata standards, geodetic data, data discovery, GGOS Commitee on DOI for Geodetic Data

Session 6: Data management, dissemination of results and networking of stakeholders

Presentation preference: Oral

GNSS and Gravity Measurements at Tide Gauges in Greek Territory

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The Hellenic Vertical Frame in Greece encompasses multiple reference surfaces due to its geographical complexity as an archipelago. Determining a mean geopotential (W0) for the Greek territory requires integrated measurements along its coastline. This study presents measurements conducted by the Hellenic Military Geographical Service, between 2019 and 2022 at 19 tide gauges across the country. These tide gauges, managed by the Hydrographic Service of the Hellenic Navy, recorded data on mean sea level. Extensive measurements were carried out at these locations using GNSS receivers, accompanied by simultaneous gravity measurements, to ascertain the absolute gravity value, referred to National Gravity Station, at each tide gauge. Analysis of the collected data revealed significant variations in mean sea level and W0 values within the Greek territory, reflecting underlying geodynamic changes.

Keywords: Greece, Geopotential, Gravity, Tide gauge, GNSS, Hellenic Vertical Frame

Session 1

Presentation preference Poster

Hellenic Geodetic Networks

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The Hellenic Military Geographical Service (HMGS), among other responsibilities, serves as the co-authoritative body (in conjunction with the Hellenic Cadastre) for the creation, maintenance, and management of the nation's geodetic networks. Established in 1889, the Service initially collected measurements with the objective of mapping the country. The measurements for the current geodetic infrastructure of the nation commenced in the 1950s. These measurements encompass, among others, the triangulation, leveling, gravimetric, and geomagnetic networks of the country. The Service provides geodetic data to interested parties (for a fee), although demand has waned in recent decades. The Service's objective is to identify the need for the digitization of the original measurements to preserve its historical archives and to develop longitudinal datasets that can be extensively utilized by other scientific disciplines and society at large.

Keywords: Greece, HMGS, Networks, Gravimetric, geomagnetic, levelling, triangulation

Session 6

Presentation preference Oral

Gravity field determination by the space-wise approach in quantum future mission studies

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Quantum technology is becoming more and more popular in science and applications, and the possibility of equipping a future satellite mission with quantum sensors with the aim of retrieving the Earth's gravity field is closer to became reality. Nowadays, numerical simulations play a primary role for assessing instrumentation performances as well as possible mission scenarios. Different processing strategies can be used for this purpose. Among them, the space-wise approach is mainly based on a least-squares collocation scheme involving the estimation of gridded values to adapt the noise filtering level to the local characteristics of the static and time-variable gravity field. This approach is inherently devised for local/regional solutions, but it can also be applied for global modelling by patching overlapping regional solutions all over the world and then performing a spherical harmonic analysis. In this work, the application of the space-wise approach to different mission studies based on quantum technology is presented. In particular, gradiometry missions with the possible inclusion of atomic clocks (MOCASS and MOCAST+ studies funded by ASI) as well as low-low satellite-to-satellite tracking missions with several pairs of satellites with different orbit inclinations (QSG4EMT study funded by ESA) were investigated. Although the quantum accelerometer has a lower error power spectrum at low frequencies than its electrostatic counterpart, the superiority of low-low satellite-to-satellite tracking with respect to gradiometry in detecting time variations of the Earth's gravity field was confirmed, unless the gradiometer error could be pushed down to the microEötvös level, which is currently quite an unfeasible technological target. Furthermore, numerical simulations by the space-wise approach for the high-low satellite-to-satellite tracking CARIOQA pathfinder mission (funded by EU) will be presented. Although the on-board instrumentation performances seem to envisage a limited improvement of the current knowledge of the gravity field, this study is particularly interesting because the mission will be actually launched in the next years and will be the first test in orbit for a quantum accelerometer.

