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Monday, 07/Sept/2026, 11:20am - 1:20pm

S1: Modelling of earth's dynamic

Session Chair: **Prof. Yoshiyuki Tanaka**

Session Chair: **Dr. Anna Klos**

11:20am - 11:40am

Towards reliable high-resolution GNSS-inferred estimates of TWS changes for Europe

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We use a dataset of daily vertical displacements observed by the Global Positioning Stations (GPS) antennae and provided by the Nevada Geodetic Laboratory (NGL) for stations located in Europe. We pre-process the time series thoroughly and correct them for the non-tidal oceanic and atmospheric loading using the estimates provided by the Earth-System-Modeling Group of the GFZ (ESMGFZ). We then divide these vertical displacements into three temporal scales: (1) from 2 days to 5 months, which we name as short-term temporal scale, (2) from 4 months to 1,4 years, which we name as seasonal temporal scale, and (3) from 1,1 years onwards, which we name as long-term temporal scale. For the latter one, the trend is modelled and removed from the estimates. Next, we use the high-resolution CLM5.0 hydrological model to classify individual GPS stations as benchmark datasets for hydrogeodesy across the three temporal scales mentioned above. We then use these unique datasets and estimate the Total Water Storage (TWS) changes using the inversion procedure for the number of 35 European river basins. We show that GNSS-inferred TWS changes on long-term and seasonal temporal resolutions agree well with the TWS estimates provided by the Gravity Recovery and Climate Experiment (GRACE) mission and GLWS (Global Land Water Storage) hydrological model, especially in the river basins, for which an efficient number of GNSS stations is guaranteed.

11:40am - 12:00pm

Differences in stochastic properties between IGS- and NGL-derived position time

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In this research, we examine the stochastic properties of the vertical position time series provided within the third reprocessing (repro3) by the International GNSS Service (IGS) and vertical position time series derived in a Precise Point Positioning mode by the Nevada Geodetic Laboratory (NGL). We selected 1019 globally distributed stations with good data quality and time spans longer than 5 years. We pre-processed them consistently and then standardized them in terms of length and data content to ensure consistency across the series. Then, we modelled them using annual and draconitic oscillation along with their overtones and inspected the differences between the parameters of the stochastic parts of time series. We noticed significant differences in both spectral indices and amplitudes of the power-law noise for the corresponding stations. The spatial patterns of these parameters also differ from one another, which we discuss in details in the presentation. One possible explanation for the observed differences could be different strategies of alignment to the reference frame, and in particular the alignment of the NGL series to the scale of the ITRF.

12:00pm - 12:20pm

Spherical Shape Functions for a Six-Node Tri-Rectangular Prism and an Eight-Node Quadrangular Right Prism

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We present the procedure to obtain exact spherical shape functions for finite element modeling applications, for generic prismatic spherical elements and for the case of spherical six-node tri-rectangular and eight-node quadrangular spherical prisms (Marotta et al., 2025).

The proposed spherical shape functions, given in explicit analytical form, are expressed in geographic coordinates, namely colatitude, longitude and distance from the center of the sphere. We demonstrate that our analytical shape functions satisfy all the properties required by this class of functions, deriving at the same time the analytical expression of the Jacobian, which allows us changes in coordinate systems.

Within the perspective of volume integration on Earth, entering a variety of geophysical and geodetic problems, as for mass change contribution to gravity, we consider our analytical expression of the shape functions and Jacobian for the six-node tri-rectangular and eight-node quadrangular right spherical prisms as reference volumes to evaluate the volume of generic spherical triangular and quadrangular prisms over the sphere; volume integration is carried out via Gauss–Legendre quadrature points.

We show that for spherical quadrangular prisms, the percentage volume difference between the exact and the numerically evaluated volumes is independent from both the geographical position and the depth and ranges from 10^{-3} to lower than 10^{-4} for angular dimensions ranging from $1^\circ \times 1^\circ$ to $0.25^\circ \times 0.25^\circ$. A satisfactory accuracy is attained for eight Gauss–Legendre quadrature points.

We also solve the Poisson equation and compare the numerical solution with the analytical solution, obtained in the case of steady-state heat conduction with internal heat production.

We show that, even with a relatively coarse grid, our elements are capable of providing a satisfactory fit between numerical and analytical solutions, with a maximum difference in the order of 0.2% of the exact value.

References

Marotta, Barzaghi, Sabadini, 2025, Math. Comput. Appl. 30, 88, <https://doi.org/10.3390/mca30040088>

12:20pm - 12:40pm

Stochastic gravity modelling of finite distributions

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Stochastic modelling of known distributions is a powerful tool for monitoring and understanding the Earth's dynamic system. The considered methodology converts polyhedral shape variations into gravity uncertainties, by applying the covariance propagation law. It involves the computation of variances in gravitational potential and its derivatives up to second order, that can be expressed as spherical harmonic expansions in both Cartesian and spherical coordinates. Shape variations are represented by a coordinate covariance matrix describing the vertex position uncertainty. The technique is versatile, since it can implement several uncertainty scenarios for the same distribution, by simply changing respective elements in the covariance matrix, while using the same harmonic coefficients. Various test cases are considered to demonstrate the applicability of the method, such as asteroids, synthetic finite distributions and the different layers of the Earth's interior extracted from current global digital databases. A special application refers to the representation of actual regional mass changes, for instance the gravity signal related to the ice melting of a mountain glacier. For validation purposes, the results are compared against a deterministic modelling of the corresponding shape changes, where numerical and analytical methods are considered for the computation of the induced gravity signal. The considered numerical method is the evaluation of gravity spherical harmonics for polyhedral sources, using a recursive technique and line integrals defined along polyhedral edges. The implemented analytical methods on the other hand involve closed expressions for the gravity signal of general polyhedra and right rectangular prisms.

12:40pm - 1:00pm

Extension of the Spectral Finite Element Method to Earth Deformation Caused by Tensile Cracks

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With the advancement of Global Geodetic Observing System (GGOS), Earth deformation over a wide range of spatial and temporal scales is being increasingly observed. Interpreting these observations and deriving geophysical implications requires appropriate physical models of the Earth. For relatively long-wavelength deformation, such as

glacial isostatic adjustment (GIA), spherical Earth models are commonly used. In contrast, deformation associated with earthquakes and volcanic activity is often modeled using half-space approximations.

However, future satellite gravity missions such as MAGIC mission are expected to capture broader-scale mass redistribution and deformation with improved temporal resolution. This highlights the need for modeling frameworks that can accurately represent volcanic and tectonic processes on a global scale.

In this study, we present a dislocation theory based on a spherical Earth model for accurately estimating deformation associated with volcanic activity. Compared with conventional half-space formulations, the spherical model enables rigorous treatment of self-gravitation and more accurate estimation of large-scale deformation. While previous studies using the spectral finite element method (SFEM) considered only shear dislocations, we extend the formulation to include tensile opening, allowing deformation associated with volcanic intrusions to be modeled.

Applying the method to Sakurajima, we find that the effect of self-gravitation on a single eruption is relatively small. However, depending on mantle viscosity, long-term differences may accumulate to levels detectable by geodetic observations.

1:00pm - 1:20pm

Exploiting Sentinel-1 burst overlaps for the reference frame connection of InSAR time series

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InSAR (Interferometric Synthetic Aperture Radar) enables the measurement of ground displacements with high spatial density over continental scales. A notable example is the European Ground Motion Service (EGMS), which provides displacement time series derived from Sentinel-1 acquisitions over Europe. However, InSAR measurements are intrinsically relative, and this characteristic, together with large-scale artifacts caused by atmospheric and orbital errors, complicates the connection of independent InSAR products to a common geodetic frame, particularly with solutions covering national or international scales.

Several approaches have been proposed to address this problem. While the theoretical relativity of InSAR measurements would only entail the estimation of a uniform bias, large-scale artifacts often require the estimation of a reference surface, typically represented by a low-degree polynomial. Current state-of-the-art solutions rely on spatial filtering combined with a dense GNSS network to reconstruct long-wavelength deformation signal. Other methodologies exploit overlapping areas between adjacent InSAR frames to connect independently processed scenes, often integrating overlap constraints with GNSS observations.

In this work, we present a methodology to connect uncalibrated EGMS displacement time series to the ETRF2000 reference frame. The proposed approach is based on the overlap regions between Sentinel-1 bursts and exploits the characteristics of the TOPSAR acquisition mode, which generates overlap areas in both range and azimuth while maintaining nearly identical acquisition geometry. A least-squares adjustment, formulated similarly to a levelling network, is used to estimate a single bias for each burst with respect to a selected reference burst. The resulting network provides a consistent reference frame across all bursts within a track, while the final connection to ETRF2000 is achieved through GNSS observations.

The quality of the solution is assessed through closure tests and comparison with the calibrated EGMS product. Unlike most existing approaches operating in the velocity domain, our methodology is implemented in the displacement domain. This allows the connection quality to be evaluated at each epoch, enabling the identification of temporal variations that would otherwise affect the entire time series. This characteristic allowed us to observe that the closure test residuals, typically below 1 mm during the early years of the time series, increase in the final year, reaching values up to 3 mm.

The current implementation focuses on single tracks and does not account for spatially variable corrections or acquisition-geometry differences. Future developments will address these limitations, aiming to provide a comprehensive multi-constellation reference frame connection methodology that combines overlap constraints and GNSS observations, operates in the displacement domain and compensates large-scale artifacts.

S2A: Geodetic quality/integrity modelling

Session Chair: **Prof. Peter Teunissen**

Session Chair: **Prof. Riccardo Barzaghi**

2:40pm – 3:00pm

Identifier-Constraints DIA: Towards Systematic Multi-Fault Identification in Geodetic Quality Control

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Quality control in geodetic estimation relies on statistical testing to decide whether observed misclosures are consistent with the null hypothesis or any alternative hypothesis, indicative of single or multiple faults. Candidate alternatives are the alternative hypotheses defined by the user, each representing a distinct fault source. Extending the candidate set by combining two or more candidate alternatives is conceptually straightforward, but in practice requires the user to manually enumerate all possible combinations, a task that grows combinatorially with the number of candidates and quickly becomes intractable.

This contribution introduces the Identifier-Constraints Detection-Identification-Adaptation (DIA), a flexible and non-iterative procedure that automatically searches over the full space of alternative hypotheses --- which may be any element of the candidate set, including multi-fault combinations of candidate alternatives --- without manual enumeration. The method is assessed through the quality of the DIA estimator and the associated testing decision probabilities. Numerical examples, supported by graphical illustrations of the probability density function of the DIA estimator and the corresponding DIA sample outcomes, demonstrate the gains achieved in the identification and adaptation steps using the Identifier-Constraints DIA method. In particular, ignoring multi-fault alternatives is shown to increase the probabilities of wrong identification significantly.

3:00pm - 3:20pm

On the choice of penalty functions and their effect on the probability of positioning failure

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Penalized testing theory enables the assignment of penalty functions according to a user-specified objective. In safety-critical positioning applications, the objective is to minimize the probability of positioning failure. Although the corresponding optimal penalty function is known, it depends on the hypothesized observational biases, which are often unknown in practice. Despite this drawback, it has been demonstrated that when the unknown biases in the optimal penalty function are replaced by their estimates, a substantial reduction in the probability of positioning failure is still achieved when compared to traditional approaches. Nevertheless, it is unknown whether this is the best one can do or whether alternative penalty functions exist that may improve performance further. In this contribution we will therefore investigate various choices of penalty functions for the bias-unknown case. Performance is assessed by comparing the resulting probabilities of positioning failure across different penalty functions in order to find the closest one to the theoretical optimum, when the biases are known. This includes a penalty function that maximizes the probability of correct hypothesis identification, thereby highlighting the advantages of the proposed penalty functions over the traditional testing.

3:20pm – 3:40pm

A simple TLS-Treatment of the partial EIV-Model as one with singular cofactor matrices, PART II: Surprising results for AR(3) Processes

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While the Errors-In-Variables (EIV) Model with singular cofactor matrices is of interest in its own right, it may also cover the important subclass of Partial EIV (PEIV) Models. In the latter case, it has been shown that published algorithms by both Snow and Schaffrin, used to find the Total-Least Squares (TLS) estimates within the EIV Model, can very well compete with the best from the PEIV-class, too. This is even the case when the extended cofactor matrix Q_1 remains singular. Under such circumstances, it may help to work with a symmetric nonnegative-definite matrix S and use it to form an extension of Q_1 that becomes nonsingular for suitable choices of S . After all, one may check the rank condition established by Neitzel and Schaffrin to confirm whether the TLS estimate exists and is unique. In this contribution, a third-order auto-regressive process is transformed into a PEIV-Model, resp. an EIV-Model with singular cofactor matrices. It is determined that a variety of choices for the matrix S does not markedly change the efficiency of Snow's, resp. Schaffrin's algorithms, but may generate a multitude of TLS estimates which do not always coincide (as they usually would). They also show different values for the Total Sum of Squared Residuals (TSSR); but the smallest TSSR may not automatically indicate the final TLS estimate as it has to be reproduced in one iteration step by all algorithms when used for the initial approximation.

Such behavior will be clarified in an illustrative example.

References

Jazaeri, S., Schaffrin, B., and Snow, K. (2024). A simple TLS-treatment of the partial EIV-Model as one with singular cofactor matrices I: The case of a Kronecker product for $Q = Q_0 \otimes Q_x$. In Freymueller, J. T., and Sánchez, L., editors, X Hotine-Marussi Symp. on Math. Geodesy, volume 155 of IAG Symp., pages 83–91, Cham, Switzerland. Springer Intl. Publ.; and all the references provided therein.

Monday, 07/Sept/2026, 4:00pm - 5:40pm

S2B: Geodetic quality/integrity modelling

Session Chair: **Prof. Peter Teunissen**

Session Chair: Prof. Riccardo Barzaghi

4:00pm - 4:20pm

The Mixed-Integer Misclosure Test in Spectral Form

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As a follow on of the methods of Fourier ambiguity resolution introduced in [1,2], this work develops the Mixed-Integer Misclosure Test (MIMT) in spectral form. The MIMT tests for misspecifications in the mixed-integer model and is constructed from the probability density function of its mixed-integer misclosure vector. Such models arise naturally in integer-constrained inference problems, such as those of carrier-phase GNSS and interferometry. In the carrier-phase GNSS context, the test provides a general framework for testing pseudorange outliers, carrier-phase slips, residual atmospheric biases, antenna or hardware biases, and other local or global departures from the assumed model.

This work develops several equivalent formulations of the MIMT, including spectral, and hybrid representations. In spectral form, the MLRT converts into a harmonic-analysis problem in which the dependence on the bias parameter appears efficiently only through phase shifts. A hybrid spatial-spectral formulation is also developed, which is particularly attractive in regimes where the precision of the integer ambiguities varies considerably. Therefore special attention is given to the computational advantages of the spectral and hybrid formulations. The spectral representation permits efficient repeated evaluation of the MIMT, fast maximization over alternative parameters, and low-rank approximations through truncation of high-frequency modes. These properties make the spectral MIMT especially suitable for large-scale Monte Carlo simulation, numerical calibration of critical values, and power-function analysis. The resulting framework establishes the spectral form of the MIMT as a probabilistically complete alternative to its spatial form and demonstrates how spectral methods provide both theoretical insight and major computational advantages for mixed-integer hypothesis testing.