Keywords: future satellite gravity missions, CARIOQA pathfinder mission, time-variable gravity field, space-wise approach, numerical simulations

Session 3: Static and time-variable global gravity field modelling

Presentation preference: Oral

Consistent pointwise determination of new geopotential numbers in a levelling-assisted regional IHRS realisation

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A common global vertical reference frame for physical heights is essential for many applications, such as studying and monitoring climate-related changes within the Earth system. The International Height Reference System (IHRS), defined by the International Association of Geodesy (IAG) in 2015, provides a global reference for physical heights. On a regional or local level, it is an option to realise IHRS using a combination of GNSS, a gravimetric (quasi)geoid model and precise levelling observations. A previous study has shown that this so-called levelling-assisted realisation has the potential to significantly improve the standard pointwise GNSS-based method in case a properly weighted least squares adjustment is made. This can result in a dense IHRF solution with reduced standard uncertainty. However, new pointwise GNSS-based geopotential numbers determined afterwards will then not agree with the already existing levelling-assisted realisation due to the smoothing obtained by the low relative uncertainty of levelling over short distances. In this contribution, we study this bias and how to construct a correction model to be applied to newly determined pointwise geopotential numbers to improve their agreement with a weighted levelling-assisted IHRS realisation.

Keywords: correction model, IHRF, IHRS, levelling-assisted realisation, levelling observations

Session 1: Reference systems and frames in Physical Geodesy

Presentation preference: Oral

The space-wise approach for regional solutions with simulations of future satellite gravity missions

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Future satellite gravity missions, like NGGM/MAGIC or other ones based on quantum technology, are promising to provide data allowing for time-variable gravity field investigations with higher accuracy and spatial-temporal resolution than those based on GRACE and GRACE-FO data. In this context, the question arises whether a sequence of global solutions in terms of spherical harmonic coefficients is still a good option to estimate local signals that have a stronger amplitude than the global average and, therefore, may be inferred with a higher spatial resolution. The space-wise approach applied to satellite gravity data processing provides a possible answer to this question. This method basically consists of two steps in the framework of a remove-restore procedure. Firstly, a global spherical harmonic solution by least-squares adjustment is computed. Then, a regional grid prediction by collocation is performed on residuals, thus refining the global solution by exploiting the local characteristics of the gravity field. In performing the latter task, a crucial role is played by the modelling of signal and noise covariances that should be empirically driven by the observations and cannot be done by neglecting the temporal aliasing due to the gravity field variations during the analyzed time span. The method also provides an estimate of the full error covariance matrix of the grid values, which may be useful for subsequent investigations. This matrix is computed by formal error covariance propagation, and it is a-posteriori rescaled according to Monte Carlo simulations. In this work, the processing scheme of the space-wise approach for regional solutions is presented from the methodological point of view and then applied to simulated data of future gravity missions to show the possible improvement of a regional solution with respect to a global one, considering as an example the estimation of the total water storage anomaly in terms of equivalent water height for some hydrological basins of interest.

Keywords: future satellite gravity missions, space-wise approach, equivalent water height grids, global vs. regional solutions, numerical simulations

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference: Oral

Recent activities of the International Service for the Geoid and implementation of a new database for regional geoid models

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The International Service for the Geoid (ISG), hosted by Politecnico di Milano in Italy, is an official service of the International Association of Geodesy (IAG). Its activities are coordinated by the International Gravity Field Service (IGFS) and are related to the IAG Commission 2 on Gravity Field. The ISG provides access to a comprehensive repository of geoid models through its website, most of them with an open access. In this archive, the latest releases of the most important and well-known geoid models, as well as less recent or less known ones, are available.

In this work, the conversion of the current geoid repository into an actual database is presented. This allows for a more structured storage of the available geoid models, introducing attributes, metadata and relationships among them. The database was developed by PostgreSQL in the framework of a WordPress website. The latter acts as front end to access and visualize the stored models by means of some predefined queries, providing users with an easier data fruition. Furthermore, the capabilities of the PostgreSQL database can be extended by PostGIS to better exploit the geospatial nature of the available information.

All the stored models are indexed by WoS Data Citation Index and some of them, under author request, are also labelled with a Digital Object Identifier (DOI) improving interoperability and reusability. The DOI service is currently running in cooperation with GFZ Data Services in the framework of the GGOS committee on “DOIs for Geodetic Data Sets”. DOI and WoS Data Citation Index are introduced as attributes of each model into the database.

Besides the model collection, validation and redistribution, the most important activity of the service at the educational level is the organization of international schools on ”The Determination and Use of the Geoid”. The latest was held in Buenos Aires (Argentina) from 13th to 17th November 2023 with more than 30 students, mainly from South America. A short report of this school is also given in this presentation.

Keywords: IAG services, geoid models, geoid schools, database, website

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference: Poster

Future satellite gravity field missions - Towards a direct time-variable parametrization

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The limited achievable temporal resolution poses one of the main limitations of current satellite gravity field missions such as GRACE and GRACE-FO and is, eventually, responsible for temporal aliasing. Increasing the temporal resolution is thus one of the most important tasks for future satellite gravity field missions. This, however, can only be achieved by means of larger satellite constellations since the temporal resolution can basically be defined as the time needed to achieve a global observation coverage. This needed (retrieval) time scales linearly with the number of satellites: e.g., a twopair mission such as the upcoming ESA next generation gravity mission (ESA NGGM) can easily achieve global coverage with sufficient spatial resolution within less than a week. For a hypothetical 6-pair mission, even an independent daily retrieval is feasible.

Future missions will hence allow to sample the gravity field in much shorter intervals. However, until now, the parametrization of the gravity field within these intervals usually only accounts for a static behavior, resembling a step function in the time domain. Obviously, such a behavior is unnatural and does not follow the actual progression of the gravity field. So, even if sufficient temporal resolution would be available, temporal aliasing will not be fully mitigated due to this misparametrization. In this contribution, we will thus investigate the impact of a direct time-variable parametrization through continuous spline functions. On the example of fictive multi-pair missions, we show how such a spline parametrization with daily support points can be applied: firstly, we prove that the spline parametrization allows numerically stable and correct solution based on a closed loop scenario. Secondly, based on a more realistic scenario with a higherresolution temporal gravity signal, we also highlight the practical limitations of the spline approach for smaller constellations and present some strategies to minimize the impact.

Keywords: future satellite gravity missions, gravity field parameterization, temporal aliasing, satellite-to-satellite tracking, orbit design

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral)

Comprehensive Geomagnetic Measurement Campaign for Accurate Magnetic North Declination Mapping in Greece

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This study presents a comprehensive overview and preliminary results obtained from the analysis of a geomagnetic measurement campaign undertaken in Greece aiming at producing an updated, densified version of the Magnetic North Declination Map of the country. The expedition encompasses consequent visits to 94 repeat stations of the National Geomagnetic Network by the Hellenic Military Geographical Service in the time span 2015 through 2022.

The methodology adopted for data collection, quality control and processing of the raw data is thoroughly discussed, whilst the emphasis is placed on data internal accuracy assessment and associated alignment procedures taking into account the latest global models of magnetic north declination and its variation. In addition, the study discusses the steps required for constructing the Magnetic North Declination Map, including the generation of isogonic and isoarithmic curves representing the annual variation of declination. To this effect, he proposed methodology involves leveraging advanced geodatabase schemata whilst adhering to stringent cartographic standards, ensuring overly that the final product is both precise and user-friendly.

In conclusion, the outcome of this study provides valuable insights into the characteristics of the geomagnetic field in Greece that, by extension, are expected to contribute to variant application areas relying on accurate geomagnetic data, such as aerial navigation and geophysical studies.

Keywords: Greece, Physical Geodesy, Geomagnetic Field, Declination, Aerial Navigation

Session 1

Presentation preference: Poster

The correction for the pole tide in the International Terrestrial Gravity Reference Frame and in the International Terrestrial Reference Frame

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The correction for the solid Earth pole tide in the International Terrestrial Gravity Frame (ITGRF) refers to the International Terrestrial Reference System (ITRS) pole. This is a continuation of the formula adopted already in the International Absolute Gravity Basestation Network (IAGBN) processing standards in 1988. It has guaranteed that all modern absolute-gravity results are consistent in this respect.

In the International Terrestrial Reference Frame (ITRF) the treatment is different: 3-D positions are corrected using a pole reference that evolves with time and approximates the secular or low-frequency polar wander, as specified in the conventions of the International Earth Rotation and Reference Systems Service (IERS Conventions). Different models have been used: versions of the “mean pole” up to IERS Conventions (2010) and to ITRF2014. The current model is the “secular pole” adopted in the 2018 update of the IERS Conventions and in ITRF2020. The secular pole is now also used in the pole tide correction to geopotential, e.g. in GRACE processing.

These discrepancies need to be considered in some situations, e.g. when gravity change rates in the ITGRF are compared with vertical velocities in ITRFxx. I discuss the size of the discrepancies, harmonization strategies, and correction formulas.