References:

[1] Teunissen PJG (2026a): Fourier ambiguity resolution for carrier-phase GNSS. Applied Sciences, 2026, 16, 4089

[2] Teunissen PJG (2026b): Fourier ambiguity validation for carrier-phase GNSS. Sensors 2026, 26, 2201

4:20pm - 4:40pm

Advancing drought assessment in Europe through temporal-scale integration

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Europe is increasingly affected by the intensification of hydroclimatic extremes driven by ongoing climate change, with droughts emerging as one of the most critical and recurrent hazards. Over recent decades, both the frequency and severity of drought events have increased, leading to widespread impacts on water resources, agricultural productivity, and river discharge regimes. Thus, there is a pressing need for robust monitoring tools capable of capturing drought characteristics across Europe. Geodetic observations offer a unique and powerful framework for addressing this challenge. Techniques such as the GRACE and GNSS enable the direct observation of TWS variations and associated solid Earth deformation through measurements of gravity field changes and surface displacements, respectively. To overcome the limitations of both geodetic techniques, we calculate a Multivariate Drought Severity Index (MDSI) using the Frank copulas concept. Further, to get a better understanding of a particular drought type or category (e.g., meteorological or hydrological), drought onset, and how it develops, MDSI are determined for decomposed signals. We apply wavelet decomposition to estimate short-term, seasonal, and long-term components. The results highlight that decomposed MDSI reacts quickly to rainfall change, the seasonal water balance and storage-driven processes as well as clearly shows smooth progression and recovery of extreme (wet and dry) events far better than total MDSI series, enhancing utility of geodetic-based DSIs for climate research.

4:40pm - 5:00pm

From Vessel Tracks to Ocean Dynamics: Assessing AIS and GNSS Data for Local Marine Variability

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The estimation and characterization of both local and global ocean dynamics remain one of the key challenges for a variety of applications, including climate studies, coastal monitoring, navigation safety, and ship routing. Sea-state information is commonly obtained from in situ measurements based on sensors onboard, e.g., wave buoys and survey ships, limiting usable spatial and temporal coverage. More recently, advances in remote sensing have provided increasingly capable observations, utilizing, e.g., radar-based systems and satellite products, albeit these still suffer from relatively low resolution and accuracy compared to in-situ systems. Data recorded onboard commercial vessels could provide a complementary source of in-situ information for geodetic applications, given that such data would be recorded and publicly distributed.

This abstract presents a research concept for investigating the relevance and potential of AIS (Automatic Identification System) relayed vessel data for the estimation and interpretation of local environmental variables, including surface currents, sea-state conditions, and wind-related effects. AIS data transmitters are generally mandatory for vessels beyond certain sizes, with the aim of improving maritime safety. AIS data includes horizontal position, speed, heading, draught, and turn rate, which can be used for collision avoidance. However, these variables contain indirect signatures of the local ocean dynamics and other conditions and could be utilized for a variety of indirect analyses. Deducing sea conditions and other similar features from this data is assumed to be difficult due to the complex models required for the interaction between the vessel and the ocean. As AIS data records are becoming more available, the amount of data is reaching levels where machine learning methods could provide substantial results in addressing the modeling difficulties. The increasing amount of data could also enable detecting minute correlations between vessel movement and local conditions at a statistically significant level.

In contrast to ongoing research, which focuses on end-to-end robustness of various methods and on comparisons of independent references, this research aims to investigate the feasibility, accuracy, and temporal and spatial coverage of AIS-based data. Hence, the expected contribution is not the direct determination of specific variables, but rather the assessment of what could be achieved with these vessel-based observations and whether they can be utilized to address the inherent gaps in the currently prominent approaches. If such a framework can provide reliable correction, modeling, and quality-control solutions, a substantial number of ordinary vessels could be used as distributed observation platforms contributing to geospatial monitoring and as a reference system. Such analysis would also indicate development requirements for future AIS-type solutions.

5:00pm - 5:20pm

The first layer of the new Italian Gravimetric Database: challenges and a proposal for handling the historical gravimetric data

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The new National Gravimetric Service has recently been established in Italy, hosted at the Istituto Nazionale di Geofisica e Vulcanologia (INGV). Among its main responsibilities is the creation and management of a national gravimetric database. A key challenge is the recovery of historical data, essential for studying variations in the gravity field over time.

Italy holds a rich gravimetric heritage collected over nearly two centuries by the former Italian Geodetic Commission, but these data are scattered across heterogeneous sources and only minimally available in digital form, severely limiting their use within the scientific community.

To address this issue, an ongoing project aims to build a unified, open gravimetric database by integrating three data layers spanning from 1825 to the present. The first layer comprises 3,565 historical gravity measurements collected between 1825 and 1958. The original data were digitized from 111 pages of hard-copy official reports using an AI-assisted OCR pipeline and stored in a PostGIS spatial database, including 605 land stations and 2,960 marine stations.

All station positions were transformed into current reference frames (WGS84, RDN2008) and expressed in both geographic and cartographic coordinates along with orthometric heights, ensuring compatibility with modern datasets. Integrating historical gravimetric datasets into a modern geospatial framework poses two main challenges: transforming coordinates from obsolete geodetic datums, and accounting for variability in data quality due to differences in instrumentation and methodology over time. This contribution focuses on the first issue.

Positional quality was assessed by comparing orthometric heights from the original records with values extracted from the TINITALY 10 m Digital Terrain Model. The resulting difference ΔH served as a reliability indicator, with the threshold set at $|\Delta H| \leq 20$ m. For stations showing large discrepancies, alternative locations were sought using the GeoNames geographical database. Where these provided better agreement with recorded heights, they were adopted as revised coordinates. This procedure corrected over 100 stations, reducing the standard deviation of ΔH for the most problematic campaign (1901–1932) from 203 m to approximately 50 m. Reliability decreases markedly for stations on slopes exceeding 10° , with only 37.5% of stations on slopes above 30° meeting the reliability criterion. Finally, geoid undulations were computed using the EGM2008 model, enabling ellipsoidal heights referenced to WGS84.

The remaining two data layers — modern terrestrial surveys and ongoing airborne campaigns — will be integrated in the near future to complete a spatio-temporal model of gravity variation over Italy from 1825 to the present.

5:20pm - 5:40pm

Sensitivity of daily GNSS displacement estimates to processing-model configurations in the CyCLOPS regional network of Cyprus

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Millimetre-level GNSS displacement monitoring requires processing strategies that are not only accurate in a long-term reference-frame sense, but also highly repeatable from one daily solution to the next. This requirement is critical for landslide early-warning applications, where small apparent daily displacements may represent either real ground motion or processing-induced artefacts. It is also important for deformation products within the Cyprus Geohazard Observatory Supersite (CyGOS), a GEO Geohazard Supersites and Natural Laboratories (GSNL) Permanent Supersite that integrates GNSS, InSAR, and Earth Observation resources for geohazard monitoring in Cyprus. We investigate the sensitivity of daily GNSS displacement estimates to key double-difference processing-model configurations using the CyCLOPS regional GNSS network of Cyprus. CyCLOPS is the core geodetic infrastructure of CyGOS and operates an expanding network of permanent GNSS stations designed to support ground-displacement monitoring, geohazard studies, and modernization of the national geodetic infrastructure.

The analysis is performed with the Bernese GNSS Software using daily regional network solutions aligned to a common ITRF2020 secular reference frame. Several processing configurations are tested while keeping the main datum-definition strategy and core modelling standards consistent. The investigated configurations include alternative tropospheric modelling strategies, such as GPT3- and VMF3-based approaches; the application of non-tidal loading corrections either at the observation level or at the normal-equation level; and different numbers and spatial geometries of EPN/IGS reference stations used to supplement the CyCLOPS network.

The impact of these configurations is assessed at multiple temporal and geodetic levels. First, we evaluate the repeatability of daily coordinate differences, a direct indicator for deformation-warning applications. Second, we examine their influence on short-term weekly velocity estimates and on secular velocity determination. Third, we analyse the noise characteristics of post-fit velocity residuals to identify processing configurations that reduce artificial variability in the coordinate time series. Finally, we assess the implications for the densification of ITRF2020 in Cyprus through daily datum-quality diagnostics and the stability of the regional frame realization.

This work aims to identify processing configurations that provide the most stable and physically interpretable daily GNSS displacement estimates for Cyprus. The results are already supporting a GNSS-based landslide early-warning system operated by national stakeholders and contribute to the geodetic framework underpinning CyGOS and the forthcoming Cyprus Ground Motion Service (CyGMS). More broadly, they provide practical guidance for regional GNSS networks used in millimetre-level geohazard monitoring, reference-frame densification, and Earth Observation applications.

S3A: High-precision GNSS

Session Chair: **Dr. Dimitrios Psychas**

Session Chair: **Prof. Bianca Federici**

9:00am - 9:20am

Vectorial Decorrelation: a new perspective for Integer Ambiguity Resolution

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The resolution of carrier-phase ambiguities in GNSS mixed-integer models is fundamental for fully exploiting the millimeter-level precision of phase data. This integer ambiguity resolution (IAR) process has several applications, from precise point positioning to time transfer, as well as attitude determination and atmospheric remote sensing. In general, the ultimate objective is not the ambiguity solution itself, but the improvement on the real-valued (estimable) parameters of interest for specific users.

Moreover, in several GNSS models, ambiguities are often highly correlated thus requiring a re-parametrization of these ambiguities based on a so-called Z-transformation given an unimodular integer matrix Z , such that $|\det(Z)| = 1$. This is for instance adopted in the Least-squares AMBiguity Decorrelation Adjustment (LAMBDA) method, where an admissible Z-matrix is computed starting from a LTDL-decomposition of the ambiguity variance-covariance (vc-)matrix, then alternating permuting operations with Integer Gauss Transformations (IGTs). Still, these permutations take place on adjacent ambiguity components, thus quite limiting the decorrelation capabilities.

In this work we investigate the Vectorial Decorrelation (VD) principle, where ambiguity subsets, whether adjacent or non-adjacent ones, are considered when reducing the original ambiguity vc-matrix to decorrelate the ambiguities. In this process the L-D factors are modified accordingly via a direct computation and different criteria for this block Z-transformations might be considered, e.g. maximizing the precision of conditional ambiguities as well as reducing correlation between ambiguity subsets – highly beneficial for Vectorial Integer Bootstrapping (VIB) estimators.

We first demonstrate that L-matrix off diagonal entries can always be bound (in module) within 0.5 based on an easy-to-compute lower unit-triangular Z-matrix, then we focus on the ordering of ambiguity components, i.e. based on their conditional variances, which is also fundamental for partial ambiguity resolution (PAR) strategies when fixing carrier-phase ambiguities. Therefore, targeted insertions of non-adjacent ambiguity components can be exploited for constructing a PAR-suitable parametrization, e.g. based on the transformed L-D factors.

Lastly, in this work we extend the VD principle to the full vc-matrix of the estimates, thereby accounting for the correlation between the integer-estimable ambiguities and the real-valued parameters. This allows ambiguity transformations and selections of ambiguity subsets to be assessed also through their impact on the precision of real-valued parameters of interest or a specific subset. As a result, we can maximize the expected precision gain in a quasi-optimal way, ultimately establishing a direct link between ambiguity parametrization, partial ambiguity resolution, and the attainable precision of the target estimable parameters.

9:20am - 9:40am

Hierarchical Ambiguity Resolution approach using Vectorial Integer Bootstrapping for multi-GNSS PPP-RTK networks

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The integration of multi-system and multi-frequency Global Navigation Satellite System (GNSS) observations in the network estimation has led to a dramatic increase in ambiguity parameter dimensions, posing severe challenges to both computational efficiency and reliability of Precise Point Positioning-Real Time Kinematic (PPP-RTK) corrections. Traditional integer ambiguity resolution methods often struggle to balance computational efficiency with an optimal fixing performance in high-dimensional scenarios. To address this limitation, this study proposes a hierarchical ambiguity resolution approach based on the Vector Integer Bootstrapping (VIB) framework, denoted as VIB-HAR. Rather than applying a single estimator or discarding medium-quality ambiguities as pure float solutions, VIB-HAR stratifies decorrelated ambiguities into distinct tiers based on their formal precision. The method then adaptively

allocates Integer Bootstrapping (IB), Integer Least-Squares (ILS), and Best Integer Equivariant (BIE) estimators to these respective tiers. This VIBHAR strategy introduces the BIE estimator on less precise ambiguities to effectively bridging the gap between a strict integer fixing and pure float solutions, thus accounting for additional information from additional ambiguity components. Experimental validations using seven days of undifferenced and uncombined GPS, Galileo, and BDS-3 data demonstrate the significant advantages of the proposed method. On the network side, VIBHAR effectively mitigates the exponential growth of solution space complexity, achieving a high computational efficiency of 0.088 s, which significantly outperforms a full FAR-ILS (1.16 s) and PAR-ILS (0.86 s) methods. On the user side, network products generated by VIBHAR enable an average convergence time of 3.03 minutes, representing improvements of 19.3% and 21.4% over traditional ILS and IB methods, respectively. At the same time, in terms of mean 3D RMS errors, it performs similarly to the optimal ILS solution, while significantly outperforming traditional PAR strategies. Ultimately, the VIBHAR method exploits the MSE optimality of the BIE estimator on less precise ambiguities, while allowing computational feasibility that is nowadays required for a large-scale, high-dimensional PPP-RTK network processing.

9:40am - 10:00am

Beyond the Best Candidate in IAR: Solution Performance Bound when the True Ambiguity is not ILS Optimal

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Integer Ambiguity Resolution (IAR) is a fundamental component of GNSS-based high-precision positioning techniques such as Real-Time Kinematics (RTK) and Precise Point Positioning–RTK (PPP-RTK). Conventional IAR approaches, including the (M)LAMBDA method, rank integer candidates and validate only the best-ranked solution through statistical testing. Recent research has explored data-driven and Artificial Intelligence (AI)-based validation strategies to improve reliability under challenging environments and user dynamics.

However, most of these approaches remain focused on assessing the best-ranked candidate, thereby largely inheriting the limitations of single-candidate conventional validation. Due to model misspecification and biases, the highest-ranked candidate does not necessarily correspond to the true integer ambiguity vector, which may instead reside among lower-ranked solutions. Consequently, validation strategies restricted to a single candidate may reject the correct solution despite its presence within the candidate set.

This study investigates the impact of ambiguity mis-ranking on positioning performance and quantifies the potential gains achievable if the true ambiguity is correctly accepted within the leading candidate set. To quantify these achievable performance bounds, a Monte Carlo PPP-RTK simulation framework is developed in which probabilistic recovery of the true ambiguity from the top-n candidate set is modeled under controlled conditions. This enables isolation of the performance loss attributable specifically to ambiguity mis-ranking. From the trade-off analysis, upper performance bounds can be derived, independent of specific validation algorithms.

Utilizing this framework, the performance gap between conventional single-candidate validation and probabilistic recovery of the true ambiguity from the leading candidate set is evaluated in both static and kinematic PPP-RTK scenarios. The results quantify the performance degradation attributable to ambiguity mis-ranking and identify the recovery reliability levels required for multi-candidate strategies to outperform conventional validation. The derived bounds set performance targets for data-driven validation models and provide a benchmark for designing future ambiguity validation techniques, under GNSS stochastic model misspecification and bias mismodeling.