Keywords: ITGRF, pole tide, ITRF, ITRS pole, secular pole

Session 1

Presentation preference: oral

The recent activities of the ICGEM Service in 2022 - 2024

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International Centre for Global Earth Models (ICGEM) has been continuing its activities as one of the five services coordinated by the International Gravity Field Service (IGFS) of the International Association of Geodesy (IAG). In 2016, the ICGEM portal has been renewed to guarantee a smooth transition for future developments concerning FAIR data and sustainable data archives. The last remaining component of the previous ICGEM portal, the G3 Browser, has been upgraded and integrated into the new ICGEM Service. The G3 Browser (http://icgem.gfz-potsdam.de/g3) aims to compute time series of equivalent water height interactively and gives users the opportunity to compare different gravity model time series as well as impacts of corrections (e.g., GIA, C20) or filters. The G3 Browser is of educational importance and complementary to existing services such as GFZ's GravIS portal which provides ready-to-use products based on GFZ and COST-G solutions with already applied corrections and filters. On the other hand, the ICGEM G3 Browser includes time series from further processing centres and institutions and different filtering options.

Recently, ICGEM has included simulated models (http://icgem.gfz-potsdam.de/sl/simulated) in its archive that are relevant to future gravity mission studies. The available simulated Level 2a models are from the ESA's MAGIC simulation studies and they are the first of their kind on the ICGEM Service. Monthly and weekly series of different orbital configuration scenarios have been made available on the relevant pages together with the links to the publications provided by the authors.

As requested by users over the years, ICGEM improved the representation of the computed results conducted via the calculation service. The results can now be saved for each user, shared with others and can be downloaded in different formats, namely ICGEM Format, XYZ Ascii, GeoTiff, and Surfer 7 Grid formats. Moreover, a new practical tool has been added to the calculation service which helps to compute the differences of gravity field functionals calculated based on two different selected models. This is useful not only at a global but also at regional scales comparisons.

Finally, a new project, SAMDAT (Service and Archive for Mass Distribution And mass Transport data), funded by the German Research Foundation will be realized during the next three years which aims to expand the ICGEM service based on FAIR (Findable, Accessible, Interoperable, Reusable) data and a sustainable data archive principles. Three new colleagues will join the ICGEM team during the next 3 years.

Keywords: ICGEM, Global gravity field models, GGMs, gravity field functionals, FAIR gravity data

Session 6: Data management, dissemination of results and networking of stakeholders

Presentation preference (Poster)

Improving the Spatial Resolution of GRACE Data for Localized Studies: A Case Study on Sri Lanka Using a Moving Window Ratio Algorithm

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The Gravity Recovery and Climate Experiment (GRACE) and its follow-on mission, GRACE Follow-On (GRACE-FO), have fundamentally transformed our understanding of Earth's gravitational field and its anomalies, opening new frontiers in hydrology, climatology, and geophysics. By tracking the movement of mass within the Earth's system, these missions have provided insights into critical environmental concerns, including water resource management, ice sheet fluctuations, and the broader impacts of climate change. The low-degree harmonics of GRACE data are integral for understanding large-scale geophysical events due to their stability and resistance to temporal noise and aliasing, making them valuable for tracking long-term changes in the Earth's gravity field. However, the spatial resolution of these low-degree GRACE models is insufficient for detailed analyses over smaller regions, such as Sri Lanka (65,610 km²). This limitation restricts the applicability of GRACE data for localized studies, which are vital for targeted environmental and geophysical research. To address this limitation, we developed a method to enhance the spatial resolution of GRACE data using a moving window ratio algorithm. The approach involves interpolating observed gravity data (48 points) to a finer resolution (0.05 degrees) and using this interpolated data to refine the coarser resolution (0.25 degrees) GRACE-only model (GGM05s). Specifically, each 5x5 grid of interpolated observed gravity data is used to calculate the ratio with the corresponding GRACE model cell. This ratio grid serves as a multiplication factor, enhancing the single GRACE grid cell into a more detailed 5x5 grid. The results show a significant improvement in the accuracy of the enhanced GRACE gravity data compared to the observed gravity data, with 45 out of 48 points showing the best agreement. The enhanced model demonstrated increased accuracy in mountainous regions compared to the 0.05-degree GGM05s model grid provided by the ICGEM calculation service. These findings indicate that the moving window ratio algorithm effectively improves the spatial resolution and accuracy of GRACE data for localized geophysical studies. This enhanced resolution is crucial for detailed environmental and geophysical research in regions with complex topography, such as Sri Lanka.

Keywords: GRACE, Gravimetric Observations, Spatial Resolution, GGM05s Model, Sri Lanka

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral/Poster)

Theoretical Application of Chronometric Levelling: A qualitative and quantitative accuracy analysis

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The study focuses on the analysis of the parameters involved in determining the accuracy of orthometric height differences with chronometric leveling. The methodology concerns the utilization and adoption of the principles of the general theory of relativity in the corresponding theory of heights of classical geodesy. Particularly the analysis of the parameters is focused both on those related to the application part of the methodology and on those related to the optical atomic clocks that will be used for the observations. In order to obtain correct results regarding the application of the methodology, and after an extensive literature research, specific parameters were established which will be used as key factors for the theoretical comparative analysis. These parameters were fundamentally distributed into two main categories according to the type of effect they will have on the final accuracy of the determination of orthometric heights. The categories include the constant parameters and the variable parameters. The parameters regarding the chronometric levelling methodology are 1) Measurement - observation of physical quantities and 2) Communication of remote measuring devices. Respectively, the parameters regarding the optical atomic clocks are 3) Category and type of atomic clock, 4) Transportation and portability of atomic clock systems and 5) Typical manufacturing details of atomic clocks. Each of the parameters affects in a different way (qualitatively and quantitatively) the final accuracy. The qualitative analysis refers to the general comparative ranking of the parameters, while the quantitative to the specific. The purpose of creating the two different analysis is to obtain a ranking of the parameters both with criteria related to the practicality and applicability of the methodology, and to study sources of errors that may affect the application of the methodology. The qualitative characteristics studied correspond to the main sources that determine the supply and demand relationships between the necessity of implementing the methodology and its current applicability. In this context, basic criteria are defined, where the scale of their observance is controlled by each parameter, acquiring certain weights. Accordingly, the quantitative characteristics studied, regard both the application of the methodology and the use of optical atomic clocks. In this context, a model is defined that is expressed with a scale of grades, which results in a function (equation) with which its contribution to the overall result can be calculated for each parameter separately.

The purpose is to find a procedure to determine the total contribution of all parameters to the final frequency determination accuracy. Following the mathematical model of the chronometric spatial leveling methodology, this uncertainty will be converted into the final accuracy of determining orthometric heights. Conclusions about the theoretical application of Chronometric Levelling are provided by creating alternative scenarios for the simulation of measurements. The scenarios are structured in such a way as to reflect real-world conditions and typical questions that will be generated when using the methodology. Main scope to using all the

analysis referred in this study, in the end, will be that each user would be able to decide which is the appropriate measurement system to achieve the desired orthometric heights accuracy.

Keywords: chronometric levelling, relativistic geodesy, accuracy & precision, optical atomic clocks, qualitative and quantitative analysis

Session 02

Presentation preference (Poster)

Preliminary results on the new Hellenic Geoid 2024 in support of a geoid-based VRF

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The determination and availability of national, high-accuracy and high-resolution, gravimetric geoid model is considered as a fundamental part of the geodetic infrastructure. This is more than even important since especially nowadays engineering projects, climate change adaptation and sustainable developed mandate for a coherent and unified geospatial information system that relies on sound geodetic grounds. In Greece, several attempts have been made, during the last 50 years, to determine local, regional and national geoid models, utilizing various data sources (from deflections of the vertical to combined models with local, marine, airborne gravity and GOCE gradiometric observations) and different methodologies (from integral to stochastic and spectral ones). Nevertheless, the determination of a national geoid model stemming from a combination of all available data sources form the main geodetic institutes and the Hellenic Military geographic Services(HMGS), has not been realized thus far. With the above in mind, and the various problems of the Greek Vertical Reference Frame, it was deemed necessary to originate and effort to compile a unified gravity database for the country, using historical and recent land and marine gravity data, and determine a Hellenic Geoid 2024. This geoid, will be a solely gravimetric one model, which will server also as a reference surface for the proposal of a new geoid-based Greek VRF. Given that, work has been initiated to compile, homogenize, validate and blunder-prove a gravity database for the Hellenic territory. In this work we report preliminary results from the gravity database generation, homogenization and blunder detection and removal. Moreover, the generation of a national digital terrain model to be used for the calculation of topographic effects during geoid modeling is reported, along with some first results of the data reduction and validation, employing the well-known remove-compute-restore method and the latest GOCE, GRACE, GRACE-FO Global Geopotential Models.

Keywords: Gravimetric geoid, Height Reference Frame, homogenization, parametric models.