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10:00am - 10:20am

GLONASS FDMA PPP-RTK realization using integer-estimability theory

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Global navigation satellite system (GNSS) network processing constitutes the first component of the three-part structure underlying the integer ambiguity resolution-enabled precise point positioning (PPP-RTK) concept. Its role is to integrate GNSS observations collected over successive epochs across a network of reference stations and to process them with a

preferred S-system such that solutions of the estimable corrections become available to PPP-RTK users. Of the constituent corrections, the network-determined satellite phase biases are known to play the key role in making user ambiguities integer-estimable. This is however only possible when the fundamental PPP-RTK realizability condition is satisfied (Teunissen and Khodabandeh, 2022). While such condition has been shown to be always met for CDMA systems, the same cannot be said for their FDMA counterparts, such as GLONASS, the satellites of which do not transmit navigation signals on same frequencies. The present contribution aims to assess the network and user sufficiency conditions that enable GLONASS PPP-RTK under various setups, and to validate GLONASS ambiguity-resolved performance via network-determined phase biases. Numerical insights are provided based on the analysis of real-world GPS and GLONASS data from several IGS network and user stations.

Teunissen, P.J.G., Khodabandeh, A. PPP-RTK theory for varying transmitter frequencies with satellite and terrestrial positioning applications. *J Geod* 96, 84 (2022). <https://doi.org/10.1007/s00190-022-01665-2>

10:20am - 10:40am

A study on PPP advances by integrating existing GNSS with LEO-PNT

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Precise Point Positioning (PPP) processes undifferenced, multi-frequency phase and code observations from a single receiver and is widely adopted in scientific applications, achieving millimeter-level accuracy in daily processing of Continuously Operating Reference Stations (CORS). A key limitation of PPP remains the time needed to converge to a good solution, driven by the slow geometric variation of GNSS satellites relative to the receiver. This issue is further aggravated in urban environments, where reduced satellite visibility and degraded geometry can severely degrade performance or prevent convergence altogether. As a result, PPP for short-duration or kinematic sessions remains an open research challenge.

Low Earth Orbit (LEO) satellites, originally deployed for telecommunication and Earth observation, are increasingly being considered for Positioning, Navigation and Timing (PNT) applications. LEO constellations, orbiting at altitudes between 400 and 1500 km with periods of 90–120 minutes, exhibit a much faster geometric variation than GNSS, making them attractive candidates to reduce PPP convergence time and improve overall positioning performance.

This work investigates the integration of LEO-PNT signals with traditional GNSS observations within a PPP framework. GNSS data from existing CORS are combined with simulated LEO code and phase observations, derived from computed LEO orbital trajectories. A dedicated PPP software has been developed to jointly process real GNSS and simulated LEO measurements: the library is based on an Extended Kalman Filter (EKF) that supports both static and kinematic receiver models, both uncombined and ionospheric free processing. The configurations GNSS-only and GNSS+LEO are compared in terms of satellite visibility, PDOP, and convergence time, both in open-sky and obstructed scenarios. In addition to traditional performance metrics, such as RMS, std and bias, a consistency analysis based on three-sigma confidence bounds is performed by comparing positioning errors with the corresponding formal uncertainties derived from EKF.

Both IGS final and ultra-rapid ephemerides are tested to assess near-real-time applicability. Preliminary results are promising and the complete analysis will be presented at the conference.

Tuesday, 08/Sept/2026, 11:00am - 12:20pm

S3B: High-precision GNSS

Session Chair: **Dr. Dimitrios Psychas**

Session Chair: **Prof. Bianca Federici**

11:00am - 11:20am

BLUE-BLUP Iteration Method for Partially Observed Models

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In many estimation problems, only part of the considered observation vector is available. Classical approaches then reformulate the model in terms of the observed subset only, often requiring repeated restructuring of the design matrix, covariance model, and associated quality-control procedures. This becomes particularly cumbersome in large-scale, correlated systems such as Global Navigation Satellite Systems (GNSS), where missing observations arise frequently due to satellite blockages, cycle slips, receiver outages, or incomplete multi-frequency tracking.

This presentation introduces a BLUE-BLUP iterative (BBI) method for partially observed linear models. It is shown how the method yields the correct parameter estimates, while still preserving the original full-system model structure. An important advantage of the BBI-method is therefore that the estimation algorithm itself can remain fixed, independent of the actual pattern of missing observations. This makes it possible to “hard-wire” the complete-data estimation architecture directly into GNSS receivers and processing engines, without requiring repeated reconfiguration of the adjustment model whenever satellites, frequencies, or epochs are missing. Missing observations are instead handled internally through the BLUP prediction step, while the original estimator structure remains unchanged.

An important contribution is also that the BBI-method provides the correct quality description of the solution. Although the completed observations are deterministic predictions and therefore do not contribute independent information, the iteration operator itself contains the necessary missing-information correction. This leads to operator-based expressions for the correct covariance matrices, global model tests, and data-snooping statistics, without requiring explicit inversion of the observed-data normal matrix. The same iterative machinery used for the parameter estimation can therefore also be used for precision analysis and statistical testing.

The framework is particularly attractive for GNSS applications such as network RTK, PPP, atmospheric field estimation, ambiguity resolution, and cycle-slip handling, where incomplete observation vectors and strongly correlated stochastic models are intrinsic features of the problem.

11:40am - 12:00pm

Optimizing GNSS Sequential Filtering Efficiency: A Variable-Dimension Update Strategy Based on Sparse Coupling Characteristics

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With the rapid development of Global Navigation Satellite System (GNSS), the increasing number of available satellites imposes a significant computational burden on mass-market GNSS chips and smartphones with limited computing power. To address this challenge, this study proposes a novel Variable-Dimension (VD) update strategy by exploiting the inherent sparse coupling characteristics between parameters and observations in GNSS models. Unlike traditional filters that maintain full-dimensional state update throughout each epoch, the proposed VD strategy dynamically manages the state-space dimensionality to eliminate redundant numerical operations. This strategy serves as a versatile framework that can be seamlessly integrated into various Sequential Kalman Filter (SKF) variants, including the standard SKF, Square Root Covariance Filter (SRKF), and U-D factorization Filter (UDF). In this work, the VD strategy is specifically implemented within the UDF framework, yielding a Variable-Dimension UDF (VD-UDF). To evaluate its performance, the VD-UDF is compared with the standard UDF, the KF in information form (KF-I), and the Square Root Information Filter (SRIF). Numerical results and time-efficiency analyses demonstrate that the VD-UDF achieves superior processing speed compared to these industry-standard benchmarks without compromising positioning

accuracy or numerical stability. Consequently, the VD-UDF offers a highly time-efficient solution for real-time, high-precision GNSS positioning on resource-constrained platforms.

12:00pm - 12:20pm

Methodological Aspects of Combining GNSS-derived Geocenter Motion: Preprocessing and Parameterization Strategies

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Accurate and internally consistent estimates of geocenter motion are essential for terrestrial reference frame realization, time-variable gravity field recovery, and the interpretation of large-scale mass redistribution in the Earth system. Despite their importance, geocenter estimates derived from different space geodetic techniques and analysis strategies still exhibit substantial inconsistencies, particularly in separating physically meaningful signals from technique-specific artifacts. This problem is mainly affected by network geometry and orbital artifacts such as draconitic signals.

Therefore, this contribution focuses on the technical and methodological aspects of combining geocenter motion time series, with an emphasis on estimates from GNSS-based geocenter series from the third International GNSS Service reprocessing campaign. Particular attention is given to preprocessing strategies required before combination, including temporal homogenization, detection and treatment of data gaps, removal or preservation of offsets and trends, spectral consistency checks, and handling technique-dependent seasonal and draconitic signatures. Several parameterization strategies are investigated within an iterative variance component estimation framework, including stochastic model definition, weight initialization, outlier thresholds, and convergence criteria. The analysis evaluates how preprocessing choices made during the data preparation stage affect the stability of the combined geocenter series, relative weights assigned to input series, and the recovery of annual and semi-annual signals.

The study serves as a methodological preparatory step towards a consistent multi-technique combination framework for geocenter motion and selected low-degree gravity field coefficients, focusing on assessing preprocessing steps and parameterization choices in combination methods. The results are intended to support identifying an optimal, broadly applicable parameterization within a given method, with robust default settings that apply across varying input configurations. Furthermore, they clarify the technical limitations that must be resolved before combined geocenter and low-degree gravity products can be reliably used for reference-frame realization and geophysical applications.

Tuesday, 08/Sept/2026, 1:40pm - 3:20pm

S4: Machine and Deep Learning in Geodesy

Session Chair: **Dr. Lotfi Massarweh**

1:40pm - 2:00pm

Learning-Based Reliable Integer Ambiguity Resolution for GNSS: A Contrastive Deep Neural Approach

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Reliable ambiguity resolution (RAR) in precise positioning GNSS is performed through the class of the Integer Aperture (IA) estimators. IA estimators accept the integer solution provided by (M)LAMBDA, if it meets a predefined quality criterion, such as passing a ratio test (RT) or achieving a certain confidence level in Fixed Failure-Rate Ratio Test (FFRT). However, these approaches rely on heuristic thresholds or model-dependent assumptions and are limited to validating only the best-ranked candidate.

Recent work has explored data-driven and AI-based validation to improve reliability; nevertheless, these approaches remain restricted to single-candidate evaluation and trained through Generative Learning (GL) or Discriminative Learning (DL). The former requires data modeling distribution, thus requiring good model assumptions for realistic data generation, while the latter learns a signal from individual data samples one at a time, hence increasing the computational complexity of learning.

This study proposes an AI-based IAR sub-module that reformulates ambiguity validation as a learned decision problem using Contrastive Learning (CL). The proposed approach evaluates multiple integer candidates jointly, enabling the model to distinguish between correct and incorrect ambiguity solutions by exploiting relative relationships within the candidate's set data. In this way, ambiguity validation is no longer restricted to a single candidate, while also leveraging the structure of the Integer Least-Squares (ILS) optimality.

The model consists of a deep neural encoder that learns contrastive representations of ambiguity candidates, followed by a neural perceptor that maps these representations to acceptance decisions. From a geometrical perspective, the method learns a data-driven acceptance region in the ambiguity space, extending beyond the quadratic forms underlying conventional validation tests.

The AI-based IAR sub-module in its initial phase is trained only on Monte Carlo simulated PPP-RTK data and preliminary evaluated on real-world, static, multi-frequency and multi-constellation datasets. Preliminary results show comparable conditional success rate and reduced false alarms compared to RT and FFRT, while remaining compatible with existing IAR pipelines and enabling efficient multi-candidate validation.

This work was funded by the European Space Agency NAVISP programme under the activity NAVISP-EL1-071bis

2:00pm - 2:20pm

AI-Driven Accelerometer Data Transplantation for Next-Generation GRACE-like Satellite Gravimetry Missions

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Accurate and continuous monitoring of Earth's gravity field is fundamental for understanding mass redistribution processes associated with climate variability, hydrology, and solid Earth dynamics. Satellite gravimetry missions such as GRACE and GRACE Follow-On (GRACE-FO) have demonstrated the capability of low-low satellite-to-satellite tracking (LL-SST) to recover temporal gravity variations with high precision. However, the performance of these missions strongly depends on the quality of the sensors like the accelerometer (ACC) used to determine non-gravitational forces, where conventional electrostatic accelerometers (EA) exhibit limitations in long-term stability and noise behavior.

This study investigates ACC data transplantation as a practical strategy to enhance ACC performance in GRACE-like and future satellite gravimetry missions. The approach aims to reconstruct and transfer non-gravitational acceleration signals between satellites in different constellations, without requiring high-end sensors on each satellite. We evaluate multiple mission configurations differently equipped with ACC, including classical EA systems, quantum-based Cold

Atom Interferometry (CAI) accelerometers, and hybrid EA–CAI architectures, using closed-loop LL-SST simulations. A particular focus is put on artificial intelligence (AI)-driven methods, where machine learning models are employed to learn cross-satellite relationships and reconstruct degraded or missing ACC observations.

Our results demonstrate that AI-supported ACC transplantation significantly improves signal reconstruction and gravity field recovery, achieving performance levels comparable to dual high-precision sensor configurations. In particular, hybrid configurations combined with machine learning provide a robust and cost-efficient alternative to fully instrumented systems, reducing mission complexity while maintaining high accuracy. Furthermore, the integration of quantum accelerometers offers promising potential for enhancing low-frequency stability, which is critical for next-generation gravimetry missions.

The findings highlight the strong potential of combining AI, data-driven signal reconstruction, and quantum sensing technologies to advance satellite gravimetry. This work supports the development of future GRACE-like missions with improved accuracy, reduced cost, and increased system resilience, enabling more reliable monitoring of Earth's dynamic gravity field.

2:20pm - 2:40pm

The Dual Estimation Problem in Geodetic Regression: Comparing Adjustment, Bayesian Inference, and Machine Learning for TLS Uncertainty Modeling

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Geodetic regression always involves a dual estimation problem: determining both the functional model — the relationship between observations and target quantities — and the stochastic model — the statistical characterization of the observation uncertainties. Classical adjustment treats these two components sequentially: parameters are estimated via weighted least squares under an assumed variance–covariance structure, which is then refined through variance component estimation. Bayesian inference resolves the duality jointly by encoding prior knowledge about both functional and stochastic parameters and estimating a full posterior distribution via Markov chain Monte Carlo. Machine learning, by contrast, dissolves the duality differently: it learns the stochastic model itself — predicting observation uncertainties or error distributions as functions of covariates — while the functional model may remain physically specified.

This contribution provides a structured comparison of these three paradigms through the lens of the dual estimation problem, applied to a single engineering geodesy scenario: the modeling of systematic distance deviations of a terrestrial laser scanner as functions of intensity, incidence angle, range, and surface properties. In the classical approach, a parametric regression model is fitted by least squares with analytic covariance propagation. In the Bayesian approach, the same parametric structure is estimated with informative priors, yielding full posterior distributions over both model parameters and predictive uncertainties. In the machine learning approach, gradient-boosted regression and deep learning architectures (PointNet) learn the error structure directly from data, achieving higher predictive flexibility but without closed-form uncertainty propagation.

The comparison is structured along four criteria rooted in geodetic inference theory: (a) calibration and coverage of the predicted uncertainties, (b) the ability to propagate uncertainty into subsequent processing steps, (c) robustness to model misspecification, and (d) physical interpretability of the estimated quantities. We argue that the three paradigms are not competitors but complementary strategies addressing different facets of the dual estimation problem: classical adjustment provides analytical traceability, Bayesian inference quantifies parametric uncertainty coherently, and machine learning captures nonlinear structure that resists explicit modeling. The contribution concludes with criteria for deciding when each strategy — or their integration — is appropriate for uncertainty-critical geodetic regression tasks.

2:40pm - 3:00pm

Trustworthy AI for Geodesy: Faulty Training Data Detection

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Artificial intelligence (AI) is playing an increasingly important role in modern geodesy and is widely applied in high-precision positioning and navigation, deformation analysis, and gravity field estimation. However, a key challenge in achieving trustworthy AI for geodetic applications lies in the quality of the training data used to develop these models. In practice, training data are rarely error-free and may contain various types of faults, including mis-tagged time-series

events, human annotation errors, instrument-induced jumps mislabelled as physical signals, and incorrect feature information. Such faulty training data can introduce systematic bias, reduce model stability, and lead to unreliable predictions, making data quality control as critical as model design itself.

This presentation introduces a taxonomy of fault labels and examines their impact on model performance. Furthermore, two methods for detecting faulty training data—based on loss-function fitting and temporal consistency checks—are proposed. Their effectiveness is demonstrated through numerical analysis in the context of regional GNSS ionospheric modelling and prediction.