Session 1: Reference systems and frames in Physical Geodesy

Presentation preference (Poster)

COST-G: status and new developments

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The Combination Service for Time-variable Gravity fields (COST-G) provides monthly gravity fields of the GRACE, GRACE-FO and Swarm missions, combined from the individual solutions of the analysis centers (ACs). With the inclusion of the Chinese ACs in the reprocessed COST-G GRACE RL02 combination, COST-G became a truly global initiative. We present validation of the new GRACE RL02 and report on the status of the operational GRACE-FO combination and the challenges related to the permanent switch to the relaxed attitude mode and the approaching maximum of the solar cycle. The monthly gravity fields derived from orbit observations of the Swarm satellites also suffer from the agitated ionosphere condition due to the increased solar activity, but the combination turns out to be stable even under these difficult conditions.

Keywords: GRACE, GRACE-FO, Swarm, Gravity, Combination

Session 3: Static and time-variable global gravity field modelling

Presentation preference (Oral)

Analysis of Extreme Flood Events Using GRACE-FO and SAR Data: A Case Study of Short-Term Flood in Thessaly, Greece

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Extreme weather events have increasingly resulted in significant disasters, impacting human life and economic development. Recently, short-term floods have caused substantial damage worldwide. Such was the case of the catastrophic flood that struck the region of Thessaly, Greece, in September 2023. In this study, we investigate the application of Earth Observation satellite data for mapping flood events, focusing on the catastrophic flood that occurred in Thessaly. Our analysis was divided into three main components. Firstly, we utilized post-event satellite images from the Sentinel-2 platform, filtered by area of interest (AOI) and date range, with a constraint of less than 20% cloud cover. The Normalized Difference Water Index (NDWI) was applied to identify water bodies in optical imagery, serving as a reference for subsequent flood mapping methodologies. Secondly, we employed Sentinel-1 Synthetic Aperture Radar (SAR) data from pre- and post-event acquisitions. SAR images underwent edge masking and were merged to generate two mosaics. Flooded areas were detected by identifying regions with low backscatter values, specifically where the VV band exhibited values below a threshold of -17 in post-event mosaics relative to pre-event counterparts. Visual inspection confirmed the accuracy of flood detection against Sentinel-2 imagery. Lastly, we integrated GRACE-FO GSM Coefficients (GFZ RL06) to derive Liquid Equivalent Water Thickness (EWT), representing water thickness per grid cell. Despite the spatial resolution limitation of monthly GRACE products, EWT effectively captured spatial characteristics during short-term flood events. Simulating water level rise involved calculating flow direction, accumulation, and depressions using SRTM DEM data. The water spread simulation incorporated EWT values, modeling water movement and accumulation across terrain. This approach considered filled depressions and flow dynamics, providing a realistic representation of flood scenarios by accounting for terrain elevation and water volume. Modeled flooded areas closely resembled the spatial extent of the actual event, although volumetric accuracy was constrained by the spatial resolution of GRACE mission data. With the upcoming Mass-Change and Geosciences International Constellation (MAGIC) mission though, it is expected to achieve higher spatial resolution at shorter time series. This advancement will enable near-real-time observation and monitoring of extreme events like those that occurred in Thessaly, significantly enhancing our ability to detect and manage such disasters.

Keywords: terrain modeling, SAR, Sentinel-1, Sentinel-2, GRACE-FO, MAGIC

Session 5: Gravity for climate, atmosphere, ocean and natural hazard research

Presentation preference (Poster)

Corrective surface over northern part of Algeria based on EGM2008/RTM geoid model as support the geodynamical applications

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Algeria is one of the most seismically active areas in the Mediterranean basin capable of generating low- to highintensity earthquakes, particularly along the boundary between the African plate to the south and the Eurasian plate to the north and therefore requires an accurate and continuous vertical reference surface for geodynamical applications. In Algeria, the lack of dense and accurate gravity data has restricted the production of precise geoid model. The only attempt for gravimetric geoid determination have been done through the combination of global models with the available scattered and few gravity data from only BGI database. The results are not accurate enough to support the GPS levelling technique (Benahmed et al., 2009). So in the framework of this work, the recommended RTM approach (Hirt et al., 2010) for modelling the high-frequency gravity field (omission error) in area without sufficient regional gravity data coverage like Algeria, is investigated to improve geoid information from global geopotential model EGM2008 for the construction of a new vertical reference surface in the northern part of Algeria for further conversion of the geodetic heights into orthometric ones. For this investigation, the global model EGM2008 on which we applied RTM reduction to restore the high-frequency gravity field using the 2D lateral density variations model and a homogenous and precise GPS/levelling network, were used. The reference surface needed for the RTM reduction has been constructed by two ways; by means of a moving average applied to the DEM based SRTM data and from DTM2006.0 spherical harmonic model of Earth's topography developed to spherical harmonic degree 2160. A comparative study was carried out between them. The least-squares Collocation technique in iterative process has been used to determine the relationship between the GPS/levelling and EGM2008/RTM based geoid model. Several models for the corrector surface and different local covariance function and prediction techniques for the generation of the continuous surface from the discrete GPS/levelling data have been assessed, and the approach has also been used to detect outliers in the GPS/levelling data.

According to our numerical results, this study shows that the effect on the EGM2008 based geoid model using the 2D lateral density variations model ranges from 0 to 13cm and remains significant for a precise geoid determination with centimeter level. In our test area, the comparisons of the EGM2008 only with the GPS/levelling data showed standard deviations of 8.5cm and 5.5cm before and after fitting using the linear trend as corrector surface, respectively. Augmentation with RTM omission error estimates reduced its standard deviation to 2.0 cm after fitting. These results demonstrate that applying RTM omission error estimates to EGM2008 based geoid model improves the geoid modelling by almost 63.5 %.

The EGM2008/RTM based geoid model shows an improvement in precision and reliability than the latest local and African tested geoids models. In addition, the analysis of the results shows that the signals in GPS/ levelling benchmarks are dominated by errors in the EGM2008 geoid model due to the inaccurate and sparse local land gravity data incorporated in its establishment, while the noise level indicates the presence of errors in national vertical datum.

Keywords: Corrector surface, EGM2008, Residual Terrain Model (RTM), Omission error, 2D lateral topographic mass density model

Session: Poster Session 4

Presentation preference (Poster)

Evaluation of GOCE/GRACE based Global Geopotential Models over Algeria with Collocated GPS/Levelling Observations and new local terrestrial and airborne gravity data

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Since 2000, the era of dedicated satellite gravity missions such as CHAMP, GRACE and GOCE has revolutionized our knowledge on the Earth's gravity field and its variations in time. This paper focuses on the comparison between the latest GOCE's GGMs with new local terrestrial and airborne land gravity data over Algeria never used in previous assessments and some of precise GPS/leveling-derived geoid heights. In addition to the tested GOCE-based GGMs, we also include three others GGMs models; GRACE-only GGM (GGM05S), the satellite combined solution (GOGRA04S) and EGM2008, in order to identify improvements of the current knowledge of the Earth's gravity field coming from the new GOCE-based models. Therefore, some a-priori filtering model should be applied first to the terrestrial point data, before they are compared to the corresponding quantities obtained from the tested GGM.

This is done in order to tune the validation data within the same spectral bandwidth provided by the GGM (Gruber, 2004). The EGM2008 model was used for the estimation of the omission error. Based in our evaluation, it is remarkable that by adding GOCE data to the combined a-priori model a significant improvement for the tested terrestrial data can be observed with respect to GRACE. The global geoid accuracy obtained from the comparison of geoid heights computed from these models with independent information from GPS-levelling points, is at the level of 6.5 cm at degree and order 200.

This indicates that the objectives of mission of 1–2 cm geoid accuracy with 100 km resolution, have not been reached yet. Further improvement should be expected with upcoming releases of GOCE-based GGMs.

Keywords: GOCE/GRACE-based GGMs models, Omission error, Airborne gravity data

Session: Poster Session 3

Presentation preference (Poster)

Effect of Implementing Moho Depths on Precise Height Datum Determination for Africa

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The coverage of gravity data is crucial in the geoid determination process, particularly in regions with sparse data, such as Africa. This paper examines the impact of incorporating Moho depths in the gravity reduction process to achieve optimally smoothed reduced anomalies for a precise height datum determination in Africa. This work is conducted under the IAG Sub-Commission on gravity and geoid in Africa. Recent advances in Moho models, which integrate seismic, gravity, and satellite data, provide new opportunities for enhancing geoid accuracy. Several Moho models were tested, ultimately leading to the creation of a composite model for Africa.