3:00pm - 3:20pm

Bathymetry Prediction from airborne gravimetry by Tikhonov Generalized Inversion – case from Greenland airborne quantum gravimetry

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Fjord and coastal bathymetry is a key boundary condition for ocean modelling, general bathymetric mapping, and climate-change-related studies, particularly for marine-terminating glaciers in Greenland, where many fjords remain poorly surveyed. In this talk, we present bathymetry inversion in the Nuuk Fjord system of southwest Greenland, using airborne cold-atom quantum gravimetry data to recover fjord bathymetry in poorly constrained regions. We use an a priori bathymetry model, BedMachine, and refine the regional gravity background field using high-precision ground gravity observations on land. This background field is also used to stabilize the inversion near fjord margins. A Tikhonov generalized iterative inversion is then applied to the residual gravity field, with a systematic search for an optimal regularization parameter space. In addition, machine learning methods are introduced to support bathymetry prediction by learning nonlinear relationships between gravity-derived features, existing bathymetric constraints, and auxiliary geophysical data. Comparable machine-learning-based approaches for bathymetry prediction have been explored at both global and regional scales, with case studies including the South China Sea and Malaysian coastal waters. The recovered bathymetry significantly improves depth estimates in near-glacier regions where direct sounding data are sparse. The results demonstrate the value of airborne gravimetry, especially quantum gravimetry, for mapping fjord bathymetry in data-poor environments. This approach is also potentially applicable to estimating sub-ice-shelf bathymetry around Antarctica. More broadly, the study highlights the importance of gravity-based bathymetric inversion for climate research, including studies of ocean heat transport, glacier–ocean interaction, and the stability of marine-terminating glaciers.

P1: Poster session 1

Session Chair: **Dr. Ilaria Ferrando**;
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Session Chair: **Dr. Paola Salmona**
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Improving gravity field determination from future SLR satellites through optimized orbital inclinations: a Kaula theorem-based analysis

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Spherical geodetic satellites observed by satellite laser ranging (SLR) networks provide key information for geodetic and geophysical studies. At present, the C_{20} and C_{30} coefficients in the GRACE and GRACE Follow-On gravity field solutions are substituted with estimates obtained from SLR measurements. It should be emphasized that the sectorial coefficients belong to the group of parameters that are least accurately recovered in GRACE Follow-On gravity field models. Beyond supporting gravity field determination, SLR is also indispensable for estimating geocenter motion, which is required for GRACE data processing and for establishing the origin of terrestrial reference frames. In this work, we use Kaula's theory of gravitational perturbations to investigate the most suitable inclination angles for a prospective geodetic satellite mission. The objective is to enhance orbital sensitivity to low-degree gravity field coefficients through the application of inclination functions. Particular attention is given to identifying inclination values that both increase the sensitivity of orbital perturbations to gravity field coefficients and reduce parameter correlations, leading to more reliable estimates of low-degree and low-order gravity field coefficients. Our results show that carefully chosen inclination angle intervals can substantially improve the accuracy and quality of the recovered coefficients.

Safety Risk Assessment of a Sequential-Combinatorial DIA Estimator for Geodetic Displacement Monitoring

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In this contribution, we investigate, within the Detection–Identification–Adaptation (DIA) framework, the safety risk of a sequential-combinatorial post-selection procedure for geodetic displacement monitoring. The motivation is that such a procedure does not merely decide whether a displacement is present and which displacement model is selected; through adaptation, it also determines the estimate delivered after testing. Therefore, its performance should not be assessed only in terms of detection, identification, and false-alarm rates, but also in terms of the effect of the selected decision on the safety of the resulting parameter estimates.

We interpret the output of the sequential-combinatorial procedure as a DIA estimator induced by a data-driven sequence of model selections. In this sequence, a global test is followed by model identification, adaptation, and subsequent testing under an updated model. The selected displacement model is mapped into a common displacement-parameter space, allowing the adapted estimate to be assessed with respect to a user-defined safety region.

This formulation provides a basis for evaluating correct and incorrect identifications according to their estimation-level consequences. In particular, it enables the distinction between decision errors that remain practically tolerable and decision outcomes that may lead to unsafe adaptation. The proposed perspective extends post-selection displacement monitoring from decision-level performance assessment to safety-oriented risk evaluation of the adapted estimate.

Adaptation of theoretical measures of global robustness to squared Msplit(3) estimation

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Msplit estimation, as a modern estimation method, has found several applications in geodesy and surveying. One can list processing Light Detection and Ranging data, deformation analysis, detection of unstable points in Global Navigation Satellite System networks, direct identification of gross errors, S-transformation, robust coordinate transformation, linear regression analysis, marine navigation, and robust estimation. Therefore, robustness to outliers is a basic and desired feature of Msplit estimation. The general idea of the method in question requires consideration of robustness in two main senses: global and local. Hence, one should also consider two types of robustness measures. The general manner of describing robustness in these two senses was proposed in several papers; however, it applied to Msplit(2) estimation (where 2 refers to two competitive parameter versions). This paper presents a description of the global robustness of the squared Msplit(3) estimation and extends the application of existing measures by introducing their new forms. The analysis includes global breakdown points (GBdP), breakdown points in extended error intervals (GBdP-e), and tolerances for growing errors of observations (TGE). The results show that increasing the number of competitive parameters (from 2 to 3) complicates the description of the method's robustness. First of all, TGE and GBdP-e both depend on the mutual placement of competitive parameter values. It all means that the robustness of the squared Msplit(3) estimation is a much more complicated issue, which has significant implications for the expected behavior of the method in the presence of outlying observations, hence also for its practical applications.

On the rigorous combination of different types of GNSS networks in local scale

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Over the past 30 years, numerous studies have examined the establishment and processing of GNSS networks. The solutions obtained for such networks vary considerably, as there are many options involving either commercial or scientific software. For reasons of simplicity, commercial software often represents a convenient choice and can achieve good precision (on the order of a few centimeters). However, commercial packages typically do not reach the level of accuracy provided by scientific software.

In this study, we analyzed four different GNSS networks in the region of Drama, Greece. Three of these networks were processed before 2010 using commercial software, while one was processed with the Bernese software. The networks share a limited number of common stations, which are not uniformly distributed. Our analysis revealed several cases where inconsistencies among the common stations reached up to 15 cm, clearly indicating problematic solutions derived from the commercial software.

To address this issue, we implemented rigorous combination methods for the GNSS networks at two levels: first, at the level of the estimated GNSS baselines produced by the commercial software, and second, at the level of the Normal Equations (NEQs).

The results demonstrate a significantly improved level of consistency among the common stations—better than 1.5 cm—which can be considered adequate for surveying applications at a local scale.

Analysis of LEO+GNSS Short-Baseline Differential Positioning Performance

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The joint use of GNSS and Low Earth Orbit (LEO) satellites designed for Positioning, Navigation, and Timing (PNT) applications is investigated.

The primary LEO constellation evaluated is inspired by the ESA Celeste LEO-PNT in-orbit demonstrator mission; additionally, different scenarios inspired to existing or proposed LEO missions, also not primary dedicated to PNT applications, are examined. The analysis focuses on the impact of various parameters, including orbital altitude and inclination, carrier wavelengths, and the expected quality of measurement of LEO-PNT signals.

The analysis is based on a simplified observation equation model in order to best highlight the advantages of a rapidly changing satellite geometry and study the relative role of various components of the variance matrices. The role of ambiguity resolution and fixing is properly considered. When the hypothesis justifying the use of a simplified model no longer hold, eigenvalue decomposition of the ambiguity space can be considered for highlight the role of the geometry.

Realistic measurement quality is also incorporated, leveraging data from the recently launched, in-orbit CENTISPACE satellites. Analytical frameworks provide a general basis for the study, while numerical simulations yield practical insights for evaluating how the analyzed parameters affect PNT solution quality. The short-baseline differential positioning scenario is evaluated for clear sky satellite visibility and further investigated for classical engineering applications in urban environments, where buildings drastically reduce the number of visible satellites.

Assessing the Interpretability and Generalization of Multi-Layer Perceptrons in Regional Gravity Recovery

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Dense terrestrial gravity measurements are a fundamental prerequisite for high-resolution geoid determination. However, the acquisition of such data is often constrained by geographical, technical, and economic barriers, leading to large data gaps, non-uniform coverage and inconsistent accuracies across regional datasets. Traditionally, these gaps are mitigated using global geopotential models (GGMs), supplemented by auxiliary sources such as digital terrain models (DEMs). These methods often reach their limits in capturing localized non-linear signal variations in topographically complex areas.

This study explores the theoretical potential of Multi-Layer Perceptrons (MLP) as non-linear functional approximators within the context of gravity modeling. To ensure geophysical consistency, we implement a physics-informed feature space by utilizing global geopotential models (GGMs) as long-wavelength constraints, while high-resolution topographic descriptors from Digital Elevation Models (DEMs) provide the high-frequency signal content.

A primary focus is the interpretability of the learned mapping through Explainable AI (XAI). We employ feature importance analysis to investigate whether the MLP honors the underlying physical correlations between mass distribution and gravitational response. Specifically, we address: (1) which geodetic features facilitate reliable generalization in previously unseen regions, and (2) the sensitivity of the functional approximation to the spatial resolution and sampling density of the input features. The model's performance is rigorously assessed using a train/validation/test data splitting strategy, with results benchmarked against classical geodetic standards. By analyzing the residual statistics, we demonstrate that the MLP-based approach offers a solid theoretical framework for reconstructing high-frequency gravity field components while maintaining geophysical traceability.

Predicting Gravity Anomalies in Topographically Complex Terrain: Machine Learning and Least Squares Collocation Modeling in Central Macedonia, Greece

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The adoption of Artificial Intelligence (AI) and Machine Learning (ML) is reshaping geodetic research. Recognizing this transformative potential, the Global Geodetic Observing System (GGOS) aims to develop higher-resolution and more accurate geodetic products through the assimilation of complex, multi-source datasets. This study addresses a fundamental challenge in that respect, i.e., the precise determination of the gravity field and the local geoid in regions exhibiting extreme topographical and morphological variations. The Region of Central Macedonia (RCM) in northern Greece serves as a highly demanding study area for this purpose. Spanning from extensive coastal zones and the Chalkidiki peninsula to some of the country's highest elevations, the region's topography complicate gravity field modeling. Furthermore, achieving high-resolution gravity mapping in such terrains is frequently hindered by a severe lack of dense terrestrial data. Alternative acquisition methods, such as airborne gravimetry, remain prohibitively expensive, while the direct downward continuation of satellite gravity data (i.e. GOCE), hinder the inherent attenuation of the gravity field signal due to the satellite altitude, hence provide only a band-limited representation to the medium wavelengths (~up to 80 km). To address these limitations, this study develops and compares three gravity prediction strategies.. First, a conventional geodetic solution is produced using Least Squares Collocation (LSC) modeling, serving

as the reference baseline. Second, a pure ML method is implemented, in which gravity anomalies are predicted directly from spatial, topographic, and geological predictors. Third, a hybrid geodetic–ML strategy, where XGBoost regression is used to model local residual gravity anomalies after the removal of an independent long-wavelength reference gravity signal. The modeling uses a dataset of 16,117 irregularly distributed land gravity observations. To capture the complex physical realities of the region, the spatial coordinates and orthometric heights of these observations are integrated with high-resolution geological and lithological information provided by the Hellenic Survey of Geology and Mineral Exploration. To ensure an unbiased assessment, all three modeling strategies are evaluated using a common validation framework. A subset of the terrestrial gravity observations is withheld from model training and used exclusively for independent accuracy assessment. First, the predictive accuracy of the ML models is assessed directly against this reserved, independent subset. Second, to evaluate spatial continuity and interpolation performance, both the ML models and LSC are utilized to predict gravity anomalies on a regular grid covering the entire study area. A comprehensive comparative analysis of the resulting grids is then conducted to demonstrate if modern AI approaches perform worse against established geodetic baselines in topographically diverse environments.

Error-State Kalman Filtering versus Physics-Informed LSTM Networks for GNSS/INS Integration in Airborne Gravimetry

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Data fusion in airborne gravimetry is a critical process that requires multi-sensor integration of data from both an Inertial Navigation System (INS) and a Global Navigation Satellite System (GNSS). This study investigates and compares two alternative methods for GNSS/INS integration using real airborne data, comprising raw IMU and GNSS observations processed with the Precise Point Positioning (PPP) technique. The first approach follows a traditional methodology that implements a complete loosely coupled error-state Kalman filter (LC ESKF) for integrating high-rate IMU measurements with lower-rate GNSS observations. In this framework, inertial mechanization is performed in the local-level navigation frame (North-East-Down, NED), while position, velocity, attitude, and accelerometer and gyroscope biases are handled through a 15-state error model. The IMU provides continuous propagation of the navigation solution, whereas PPP-derived position and velocity updates are applied only at the common GNSS epochs, thereby avoiding the artificial use of interpolated GNSS values as independent measurements during data synchronization. Attitude is represented internally with quaternions to ensure stable propagation of the body-to-navigation transformation, and the estimated attitude is then used for lever-arm corrections and for transforming raw accelerations from the aircraft body frame to the navigation frame. Final velocities are derived from the GNSS/INS ESKF solution, while the final position is obtained from PPP interpolation corrected for the antenna-to-IMU lever arm. The second approach evaluates two distinct neural network architectures for the fusion of high-frequency IMU and low-frequency GNSS data. The first uses a purely data-driven Long Short-Term Memory (LSTM) network to predict trajectory error states directly from raw body-frame sensor data, requiring the model to implicitly learn complex spatial transformations. The second introduces a Physics-Informed Neural Network (PINN) framework, in which deterministic kinematic calculations - specifically Direction Cosine Matrix rotations and WGS84 lever-arm corrections - are applied prior to inference, offloading the geometric complexity from the network and thus allowing the LSTM to isolate and predict pure sensor noise for trajectory reconstruction. The resulting navigation and acceleration products from both methods are validated against reference data from the DALO Green Quantum project. The comparison focuses on the estimation of position, velocity, attitude, and acceleration, with attitude determination being one of the most challenging and critical steps for producing high-accuracy airborne gravimetry products.

A Representation-Learning Framework for Identifying Evolving Hydrological Regimes from GRACE & GRACE FO and ERA5

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GRACE and GRACE FO satellite gravimetry provide a unique record of terrestrial water storage anomalies (TWSA), integrating changes in groundwater, soil moisture, surface water, snow, and ice at basin scale. Yet, interpreting these

mass variations remains challenging because basin storage may respond rapidly to rainfall, react with delay to accumulated water deficits, or retain the effects of climate anomalies for several years. Existing machine-learning studies linking climate forcing to GRACE TWSA have largely focused on prediction, leaving further scope to interpret the learned relationships in terms of basin-scale storage processes. In parallel, many basin classification studies assign fixed climate labels, limiting their ability to represent time varying behaviour under droughts, wet extremes, groundwater depletion, and long-term climate variability.

This study proposes a representation-learning framework to characterize the evolving mass-storage behaviour of global river basins. The analysis is conducted at the HydroBASINS Level 4 scale, providing a practical compromise between the coarse resolution of GRACE and the finer spatial variability of ERA5 meteorological forcing. ERA5 variables and GRACE-derived TWSA are decomposed using a Stationary Wavelet Transform to separate short-term meteorological variability from slower storage responses and multi-year geodetic memory. Within 24-month rolling windows, a temporal convolutional autoencoder learns compact 16-dimensional representations of the coupled climate–storage behaviour of each basin. The learned latent space is used to identify hydrological regimes based on similarities in basin response. UMAP projection and K-Means clustering group basins with comparable mass-transfer characteristics. Because representations are generated through rolling windows, each basin can be followed through time, allowing the framework to distinguish persistent regimes from gradual migrations or abrupt shifts during droughts, wet extremes, or prolonged water-storage stress.

The physical relevance of the learned regimes is evaluated through three complementary analyses. First, climatological validation compares basin trajectories with documented droughts, wet extremes, and large-scale climate indicators, including ENSO and drought metrics such as SPEI. Second, physical consistency assessment examines whether each regime has a distinct and internally coherent climate–storage signature, using ERA5 anomalies, SPEI-based drought or wetness conditions, and GRACE-derived TWSA metrics. Third, regime transition analysis tracks how basin classifications change across successive 24-month windows, helping identify stable, gradually changing, and abruptly shifting storage behaviours.

Overall, this study offers a geodetic, data-driven basis for identifying evolving hydrological regimes and for assessing how basin-scale water-storage mechanisms respond to climate fluctuations and longer-term shifts in hydrological behaviour.

S5A: Geodesy: present state and future horizons

Session Chair: **Prof. Mattia Crespi**

Session Chair: **Prof. Domenico Sguerso**

9:00am - 9:30am

'New' and 'new-new' results on the convergence problem in collocation theory

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In physical geodesy, collocation theory is applied to the prediction of the anomalous potential of the Earth's gravity field, T . The predicted field belongs to a space that is harmonic down to a Bjerhammar sphere internal to the Earth's surface; that is, it is more regular than the actual T , which is harmonic only outside the Earth. The convergence of this approximated collocation solution to the actual anomalous potential, as the number of noiseless observations tends to infinity, has recently been revised and proved under quite general conditions by the authors.

Yet, in order to apply it to the case of a geodetic boundary value problem, too restrictive smoothness conditions had to be imposed on the data.

These new results are going to be published in the Journal of Geodesy.

Stimulated by the comments of one reviewer, further new results have been achieved by the authors. After analysing what can be considered realistic requirements on the data, we have found that the conditions on the regularity of the boundary, S , can be relaxed significantly, whereas the conditions on the regularity of the boundary data, namely gravity disturbances, cannot. This is the case if one wants to remain within Hilbert space theory. The analysis shows that a theory for Banach-space solutions of the boundary value problem, together with a Banach-space version of collocation, would provide the desired result. This has already been partly developed for Banach collocation theory in the machine learning community, where it is referred to as Banach Support Vector Machines. For us, this is clearly future work.

9:30am - 10:00am

Kalman filter from the geodetic point of view

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The problem of predicting the state of noise-driven dynamic systems, utilizing noisy observations at discrete time epochs, is studied as a global prediction problem where all epoch states are determined simultaneously, unlike the usual sequential approach Kalman filtering and smoothing.

Four different global solutions are presented depending on the treatment of the system at an initial epoch x_0 before the observations: (a) x_0 is an unknown random variable to be predicted, (b) x_0 is a deterministic unknown to be estimated, (c) x_0 is ignored and the state at the first epoch is a deterministic unknown to be estimated and (d) x_0 is an unknown random variable for which an outcome from the same realization as the observations is somehow available.

The global "geodetic" solutions do not require knowledge of the probability distribution of the system noise and the observation errors and are solely based on their (zero) means and their covariance matrices. The solutions follow from the straightforward application of standard results from either the random effects model (cases a and d) or the mixed effects model (cases b and c).

From the last solution (d) simple matrix algebra without any additional statistical tools lead to the derivation of the Kalman filter and the Rauch-Tung-Stiebel smoothing algorithms. In addition, a simple sequential smoothing algorithm is obtained that also allows the determination of correlation (cross-covariance matrices) between all epoch errors of predicted states.

Finally, it is demonstrated that Kalman filtering is just an application of the general theory of sequential prediction, that parallels the well-known one of sequential estimation via the so called Kalman form.

10:00am - 10:30am

When Success Hides the Need to Understand

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Mathematical Geodesy in an Age of Data and Computing Abundance

Modern geodesy operates in an era of unprecedented data availability, computational power, and sophisticated software, making it increasingly easy to obtain successful results. Yet success does not automatically imply understanding, and abundant data can sometimes conceal limitations that only become visible under unfamiliar conditions. The presentation reflects on the changing role of theory in a data-rich environment to illustrate the risks of taking successful computation at face value.

Wednesday, 09/Sept/2026, 10:50am - 12:20pm

S5B: Geodesy: present state and future horizons

Session Chair: **Prof. Mattia Crespi**

Session Chair: **Prof. Domenico Sguerso**

10:50am - 11:20am

The International Terrestrial Reference Frame: Past, Present and Future

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After briefly reviewing some basic concepts regarding reference systems and frames—as well as the ways of representing a terrestrial reference frame for a deformable Earth—the presentation will outline the research and developments concerning the ITRF from the mid-1980s to the present day. Emphasis will also be placed on the international adoption of the ITRF for applications in Earth science, satellite navigation, and operational geodesy. The presentation will draw on key results from ITRF2020 and its updates, with a special focus on the uncertainty evaluation regarding the stability of the frame physical parameters (origin and scale), as well as Earth Rotation Parameters. Future developments aimed at improving the ITRF model updates and consequences for the most demanding user needs will conclude the presentation.

11:20am - 11:50am

Geoid and height anomaly: a possible summary on theory and estimation methods

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The geoid is a fundamental concept in Geodesy, and its definition and estimation methods have been extensively investigated over the years. Nowadays, the geoid can be determined with an accuracy of the order of 12 cm. Moreover, global geoid models are available in spherical harmonic representation up to very high degree and order (e.g., degree/order 5540). Also, time-varying gravity field solutions derived from satellite missions such as GRACE and GRACE-FO are available on a monthly basis.

These advances have had a significant impact on both scientific research and engineering applications. One important scientific application is the estimation of the Mean Dynamic Topography, which provides essential information for determining the steady-state ocean circulation. In engineering, as it is well-known, geoid models are widely used to transform ellipsoidal heights obtained from GNSS observations into orthometric heights.

This presentation summarizes the relationship between Geodetic Boundary Value Problems and the estimation of geoid and height anomaly. It also reviews the principal methods currently applied in geoid and height anomaly determination and concludes with a discussion of some critical points on geoid and height anomaly computation.

11:50am - 12:20pm

Integrating Geophysics and Geodesy

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The best way to realize how Geophysics and Geodesy are so intimately linked to one another is to consider that the momentum equation, mainly thought related to Geophysics, the Poisson equation, mainly thought related to Geodesy, and mass conservation must be solved simultaneously when dealing with any dynamic process, related to the Solid Earth in my presentation: buoyancy forces are driven in the momentum equations by gravity and gravity perturbations which in turn solve the coupled Poisson equation forced, among other terms, by compression/dilatation of the medium entering also the momentum equation. If we are interested in dynamic processes occurring in our Planet, there is no way to separate these fundamental equations, as there is no way to separate Geodesy and Geophysics. I purposely used the

word gravity, because the focus of my talk is the story of what we have been learning in the last decades, including the most recent achievements, about fundamental dynamic processes affecting the Solid Earth thanks to the tremendous work that geodesists and geophysicists made on recovering the gravity anomalies with the perpetual target to increase their resolution in space and time, for a wide spectrum of geophysical processes. Compared to other geodetic observables, gravity allows us to sample our Planet also at great depths, as I will show. Starting from changes in J_2 , we first realized the importance of the global response of the mantle to Pleistocene deglaciation; then, after improving to some extent the spatial resolution up to J_6 and to some odd low harmonics, we have been able to constrain present day melting in Greenland and Antarctica, to values that are in general agreement with what we have obtained from GRACE at much higher resolution at harmonic degree and order 60. The incoming ESA/NASA gravity mission MAGIC has the sensitivity to disclose the gravity changes caused by tectonics, linked to the opening of the Gulf of Aden for example where the extension of the oceanic dense lithosphere due to the clockwise rotation of Africa with respect to Asia substitutes lesser dense continental lithosphere, after GOCE has first shown accurate static gravity gradients due to tectonics. This is a never-ending story of course, because we cannot avoid to seek for higher and higher resolution in space and time, but today we can take some time to have a look to where we have arrived after the pioneering works of the eighties.

S6A: Geodetic reference frames

Session Chair: **Prof. Christopher Kotsakis**

Session Chair: **Prof. Riccardo Barzaghi**

1:40pm - 2:00pm

On the Definition of Vertical Velocity in Space Geodesy

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The concept of vertical motion in geodesy is inherently dependent on the adopted definition of the vertical direction, particularly in the context of space geodetic techniques, where “vertical” velocities are obtained through projection of three-dimensional station velocity vectors onto a specified direction. This study investigates the differences between GNSS-derived vertical velocities defined along the ellipsoidal normal and the geocentric radial direction. Analytical expressions are developed to quantify the relationship between the two quantities and to identify the principal factors controlling their differences, with particular emphasis on the contribution of horizontal station motion. A global analysis based on GNSS station velocities is further performed, leading to the construction of a worldwide map of the differences between the two vertical velocity definitions. The results reveal systematic and spatially structured discrepancies that barely exceed the noise level of current products but can locally approach 0.2 mm/yr. Although relatively small in magnitude, these differences may become relevant in applications requiring sub-millimeter per year consistency, including the realization and interpretation of terrestrial reference frames, regional deformation studies, long-term sea-level and vertical land motion analyses, and the comparison or combination of geodetic products relying on heterogeneous definitions of vertical motion. The study highlights the importance of maintaining conceptual and geometric consistency in the interpretation and use of GNSS-derived vertical velocities within modern Earth monitoring applications.

2:00pm - 2:20pm

Can the observed ITRF2020-JTRF2020 frame discrepancies be reconciled with the stochastic error budget of ITRF2020?

Christopher KOTSAKIS¹, Miltiadis CHATZINIKOS^{2,3}

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The latest realizations of the International Terrestrial Reference Frame (ITRF2020) and the JPL Terrestrial Reference Frame (JTRF2020) are based on the same underlying space geodetic observations but employ fundamentally different combination methodologies and stochastic modeling strategies. Previous comparisons between the two solutions have mainly focused on the estimation of daily or weekly Helmert transformation parameters, which quantify their mutual discrepancies in origin, orientation, and scale. The interpretation of these discrepancies, however, remains incomplete unless considered in relation to the uncertainty with which such coordinate-system elements are internally realized within the participating frame solutions.

In this study, we investigate whether the observed ITRF2020-JTRF2020 frame discrepancies can be reconciled with the stochastic error budget of ITRF2020. Daily seven-parameter Helmert transformations between the two realizations are estimated over the period 1979–2025 using common, quality-controlled station networks. In parallel, the stochastic uncertainty associated with the realization of the ITRF2020 origin, orientation, and scale is quantified through covariance-projection techniques applied to the full frame solution. This yields time-dependent uncertainty measures for the corresponding coordinate-system parameters, enabling a direct comparison with the daily Helmert transformation series in a common parameter space.

The proposed framework combines information from the observed coordinate-system discrepancies and the internal stochastic error budget of ITRF2020 in order to assess their mutual consistency. To this end, the systematic long-term behavior of the daily Helmert transformation parameters is estimated and removed prior to their comparison with the corresponding uncertainty measures derived from ITRF2020. The sensitivity of the resulting assessment to stochastic modeling is further investigated by repeating the daily Helmert-parameter estimations using covariance information from JTRF2020. In this way, the robustness of the inferred consistency between the observed frame discrepancies and

the uncertainty budget implied by the ITRF2020 realization can be evaluated with respect to the adopted weighting scheme.

By linking inter-frame discrepancies with the internal realization uncertainty of a reference frame solution, the proposed approach provides a complementary framework for assessing and interpreting consistency between contemporary terrestrial reference frame realizations.

2:40pm – 3:00pm

Geometric Estimation of Geocenter by SLR technique among the challenges of GENESIS mission

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The ESA GENESIS mission plans to inject in orbit a MEO satellite, at ~6000 km altitude. It will be a platform with a payload of collocated instruments of four geodetic techniques: SLR, VLBI, GNSS and DORIS. The main GENESIS science objective is to contribute to improve the ITRF accuracy and stability at level in turn of 1 mm and 0,1 mm/yr at least. We expect that such fully calibrated satellite based platform can improve the Geocenter estimation (GC), refine ITRF scale and ERP parameters. SLR is the most suitable technique able to estimate the GC. This parameter is of utmost importance not only for ITRF but for Earth Observations. The technique which mainly contribute to its estimation is SLR. We will perform a geometrical analysis in order to understand what is the optimal orbit of GENESIS which, combined with other SLR satellites, namely LAGEOS and LARES I and II, can provide the most precise estimation of Geocenter. At this purpose in the present work we propose a fully geometric approach, based on the analysis of Dilution of Precision (DOP) , in order to perform a precise estimation of Geocenter.

S6B: Geodetic reference frames

Session Chair: **Prof. Christopher Kotsakis**

Session Chair: **Prof. Riccardo Barzaghi**

3:20pm – 3:40pm

Evaluating the consistency of normal heights

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One can compute the normal height of a point on the Earth's surface in three different ways. The first approach follows from the definition of physical heights, which is based on the geopotential number, therefore, related to the geoid. It states that the normal height is the ratio of the geopotential number and the mean value of normal gravity along the tangent to the normal plumbline between the ellipsoid and the telluroid. The second approach, from geodetic height defined as a segment of a straight ellipsoidal normal between the surface point and the reference ellipsoid and the height anomaly, defined as the segment of the normal plumbline between the surface point and the telluroid. It is our understanding that, by relating geoidal height and height anomaly, the vertical reference of normal heights, estimated in this way, is the geoid. In Molodensky's theory, height anomaly is considered equivalent to the segment of the normal plumbline from the reference ellipsoid to the quasigeoid. Obviously, Molodensky's assumption is valid only for points on the Earth's surface, but the implication of his assumption is that normal heights relate to the quasigeoid, not to the geoid. The second approach is ambiguous. The third approach, from a local quasigeoid model which can be used to interpolate the value of normal heights for the given surface point. Clearly, in this way, normal heights relates to the quasigeoid. In this investigation, we perform numerical evaluations of normal heights using the three approaches, comparing and analyzing the results. We use data from the Colorado Experiment.

3:40pm - 4:00pm

Considering repro-BLUUE for network adjustments in the modernized national spatial reference system

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The U.S. National Geodetic Survey (NGS) is actively preparing for the readjustments of its 3D geodetic and leveling networks as a part of their modernization of the National Spatial Reference System (NSRS). The geodetic network is comprised of around 132,000 points, while the leveling network has over one million points; approximately 53,000 points are common to both networks. For several practical reasons, these two adjustments will be conducted independently, though the same numerical software library will be used for both of them.

The common points are related by their respective heights. In the 3D geodetic network, heights h are geodetic, while in the leveling network heights H are orthometric. Taking into consideration the geoid undulation N at the common points, the two types of heights at each point are related by the well-known Helmert projection $h = H + N$, where estimates for geoid undulations, and their variances, come from a separate process used to determine a new NGS geoid model called Geoid 2022.

The fact that orthometric heights at the common points can be determined either as $H = h - N$, with h coming from the adjustment of the geodetic network, or directly from the leveling network adjustment leads to a dilemma not unlike that encountered in classical network densification problems, especially if the orthometric heights computed by $h - N$, with h from the geodetic network adjustment, will be used as control points in the leveling network adjustment such that their values should be reproduced by the adjustment without losing or neglecting their variances that resulted from the geodetic network adjustment and the process used to determine the geoid.