This model was derived using least-squares interpolation, trend remove-restore, and covariance function fitting techniques. The window remove-restore technique was also applied. Three scenarios for implementing Moho depths were investigated: (1) assuming a constant density contrast between the lower crust and upper mantle, (2) assuming a variable density contrast calculated using the mass balance principle between topography and Moho depths, and (3) using plate loading theory to generate Moho depths. The best results were obtained with a constant density contrast assumption.

Comparable results were achieved with the variable density contrast approach.

Keywords: height datum, geoid, Moho depth, gravity, Africa

Session 4: Regional gravity field modelling and geophysical interpretation

Presentation preference (Oral)

Reprocessing, validation and homogenization of historical marine gravity data from the southern and eastern Baltic Sea - the BalMarGrav project

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The BalMarGrav project, co-funded by the European Union program Interreg Baltic Sea Region 2021-2027, aims to improve the insufficient mapping of the gravity field in marine areas of southern and eastern Baltic Sea region. This task is critical due to the decision of the Baltic Sea Hydrographic Commission (BSHC) to implement a common height reference system called the Baltic Sea Chart Datum 2000 (BSCD2000), which will be based on a geoid model determined by gravity measurements of the Earth. A uniform datum in the Baltic Sea region will allow to improve satellite navigation on vessels, in particular the monitoring of under-keel clearance, thereby optimizing their routes, reducing fuel consumption and pollution. National geological surveys and marine geophysical explorationcompanies are also interested in the results of the research conducted during the research.

In the decades of 1960s, 1970s and 1980s, multiple marine gravity campaigns were conducted in the coastal areas of Germany, Poland, Lithuania, Latvia and Estonia, mainly with the support of the research infrastructure of the Soviet Union. After becoming independent from the Soviet Union and the political transition of former Eastern Block countries, much of this data was forgotten or underutilized. Because gravity measurements at sea following modern standards are very costly and timeconsuming, during the BalMarGrav project, an international network of experts from the Baltic Sea region is being built to reconcile and standardize historical gravity marine data.

During the presentation, validation and homogenization of historical marine gravity data in modern geodetic and gravimetric reference systems, allowing these data to be harmonized with the current surveys of the gravity field in the Baltic Sea region, will be presented.

The BalMarGrav Working Group: Tobias Bauer, Mirjam BilkerKoivula, Przemysław Dykowski, Artu Ellmann, Orjan Josefsson, Jānis Kaminskis, Jan Kryński, Tobias Nilsson, Per-Anders Olsson, Tomasz Olszak, Eimuntas Kazimieras Paršeliūnas, Jerzy Pyrchla, Krzysztof Pyrchla, Olga Rosowiecka,

Joachim Schwabe, Gabriel Strykowski, Małgorzata Szelachowska, Jakub Szulwic, Arkadiusz Tomczak, Sander Varbla, Monika Wilde-Piórko, Vents Zuševics.

Keywords: gravity anomalies, historical data, Baltic Sea, maps

Session: Poster Session 6

Presentation preference (Poster)

The Greek National Small Satellite Programme and its Data Eexploitation Framework

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The Greek National SmallSat Programme is a key initiative within the Greek Strategic Plan for Space, aimed at enhancing Greece's capabilities in satellite technologies and applications. This programme seeks to foster the use of space data by Greek authorities and facilitate European cooperation through shared infrastructure and data exchange. Key applications include secured connectivity, space situational awareness, STEM education, agriculture, forest management, water resources management, maritime surveillance, safety and security, and land coverage.

The programme encompasses the development of CubeSats for secured connectivity and multi-application demonstrations focusing on the national capacity building, the establishment of Hellenic Assembly and Integration Test (HAIT) facilities for satellite assembly and testing, and the creation of an Optical Ground Station network to enhance European optical communication infrastructure. It also involves the construction of a radar tracking station for European space situational awareness, the deployment of radar and thermal infrared (TIR) satellites for disaster monitoring, the development of a metric optical multispectral & hyperspectral Earth Observation constellation in the VNIR & SWIR spectrum for diverse applications, and the formation of a governmental hub to manage and disseminate space data and services for public users.

The Greek National SmallSat Programme will significantly contribute to environmental mapping and monitoring, disaster management, agricultural efficiency, and national security, leveraging advanced satellite technologies to address critical national and regional needs. This initiative underscores Greece's commitment to innovation, collaboration, and technological advancement in the space sector.

Keywords: Greek National SmallSat Programme, CubeSats, radar and thermal infrared, optical multispectral & hyperspectra

Session 6: Data management, dissemination of results and networking of stakeholders

Presentation preference (Oral)

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