Here we pick up with the earlier work of Schaffrin, who authored (and coauthored) a series of papers from 1997 to 2012 on the topic of network densification, where he showed the superiority of a newly derived and optimal reproducing estimator, that he eventually dubbed repro-BLUUE (standing for reproducing Best Linear Uniformly Unbiased

Estimator), over previously used estimators that might be considered ad hoc and which he showed were not optimal within the appropriate model.

After reviewing Schaffrin's earlier developments, we will apply those to relatively large sub-networks of the national geodetic and leveling networks to demonstrate the suitability of repro-BLUUE on a large scale, potentially leading to its adoption at the national scale.

Main references

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4:00pm - 4:20pm

A Hybrid Approach for Unifying the Height Systems of Egypt and Germany Using Classical and Relativistic Geodesy

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One can compute the normal height of a point on the Earth's surface in three different ways. This study proposes a hybrid approach for unifying the height systems of Egypt and Germany by integrating classical geodetic techniques with relativistic geodesy. Traditional methods such as precise leveling and gravimetric geoid modeling are widely used within national boundaries; however, their accuracy degrades over long distances and across continents due to accumulated systematic errors and inconsistencies between reference datums. To overcome these limitations, this research introduces relativistic geodesy as a linking tool between the Egyptian and German height systems. Based on general relativity, differences in gravitational potential are derived from frequency comparisons between highly accurate atomic clocks. In this study, classical methods are first applied to define the local height systems in Egypt and Germany independently. Then, a relativistic connection is established between a reference station in Egypt (e.g., Alexandria) and a reference station in Germany (e.g., Potsdam) using simulated atomic clock data and microwave links within the ACES framework. The Tri-Frequency Combination (TFC) method is employed to mitigate major error sources such as Doppler shifts and atmospheric effects. The results demonstrate that the integration of both approaches enables the determination of geopotential differences with an accuracy corresponding to height differences at the decimeter to meter level. This hybrid methodology provides a practical and scalable solution for intercontinental height system unification and contributes to the realization of the International Height Reference Frame (IHRF).

4:20pm - 4:40pm

The Local Mean Sea Level: a major research challenge

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The local mean sea level (LMSL) represents a critical reference datum in hydrographic surveying and geodesy, serving to define the ideal sea surface at rest and approximating the geoid. However, accurate LMSL determination is hindered by instrumental limitations and complex environmental factors. Specifically, fully quantifying the qualitative and quantitative interactions between atmospheric phenomena and the free surface of oceans and seas remains a significant challenge. This study presents the methodology and research conducted by the Italian Hydrographic Institute to compute the LMSL. Particular emphasis is placed on identifying and analyzing the specific variables that influence the uncertainty of the final estimate.

Thursday, 10/Sept/2026, 9:00am - 10:40am

S7A: Gravitational field modelling

Session Chair: **Dr. Michal Šprlák**

Session Chair: **Dr. Zhi Yin**

9:00am - 9:20am

Green's functions in geodesy

Pavel NOVÁK

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The determination of the Earth's gravity field belongs to fundamental challenges in modern geodesy. Central to this task is the solution of various geodetic boundary value problems (BVPs), which relate observable quantities – such as functionals of the gravitational potential – to the underlying gravitational potential. This study provides a comprehensive review and theoretical synthesis of Green's functions as primary mathematical structures required for solving these problems. Named after the British mathematician George Green, these functions allow for solving complex partial differential equations governing the continuous gravitational field by computable boundary or volume integrals. Specialized (modified, spectrally limited) Green's functions used in solutions to geodetic BVPs for different approximations of the boundary will be discussed. It will be demonstrated that Green's functions remain an indispensable tool for transforming observed heterogeneous geodetic data – from satellite altimetry or anomalous mass density to surface gravity – into high-accuracy and high-resolution gravitational field models.

9:20am - 9:40am

Spheroidal Integral Formulas for Computing the Disturbing Gravitational Potential and Its First- and Second-Order Directional Derivatives from the Disturbing Gravitational Potential and Its Vertical and Horizontal Derivatives

Martin PITOŇÁK, **Jiří BELINGER**, Michal ŠPRLÁK, Pavel NOVÁK

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Integral transformations derived from boundary-value problems (BVPs) of potential theory form the mathematical foundation of physical geodesy and gravity-field modelling. The classical Green's function solutions of the Dirichlet, Neumann, and Stokes problems give rise to a comprehensive family of integral transformations relating the disturbing gravitational potential to its directional derivatives. Under the spherical approximation, this framework—encapsulated in the Meissl scheme—has attained a high degree of completeness, enabling mutual transformations among all components of the gravitational-gradient tensor up to the second order. These methods are essential for processing heterogeneous gravity observations from terrestrial, airborne, and satellite platforms.

However, growing accuracy demands and the Earth's close geometric resemblance to a rotational ellipsoid call for a transition from spherical to spheroidal formulations. Although analytical solutions to the three fundamental BVPs on an oblate spheroid have been established and several corresponding integral equations proposed, a complete spheroidal counterpart to the Meissl scheme has yet to be developed.

In this contribution, we derive spheroidal integral formulas that compute the disturbing gravitational potential and its first- and second-order directional derivatives from the disturbing potential and its vertical and horizontal derivatives. The validity of these newly derived formulas is confirmed through closed-loop tests using data from a global geopotential model.

9:40am - 10:00am

Contribution of complete Bouguer anomalies to the accuracy of gravimetric geoid model

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Gravity measurements collected at the Earth's surface are not directly used in geoid modelling; therefore, they must be reduced to free-air gravity anomalies. However, most software packages employed in geoid determination require gridded free-air gravity anomalies. Consequently, gravity anomalies observed at irregularly distributed points must be interpolated onto grid nodes using appropriate interpolation techniques.

Since free-air anomalies are not well suited for interpolation due to their strong correlation with topography, Bouguer anomalies are generally preferred for this purpose. In this context, two types can be considered: simple and complete Bouguer anomalies. While simple Bouguer anomalies may be sufficient in flat areas, complete Bouguer anomalies are essential in mountainous regions.

In this study, the extent to which complete Bouguer anomalies affect the accuracy of the geoid model in high-mountainous areas is investigated. The comparisons show that complete Bouguer anomalies provide significantly more accurate results than simple ones when evaluated against GNSS-levelling data. Therefore, the use of complete Bouguer anomalies is strongly recommended for geoid determination in mountainous areas.

10:00am - 10:20am

Spectral characteristics of forward-modelled global gravitational fields for selected planetary bodies

Michal ŠPRLÁK, Jiří BELINGER, Martin PITOŇÁK, Pavel NOVÁK

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External spherical harmonic expansions are the most preferred parametrisations of the gravitational potential and its higher-order spatial derivatives in global geodetic, geophysical, and planetary science applications. Constant harmonic coefficients conveniently define physical properties of the gravitating body. Having a set of such coefficients at our disposal, we can synthesise various quantities of the gravitational field anywhere in three-dimensional space. While the convergence domain of external spherical harmonic expansions is the space above the minimum Brillouin sphere, these series are commonly employed inside the bounding surface. Moreover, observations of gravitational field quantities, which form the basis for the harmonic analysis, are affected by measurement noise. To suppress any divergence issues and/or gravitational data noise, the spherical harmonic coefficients are often constrained by a degree-dependent behaviour, known as Kaula's rule. The selection of this rule, however, may be subjective without any relevance to the realistic gravitational field.

In this contribution, we systematically analyse gravitational fields of seven planetary bodies (i.e., Bennu, Ceres, Eros, Mars, Moon, Ryugu, and Vesta). The basic assumption of our study is that the gravitational field generated by topography perfectly correlates with its realistic counterpart at high frequencies. We calculate gravitational fields for each planetary body from a detailed geometry and a constant volumetric density. For this purpose, we employ the rigorous forward modelling approach, which has been extensively validated previously. We examine the gravitational spectra for each planetary body at the minimum Brillouin sphere and selected levels inside the corresponding bounding surface. We attempt to search for an empirical dependence of Kaula's rule not only on the spherical harmonic degree, but also on the planetocentric radius when the analytical downward continuation is performed.

10:20am - 10:40am

Utilization of Spheroidal Harmonics in Gravitational Field Modelling of Irregular Planetary Bodies

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Gravitational field modelling represents essential part of modern Geodesy. There are various approaches considering calculation of gravitational field quantities, such as least squares collocation, radial basis functions, integral transformations and spherical harmonics. The latter method utilizing spherical harmonic functions is one of the most common currently used approaches. However, this method may not be suitable when applied on irregular planetary bodies, especially when given bodies are significantly flattened or elongated. On the other hand, spheroidal harmonics, considered in our research, could represent ideal solution for these irregular geometries. Compared to spherical harmonics, spheroidal approximation allows for stable calculation even for areas much closer to body's surface and calculated quantities are geometrically closer to their physical counterparts. In this contribution, we will discuss spheroidal harmonics theory derivation and implementation of related software including both outer and inner

expansion and considering derivatives of the gravitational potential up to the third order. The emphasis will be mainly on numerical aspects of proposed solution, e.g. singularities on poles and stability of Legendre functions.

S7B: Gravitational field modelling

Session Chair: **Dr. Ropesh Goyal**

Session Chair: **Prof. Dimitrios Tsoulis**

11:00am - 11:20am

Effect of Land Depressions in Africa on Gravity and Geoid

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The determination of the gravimetric geoid is based on the magnitude of the gravity signal observed at the topographic surface of the Earth. In order to satisfy Laplace's equation, in the context of Stokes theory, the masses between the surface of the Earth and the geoid must, mathematically, be removed or shifted inside the geoid by means of an appropriate reduction. Subsequently, the gravity values have to be reduced to the geoid, forming the boundary values on the boundary surface, using a terrain correction software (TCS). If the TCS uses unclassified Digital Terrain Models (DTMs), it pre-assumes that grid cells with negative heights are filled with water, and those with positive heights are filled with rock topography. For example, the widely used TC software for topographic reduction handles negative topography in the incorrect way described above.

Africa has a number of land depressions. These depressions have negative heights, but they are not filled with water. Accordingly, the TC software treats them as if they are filled with water, rather than as massless volumes. In addition, the program computes the terrain corrections at the zero level (geoid level), rather than at the actual negative topographic surface of the depression.

Hence, the main aim of the current investigation is to determine the impact of the land depressions in Africa on both the gravity reduction and the geoid undulation. The current investigation employs the non-ambiguous window remove-restore technique for accurate determination of the effect of the land depressions on gravity and geoid. A special software package has been written to compute the effect of the land depressions on the gravity and geoid. The results proved that the effect (of using unclassified DTMs) of the land depressions in Africa on the gravity anomalies is restricted to the areas of the land depressions only, reaching a value of about 27 mGal. The effect of the land depressions on the geoid undulation is concentrated at the areas of the land depressions and spread out to a relatively large radius, reaching a value of about 1.15 m.

11:20am - 11:40am

FEM approach in view of cm-accurate quasigeoid modelling in high mountains

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This study presents local gravity field modelling in high mountains using the finite element method (FEM). FEM numerical approach is applied to solve the fixed gravimetric boundary value problem (FGBVP) in spatial domain on the discretized Earth's surface. 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. Our numerical experiments have indicated that the FEM numerical scheme based on hexahedron finite elements may have difficulty converging on very rugged topography, while the FEM scheme based on pentahedron finite elements with linear basis functions converges better. In addition, GNSS-levelling tests and validation using deflections of vertical (DoV) has shown that the obtained FEM numerical solutions to FGBVP suffer from some kind of a discretization error that increases by refining the computational mesh, especially in high mountains regions. A reconstruction of the harmonic function generated by spherical harmonics (e.g. EIGEN-6C4) on a specific computational mesh can estimate this discretization error, which must be later removed from the FEM solution.

The case studies present detailed quasigeoid modelling in the Tatra Mountains (Slovakia/Poland), in the Zugspitze test area (Germany/Austria) of the European Alps geoid project (EAlpG) and in the Colorado test area (USA). Comparisons

of the obtained FEM local quasigeoid models with those computed in spectral domain indicate an agreement in a few cm. This is quite promising taking into account that the FEM approach is solving FGBVP in spatial domain directly on the discretized rugged Earth's topography.

11:40am - 12:00pm

Combination of Time-Variable Gravity Field Solutions from Multi-Satellite Datasets (1993-2024) via Constrained Collocation Model

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Time-variable gravity field solutions from GRACE and GRACE-FO are widely used in hydrological and geophysical studies, yet their broader application is limited by inter- and intra-mission gaps and the relatively short observation span. To address this issue, we derive gapless monthly Time-Variable Gravity (TVG) solutions up to degree/order 60 from January 1993 to December 2024 by combining the TVG solutions of ITSG-Grace2018, Tongji-LEO2021, IGG-Swarm, IGG-UPWR-SLR, and IGG-SLR-HYBRID models using a Constrained Collocation Model (CCM) based on Tikhonov regularization. To balance magnitude disparities among various TVG solutions, variance factors are introduced into their observation-error covariance matrices and estimated using bias-corrected Variance Component Estimation (VCE). In the collocation model, the gravity signals are expressed with deterministic parameters (trends, annual and semi-annual terms) and non-seasonal signals, which are described as a stochastic multi-order Gauss-Markov process. The covariance matrices of observation errors and gravity signals are jointly incorporated, with signal covariance matrices constructed using temporal-correlated exponential functions. The CCM achieves simultaneous solution combination and denoising through an iterative scheme, in which the combined deterministic parameters are estimated using Tikhonov regularization and combined non-seasonal signals are recursively updated through Kalman smoothing. Results indicate that CCM-based Combined Solutions (CCM-CS) effectively suppress striping and high-degree coefficient noise while preserving key low-degree signals (e.g., C20 and C30) and maintaining high signal-to-noise ratios. Compared with three reconstructed products (IGG-SLR-DORIS, RESDCAE, BNML), CCM-CS achieves the lowest sea-level budget misclosures, reduced by 40.0%, 2.9%, and 49.0%, respectively, and the smallest water-balance errors across 52 major basins, reduced by 4.6%, 2.6%, and 1.5%, respectively. It also agrees more closely with IMBIE estimates of Antarctic and Greenland ice-sheet mass changes, with trend consistency improved by 46.8% and 32.7% relative to IGG-SLR-DORIS and by 48.6% and 67.4% relative to RESDCAE, respectively.

12:00pm - 12:20pm

What can redundancy contribution matrices tell us about regularized mascon solutions?

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The mascon solutions provide an alternative method to estimate surface mass variations from GRACE data in the spatial domain directly as opposed to the spherical harmonic solutions that provide the solution in the spectral domain. Due to this direct spatial domain modelling of the surface mass variations, the signals are localized by the mascons. However, the ideas of spatial resolution and signal leakage, which are closely related to signal localization, are not well understood in the case of mascon solutions. As all the mascon solutions are regularized, where the regularizing quadratic constraint controls the level of signal retrieved from the observed data, the redundancy contribution matrices (a.k.a. resolution matrices) provide an opportunity to study these aspects of the mascon solutions. Redundancy contribution matrices allow us to study the relative contribution of the data and the constraint. Here, we investigate the utility of contribution matrices in understanding the spatial resolution and signal leakage in mascon solutions. We use the fast mascons approach for estimating the mascon solutions.

Thursday, 10/Sept/2026, 1:40pm - 3:00pm

S8: International projects

Session Chair: **Prof. Pavel Novak**

Session Chair: **Prof. Domenico Sguerso**

1:40pm - 2:00pm

Genesis: ESA's international geodetic satellite mission

Gaia FUSCO, Sara GIDLUND, Evelyn HONORÉ-LIVERMORE, Antonia BIERINGER, Erik SCHOENEMANN, Jean-Christophe BERTON, Francesco GINI, Alexandru MANCAS

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The Genesis mission is conducted by the European Space Agency (ESA) Resilience, Navigation and Connectivity (RNC) Directorate as part of the FutureNAV program. Its primary objective is the contribution to the improvement of the International Terrestrial Reference Frame (ITRF) towards an accuracy of 1mm and a long-term stability of 0.1mm/year. Secondary objectives include the contribution to a high number of other scientific disciplines (geodesy, geodynamics, earth rotation, geophysics, earth gravity field, atmosphere and ionosphere sciences, metrology, relativity...) [1].

The Genesis Space Segment consists of a spacecraft in MEO (400kg, 6000km altitude, 95° inclination) co-locating for the first time in space the four geodetic instruments used for the realisation of the ITRF: a GNSS receiver, an SLR reflector, a VLBI transmitter and a DORIS receiver. The Ground Segment is composed of a Mission Control Centre (including a Ground Station) and will make use of the existing ground infrastructure, operated by the Services of the International Association of Geodesy (IAG): GNSS sensor stations network

of the IGS, SLR stations of the ILRS, VLBI antennas of the IVS, and DORIS beacons of the IDS. The scientific mission data and related Precise Orbit Determination products will be processed by the ESA Navigation Support Office, before being archived, and distributed by the ESA GNSS Science Support Centre (GSSC), together constituting the ESA Genesis PROcessing, Archiving and Distribution Centre (PROAD) in close collaboration with the scientific community. Genesis' fully calibrated satellite will establish precise and stable ties between the key geodetic techniques, implementing a unique dynamic space geodetic observatory. As the ITRF is recognised to be the foundation of countless space and ground-based applications, Genesis will have a major impact on almost any space mission and, in particular, on Navigation and Earth Science.

On the industrial side, a consortium led by OHB Italia S.p.A. has been contracted by ESA for the development, qualification, launch and 2 years operation of the mission (with option for extension), with a launch currently planned in 2029. Antwerp Space, as payload prime, is responsible for the geodetic instruments and the Ultra Stable Oscillator (USO) for instruments' synchronization.

On the scientific side, a Genesis Scientific Exploitation Team (GSET) was set-up and members appointed already in 2024. This structure encompasses representatives of ESA, a lead Scientific Coordinator and Co-Coordinator, as well as five Working Groups covering the four geodetic techniques and their combination.

The GSET includes members of the international geodetic services and will interact with them for the coordination of the ground infrastructure. Three successful Genesis Scientific Workshops have been held in February 2024, April 2025, and March 2026. The GSET are actively supporting the mission development, the design consolidation, and will play a key role in the future exploitation of the mission data.

This presentation will provide an up-to-date overview of the Genesis mission from a system and programmatic point of view.

[1]: Delva et al. Earth, Planets and Space 75, 5 (2023)

2:00pm - 2:20pm

IRIDE: From Earth Observation to Operational Geospatial Services

Gabriella COSTA, **Enrico Giuseppe CADAU**, Luca SAPIA, Cristiano STELLA

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IRIDE is Italy's flagship Earth Observation (EO) programme, funded through the National Recovery and Resilience Plan (PNRR) and implemented by the European Space Agency (ESA) in collaboration with the Italian Space Agency (ASI). Conceived as a national end-to-end EO ecosystem, IRIDE integrates space, ground, and service segments to

deliver operational geospatial information, thematic products, advanced analytics, digital twins and decision-support capabilities to institutional, scientific, and commercial users.

By mid-2026, the IRIDE space segment included 15 operational HEO satellites and 16 EAGLET-2 satellites already in orbit, while additional constellations, including NIMBUS-SAR, NIMBUS-VHR, NOX-SAR, and PLATINO-Hyperspectral, were progressing through manufacturing and deployment. A major programme milestone was reached in June 2026 with the transfer of HEO Batch #1 and its associated downstream infrastructure to ASI for routine operations, demonstrating the maturity of the first operational components of the system.

The IRIDE architecture integrates central mission planning facility, satellite tasking, data acquisition and processing, exploitation tools, and a user-oriented Marketplace for data discovery and service delivery. A key element is the Service Segment, which transforms EO and complementary data into operational information products addressing national needs across domains including coastal and marine monitoring, air quality, ground motion, critical infrastructure, landslides, water resources, climate, land monitoring, security, and emergency management. In parallel, the Cyber Italy initiative introduced Digital Twins integrating Earth observation data, in situ measurements, artificial intelligence, and advanced computing to support predictive analyses and what-if simulations for environmental and risk-management applications. By 2028, more than forty operational services and associated added value product chains are expected to be progressively deployed.

A major achievement in 2026 was the IRIDE pre-operational campaign conducted between April and June to validate infrastructure, services, operational procedures, and user interfaces. More than one hundred institutional and technical users participated in the campaign, including ESA, ASI, ISPRA, CNR, CMCC, the Italian Civil Protection Department, defence stakeholders, and regional authorities. The campaign demonstrated the capability of the system to support both routine monitoring and time-critical applications while providing valuable feedback for the transition towards full operations.

This paper presents the current status of the IRIDE programme and the ongoing transition towards routine operations. The results achieved to date demonstrate the progressive integration of satellite constellations, downstream infrastructures, and thematic services into a unified national EO ecosystem.

2:20pm - 2:40pm

CYGOS: An Integrated GNSS–InSAR Geodetic Observatory for Monitoring Crustal Deformation and Geohazards in the Eastern Mediterranean

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The Eastern Mediterranean is one of the most complex active plate-boundary regions worldwide, where the convergence of the African and Eurasian plates generates significant crustal deformation, seismicity, uplift, subsidence, and slope instability. Cyprus occupies a key position within this tectonic transition zone and constitutes a natural laboratory for investigating the interaction between subduction, continental collision, and surface deformation processes. Despite its geodynamic importance, the region has historically lacked dense geodetic infrastructure capable of supporting long-term deformation monitoring and reference frame realization.

To address this gap, the Cyprus Geohazard Observatory Supersite (CYGOS) was established as a permanent geodetic and Earth Observation observatory built upon the CyCLOPS strategic research infrastructure. The observatory integrates Tier-1 GNSS stations, meteorological sensors, tiltmeters, calibration-grade InSAR corner reflectors, and multi-mission SAR observations within a unified monitoring framework supporting both scientific investigations and operational geohazard monitoring.

A key objective of CYGOS is the development of a national geodetic framework for high-precision deformation monitoring in a tectonically active environment. GNSS observations are processed to provide consistent coordinate time series and velocity estimates in global reference frames, contributing to the densification of the EUREF Permanent Network (EPN) and the European Plate Observing System (EPOS). Collocated GNSS and InSAR infrastructure enables the integration of satellite-derived deformation products with geodetic reference frames, improving the estimation of absolute ground motion and the validation of multi-temporal SAR analyses.

The recent designation of CYGOS as a Permanent Supersite within the GEO Geohazard Supersites and Natural Laboratories (GSNL) initiative further expands its scientific potential through access to multi-mission SAR datasets and international collaborations. Under CYGOS, the Cyprus Ground Motion Service (CYGMS) has been developed as a national GNSS–InSAR monitoring service delivering displacement time series, velocity fields, and ground motion products interoperable with the European Ground Motion Service (EGMS). CYGMS provides locally validated deformation products referenced to both regional and global reference frames, addressing the challenges posed by the active tectonic environment of the Eastern Mediterranean.

This contribution presents the geodetic architecture of CYGOS and its role as a regional hub for integrated GNSS–InSAR monitoring, with emphasis on reference frame realization, geodetic infrastructure development, and the generation of deformation products supporting both scientific research and operational geohazard applications.

2:40pm - 3:00pm

The new Italian LiDAR Digital Surface and Terrain Models and Aerogravimetric Database

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This project has the twofold goal of creating, at the national level, a new high-resolution (10 points/m²) and high-accuracy (6 cm RMSE in ellipsoidal height, 10 cm RMSE in horizontal position) LiDAR Digital Surface and Terrain Model (DSM/DTM), alongside a new homogeneous, high-resolution (2.5 km x 2.5 km grid) and high-accuracy (0.8 mGal RMSE on crossovers) aerogravimetric database for the computation of the new Italian geoid. It is a key component of a long-term national integrated surveillance and monitoring system (SIM – Sistema Integrato di Monitoraggio) for scheduled land and infrastructure maintenance and modernization. The project is funded under the National Recovery and Resilience Plan (PNRR).

This initiative aims to align Italy's foundational geoinformation with that of most European countries by acquiring state-of-the-art data using advanced LiDAR sensors and modern airborne gravimeters. This will resolve current qualitative and chronological inconsistencies in geoinformation related to the understanding of national terrain morphology and the gravity field, providing fundamental data crucial for various applications analyzed by the SIM system.

The resulting morphological and aerogravimetric databases will meet nearly all knowledge and data requirements regarding national surface morphology and the gravity field, benefiting both public and private stakeholders. Additionally, they will be integrated with previously developed databases (e.g., national or regional-scale DSMs and DTMs, as well as the currently available national gravimetric database) and those under ongoing development.

In particular: (i) The new national DSMs and DTMs will enable key functionalities for hydrogeological instability monitoring, providing valuable support for slope stability analyses and hydraulic modeling. These are essential for delineating potentially flood-prone areas and serve as indispensable tools for land-use planning and management; (ii) The new national aerogravimetric database will enable the computation of the new Italian geoid and the consequent update of the national height reference frame, in close connection with the simultaneous update of the Italian fundamental leveling network. Furthermore, comparing the new aerogravimetric database with previous gravimetric data collected across the national territory and surrounding seas over the past 150 years will allow for the estimation of long-term, mid-to-long wavelength variations of the gravity field in Italy.

Overall, the project has currently reached approximately its midpoint, and ongoing quality controls confirm that all technical parameters are fully met and frequently exceeded. The project is expected to be completed in the first half of 2027, with results made publicly available through a dedicated infrastructure established by the Ministry of the Environment and Energy Security.

Thursday, 10/Sept/2026, 3:20pm - 4:20pm

S7C: Gravitational field modelling

Session Chair: **Dr. Michal Šprlák**

Session Chair: **Dr. Zhi Yin**

3:20pm - 3:40pm

Transformation of first-, second-, and third-order potential gradients in different coordinates

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Knowing how to transform potential gradients between different coordinate systems is of fundamental importance in potential field theory. For first- and second-order gradients, such transformations are conventionally dealt with in terms of vector-matrix notation. However, matrix notation is not helpful for deriving the expressions for transformation of third-order potential gradients. In this contribution, we derive the general detailed expressions for transformation of first-, second-, and third-order potential gradients between two coordinate systems by using the direct expansion method. As examples of these general expressions, we derive detailed expressions for forward and inverse transformations of physical components of first-, second-, and third-order potential gradients among Cartesian, cylindrical, and spherical coordinates. Laplace's equation has been applied for a first validation of partial expressions. However, to validate all newly derived expressions in a systematic way, we propose the closed-loop transformation cycle method that presents a full-fledged commutative diagram of forward and backward transformations among all three coordinate systems, i.e., potential gradients can become themselves after the closed round-trip transformation cycle among Cartesian, cylindrical, and spherical coordinates. Results reveal that this transformation cycle method confirms the correctness of all derived expressions. These general expressions for transformation of first-, second-, and third-order potential gradients can be applied under arbitrary two coordinate systems, and their detailed expressions can be systematically validated by the proposed transformation cycle method.

3:40pm - 4:00pm

A comparative study of gravitational field modeling for Bennu asteroid

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The presentation addresses the models of the gravitational field of the near-earth asteroid 101955 Bennu using three numerical spatial-domain approaches and their comparison with spectral-domain method based on spherical harmonics. Due to its irregular shape, accurate gravitational field modeling represents a challenging task that is essential for precise orbit determination and spacecraft navigation. A mutual comparison of spectral- and spatial-domain methods is therefore vital. The spherical harmonic method is known as spectral gravity-forward modeling and produces a spherical harmonic series that is valid only outside the smallest sphere completely encompassing Bennu. Opposed to the spherical harmonic method, three numerical approaches based on the finite element method are considered: the first solves the exterior boundary value problem (BVP) for the Laplace equation with the Neumann boundary condition (BC) in the semi-infinite domain, the second the exterior BVP for the Laplace equation with the Neumann and Dirichlet BCs in the bounded domain, and the third addresses a coupled bounded interior–exterior BVP for the Poisson equation, where a constant mass density is assumed, and the Dirichlet BC are prescribed.

4:00pm - 4:20pm

Assessing the gravitational force acting on a celestial body from the total gravitational vector field given on an enclosing surface

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The overall force acting on a small celestial body governs its dynamical evolution. Among its components, gravitation is a conservative body force. Accurate estimation of its integrated effect is essential in deep-space science, for example, in determining the orbit of an asteroid or comet within a multi-body dynamical system. Conventional methods rely on the internal density distribution and compute the total gravitational force via volume integration based on Newton's law of gravitation. However, the internal density structure and interior force information are difficult to obtain, which complicates the estimation of the total gravitational force. To address this issue, this study derives a formula for computing the gravitational force acting on an entire celestial body, only with the external gravitational vectors given on an enclosing surface.

Assuming an arbitrarily shaped closed surface outside the mass body, we first construct an outer-product identity for the gravitational force. We then apply Gauss's divergence theorem to transform the original volume integrals, which involve scalar, vector and tensor terms, into surface integrals. The Laplace and Poisson equations are introduced during the formulation. As a result, the expression for the total gravitational force is obtained, which depends solely on the gravitational vectors over the external enclosing surface. Numerical experiments are designed and conducted using prescribed mass distributions in a parallel background gravitational field. The results show that the proposed formula accurately recovers the gravitational force acting on the entire mass body in all simulation cases. This approach offers a feasible theoretical framework for estimating the net gravitational force of irregular solar-system bodies in complex deep-space environments. However, current observations are mainly limited to scalar gravity data, and high-precision and efficient gravitational vector measurements remain challenging. This limitation restricts the currently practical applications. Advances in gravitational vector observation or inversion methods may further extend the applicability of the proposed formula.

Funding: Supported by the National Natural Science Foundation of China (Grant No. 42204088).

P2: Poster session 2

Session Chair: **Prof. Bianca Federici**

Session Chair: **Dr. Paola Salmona**

Exploring links between surface fluid mass redistribution and polar motion excitation using a direction-of-maximum-correlation analysis of effective and geodetic angular momentum

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Variations in Earth's rotation are driven by gravitational forcing from celestial bodies as well as by mass redistribution within the atmosphere, oceans, hydrosphere, and cryosphere. These processes can be quantified through effective angular momentum (EAM).

This study revisits the contribution of surface fluid mass redistribution and transport to polar motion (PM) excitation at non-seasonal time scales over the period 1984–2024. The equatorial components (χ_1 , χ_2) of EAM are computed as the combined contributions of atmospheric (AAM), oceanic (OAM), hydrological (HAM), and sea-level angular momentum (SLAM), derived from reanalysis products and observation-constrained numerical models.

In this study, AAM series are derived from reanalysis products of the European Centre for Medium-Range Weather Forecasts (ECMWF). OAM estimates are based on the Max Planck Institute Ocean Model (MPIOM), while SLAM estimates are obtained from ECMWF reanalysis data and the Land Surface Discharge Model (LSDM). The AAM, OAM, and SLAM datasets are provided by the German Research Centre for Geosciences (GFZ). HAM estimates are derived from three independent datasets. The first two are derived from simulations produced with the OS LISFLOOD global hydrological model and the Land Surface Discharge Model (LSDM), both provided by GFZ. The third dataset is derived from temporal variations in the C_{21} and S_{21} geopotential coefficients estimated from a new hybrid gravity field solution. This solution, developed by the Institute of Geodesy and Geoinformation at the University of Bonn, combines empirical orthogonal functions derived from Gravity Recovery and Climate Experiment (GRACE) observations with Satellite Laser Ranging (SLR) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) measurements, thereby providing an extended time series spanning the period from 1984 to the present.

The main objective of this research is to assess the consistency of the EAM (AAM + OAM + HAM + SLAM) series with geodetic angular momentum (GAM) derived from geodetic observations of PM and provided by the International Earth Rotation and Reference Systems Service (IERS). Rather than analysing the χ_1 and χ_2 components separately, we evaluate the agreement between EAM and GAM along the direction of maximum correlation, providing a more robust and physically meaningful measure of their consistency.

The results reveal strong agreement between EAM and GAM in terms of both amplitude and correlation. Selecting the optimal comparison direction further improves the agreement, confirming the close coupling between surface fluid processes and variations in Earth's rotation.

The improved consistency between model-based and observation-based estimates of PM excitation obtained in the direction of maximum agreement may provide new insights into the links between Earth's rotation, mass redistribution within terrestrial fluid reservoirs, and climate-driven processes.

High-precision terrain modelling towards a cm-level IHRF realization

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Topographic masses near gravity stations strongly influence the observed gravity field. In this context, the implied regional gravity signal needs to be calculated with the highest possible precision. The requirement for a detailed terrain representation arises especially due to the rapid improvement in resolution and accuracy of the current satellite-derived geopotential models. The upcoming missions Next Generation Gravity Mission (NGGM) and Mass change And Geosciences International Constellation (MAGIC) will surpass the accuracy capabilities of all previous satellite gravity

products, providing 5-days solutions with a 100-150 km spatial resolution. Considering also that the International Height Reference Frame (IHRF) accuracy threshold aims at a 1 cm level, precise terrain modelling is a crucial process that needs to be thoroughly addressed. Typically, topographic masses are approximated as right rectangular prisms which lead to a representation of the actual terrain surface as a step function. We introduce two alternative geometric elements in order to achieve a better modeling precision, namely tesseroids and general polyhedra. The techniques are compared in terms of computational efficiency and accuracy of the derived terrain corrections, topographic and Residual Terrain Model (RTM) effects for twelve selected IHRF stations. Evaluated are the gravitational potential, its first order derivatives and geoid heights. Copernicus Global Digital Elevation Models (DEMs) of 30 m resolution are implemented to provide the required surface elevation information for an area of a 200 km radius surrounding the stations. The obtained results demonstrate that the polyhedral representation is superior compared to the other two modelling techniques. Focusing on the station AUT1 located in Thessaloniki, Greece, general polyhedra provide differences at a 1 m level in geoid heights with respect to prismatic model and 1 cm compared to tesseroids.

Datum-Consistent Shoreline Monitoring as a Geodetic Integration Problem

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Monitoring the morphological evolution of the coastline is a crucial issue for coastal areas, which are affected by climate change and anthropogenic interventions, both of which have led to phenomena such as coastline erosion and coastal front subsidence. Earth observation data from remote sensing satellites play an important role in recording the morphological evolution of coastlines, and in particular imagery from mission like Sentinel-2, which allow the systematic and financially viable extraction of coastlines on a 10 m and 6-day spatial and temporal scale. The “line” resulting from a single satellite image does not necessarily correspond to a “fixed” coastline, on the contrary it captures the instantaneous position of the land-sea boundary at the time of acquisition, which is directly influenced by the tide, the meteorological component of the level surface and the vertical reference system of the data. In this paper, a geodetic framework is proposed for the reliable normalization of coastlines extracted from satellite images. The basic idea is that, before any comparative analysis between different time periods, as well as before studying sea level forcing combining altimetry data and digital elevation models, coastlines must be reduced to the same reference level and all height data need to be homogenized in terms of solid earth tide conventions and the vertical reference system used. For this purpose, remote sensing data are combined with tide gauges measurements, satellite altimetry data and digital elevation models (DEM/DTM). Tide gauges provide the local temporal change of the sea level, satellite altimetry provides the absolute sea level, while the elevation model is used to estimate the local morphology and slope of the coast. Particular emphasis is given to ensuring consistency between vertical datums and tide systems, so that all observations are referenced into a single geodetic framework. The proposed methodology converts the level difference between the acquisition moment and the selected reference level into a horizontal correction of the coastline position, taking into account the local slope of the coastal zone. In this way, the extracted coastline is not directly compared with those of other moments in time, but is geodetically corrected to correspond to the same vertical reference plane. At the same time, the approach allows the quantification of the uncertainty resulting from the image classification, georeferencing, level changes, the elevation model and conversions between different reference systems. The method separates real coastline change from apparent displacements caused by tides, datum inconsistencies, and elevation data errors. Thus, coastline extraction becomes not merely an image classification task, but a geodetic problem of observation unification and homogenization. The proposed framework supports more reliable coastal evolution estimates and links remote sensing with modern vertical reference systems.

Testing the prediction quality of the GRACE/GRACE-FO time series in Danube River basin

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GRACE and GRACE-FO missions give us a great tool to monitor terrestrial water storage changes by providing the monthly global gravity field models. Our contribution focuses on the area of Danube River basin, second largest river basin in Europe. First, we describe our approach for monthly equivalent water thickness (EWT) time series preparation from the GRACE/GRACE-FO spherical harmonics global models. Next, we decompose the time series into the

polynomial trend, seasonal component and several cyclic components obtaining the intermediate residual time series. Finally, we apply the ARIMA models to intermediate residual time series to see whether there is any relevant statistical information left to be modelled. Subtracting this model from the intermediate residual time series we get the final residual time series which suppose to be approximately the white noise. This way, we prepare several time series models using the GRACE/GRACE-FO data up to different epochs. Then we use the corresponding models to predict the EWT time series for several next months and compare our predictions with the data which has not been included in the modelling process. Finally, we statistically estimate the differences between the predicted and measured values to see what we can expect when doing such prediction of one month or several months ahead.

Generation of a shape model as a series of surface ellipsoidal harmonics

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The generation of shape models for celestial bodies such as planets, comets, and asteroids is critical for satellite missions involving spacecraft navigation and the study of physical properties. Shape representation using spherical harmonics is widely employed for such applications. However, for highly irregular bodies, this approach becomes inadequate due to convergence limitations of the spherical harmonic series. In such cases, representation as a series of surface ellipsoidal harmonics provides a promising alternative, offering significantly improved convergence behavior. In this work, the ellipsoidal harmonic analysis procedure is formulated and applied within a least-squares framework. The objective of this study is to evaluate and compare spherical and ellipsoidal approaches in terms of accuracy and computational efficiency. Special attention is given to the optimized computation of Lamé functions of the first kind. Given that the available measurement data are typically irregularly distributed, the classical least-squares method is implemented for both approaches. To assess their performance, several numerical experiments are conducted on different celestial bodies exhibiting both near-spherical and highly irregular geometries.

Numerical computation of ellipsoidal harmonics: problems and challenges

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Although the theory of ellipsoidal harmonics has been used to represent the gravitational field of irregularly shaped celestial bodies, the numerical computation of these functions at high degree and order remains challenging because of numerical instabilities. While several algorithms have been developed for computing Lamé functions of the first and second kinds, relatively few practical methods have been proposed to improve computational efficiency. In this work, we introduce suitable transformations of ellipsoidal coordinates together with numerical stabilization techniques, including extended-range arithmetic and logarithmic scaling, to overcome arithmetic limitations in the computation of Lamé functions. Through a series of numerical experiments, we demonstrate that the proposed algorithm is stable, accurate, efficient, and capable of computing functions of high degree. Furthermore, the gravitational potential is represented as a series of generalized ellipsoidal harmonics both inside and outside a triaxial ellipsoid. Finally, we show that, contrary to the classical theory, spheroidal harmonics can be derived as a degenerate case of generalized ellipsoidal harmonics.

A regional point-mass inversion for terrestrial water storage retrieval from satellite gravimetry

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Retrieving the terrestrial water storage anomalies (TWSA) from the observation of time variable gravity field is mainly performed by direct inversion of the spherical harmonic (SH) coefficients of the gravity field. It consists in the linearized solution of a standard two-layer inverse gravimetric problem. This approach has proven effective for GRACE and GRACE Follow-On. However, it presents potential limitations especially related to the spherical geometry

approximation and spectral truncation which may become limiting for future high-resolution gravity missions such as NGGM/MAGIC.

To overcome these limitations, this work investigates a regional inversion framework based on point-mass (PM) parameterization for the recovery of hydrological mass variations from satellite gravimetric observations. The method formulates the relationship between mass and gravity through localized mass elements and solves the inverse problem by least squares adjustment regularized by SH-derived prior information.

The numerical consistency of the complete forward-inverse chain is first assessed through noiseless closed-loop experiments over different regions. In particular, the impact of geometrical approximations is evaluated by simulating signal generated from masses positioned on a reference sphere, on a reference ellipsoid, or on a more realistic Earth obtained exploiting a digital elevation model (DEM). For each of these cases, the inversion is performed considering the three inverse operators (with spherical, ellipsoidal or DEM approximations). When inverting the realistic DEM scenario by the spherical operator a difference in mass estimation up to 6% can be expected.

The methodology is subsequently applied to realistic gravity simulations of the future MAGIC mission concept exploiting hydrological mass variations derived from ERA5-Land model. The results show that localized and geometry-consistent inversion strategies provide a flexible framework for regional mass-change estimation and represent a promising alternative to conventional global spherical harmonic approaches for the next-generation satellite gravimetry.

Sensitivity of geoid undulations and gravity anomalies to changing versus unchanging ellipsoidal parameters among solid Earth permanent tide system

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There exist well-defined formulas for conversion of physical Earth parameters and changing the second-degree zonal harmonic of a global geopotential model among the three solid Earth permanent tide systems. Though there also exist conversion formulas for dynamical form factor, semi-major axis, and flattening of a normal ellipsoid, these are rarely used in the spherical harmonic synthesis of the gravity field. Further, considering the facts that (1) tide-system of normal ellipsoid or its parameters have been mentioned in the literature (sometimes inconsistently also), (2) the existing conversion formulas of ellipsoidal parameters are calculated using truncated expansion series formulas, (3) SHS have been implemented with 'as-is' tide-system ellipsoidal parameters, and (4) a new normal ellipsoid is being thought of to be made available in different tide-system, this study provides arguments and numerical assessment for both the cases: change and no-change in ellipsoidal parameters due to different tide-systems. Further, more rigorous conversion formulas for ellipsoidal parameters have been provided along with parameters of GRS80 and GGOS-IHRS parameters implied new normal ellipsoid in the three permanent tide-systems. It is shown that (in SHS) geoid and free-air anomalies are independent of the permanent tide-system if we consider that there is a change in the ellipsoidal parameters for different tide-systems. The study recommends towards a required resolution on changing vs unchanging ellipsoidal parameters for geoid modelling, especially for the methods utilising remove-compute-restore.

On local gravitational field modelling by the spectral weighting of airborne gravimetry

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Airborne gravimetry and gradiometry offer valuable observations for regional gravity field modelling, particularly over areas with limited ground data. This study presents an alternative method for local downward continuation of the first-order radial derivatives of the disturbing gravitational potential at constant flight altitude onto disturbing gravitational potential, gravity disturbances and gravity anomalies. A spectral weighting scheme with limited integration radii is introduced to recover disturbing potential, gravity disturbances and gravity anomalies from radial derivatives of the disturbing potential. The spectral weights are determined analytically by the least squares method as functions of signal and error degree variances, balancing signal content and expected measurement noise.

Investigation of Kenyan Rift Valley lakes expansion through integrated SWOT, GEDI and optical remote sensing: Lake Naivasha, Nakuru, Baringo, Elementaita and Bogoria

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Over the past decade, the Kenyan Rift Valley lakes have experienced persistent water-level rises, significantly impacting hydrology, flood risk, ecosystems and local livelihoods. Although land-use changes and rainfall variability have been identified as contributing factors, they do not fully explain the observed lake expansion. It is hypothesised that tectonic shifts might also be playing a role, highlighting the need for improved long-term monitoring of lake-level dynamics. Ground-based gauge measurements are further challenged by tectonic movements and gauge submergence as the water levels rise, limiting consistent long-term monitoring. This study investigates the potential of integrating multi-source earth observation data to monitor the lake levels and extent variations over time.

Long-term lake surface area dynamics were derived from fused Landsat 5 – 9 and Sentinel-2 imagery using NDWI-based classification. Normalized Median Absolute Deviation (NMAD) filtering was applied to remove outliers and improve data reliability. Water level variations were obtained from GEDI LiDAR and SWOT radar altimetry, and additional filtering was applied to ensure consistency in temporal and spatial measurements. In-situ gauge data, where available, were used to validate the satellite-derived water levels.

NMAD filtering significantly reduced noise in both surface-area and altimetry datasets, producing robust time series suitable for analyzing Rift Valley lake dynamics. Strong agreement was observed between SWOT-derived water levels and in-situ gauge measurements for Lake Naivasha, Nakuru, and Baringo, with RMSEs of 0.53m, 0.57m and 0.75m, respectively, confirming the reliability of satellite altimetry for lake-level monitoring. Due to limited gauge records overlapping with GEDI observations, validation of GEDI using in-situ data was not possible. On average, between 2016 and 2018, the lakes extent increased by 11%, accompanied by water-level rises of 2.36m.

Strong agreement between lake extent and water-level variations was observed across all datasets, indicating that surface area changes closely reflect lake-level fluctuations. On average, the correlation value between area and SWOT-derived water levels for the lakes was 0.94, demonstrating the effectiveness of integrated multi-sensor observations for long-term lake monitoring, especially in lakes with limited ground-based observations.

Friday, 11/Sept/2026, 9:00am - 11:00am

S9: Troposphere and ionosphere

Session Chair: **Dr. Michela Ravanelli**

Session Chair: **Dr. Ilaria Ferrando**

9:00am - 9:20am

GNSS-based spatial prediction of zenith and slant tropospheric delays using the Augmented Iterative Tropospheric Decomposition model and data-driven refinements

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The Augmented Iterative Tropospheric Decomposition (AITD) model was recently introduced as a spatial prediction strategy for generating Zenith Total Delay (ZTD) maps from permanent GNSS station networks.

The method mitigates interpolation artifacts that may arise when the original Iterative Tropospheric Decomposition (ITD) strategy-implemented in the state-of-the-art GACOS service-is applied to sparse and irregularly distributed GNSS observations instead of gridded ZTDs derived from Numerical Weather Prediction (NWP) models.

The present contribution first recalls the main features of the AITD framework and then introduces a data-driven refinement aimed at extending the approach from ZTD prediction to the prediction of Slant Tropospheric Delays (STDs) within a regional permanent GNSS network.

By exploiting single-epoch Precise Point Positioning (PPP) estimates of ZTDs and STDs at permanent GNSS stations, the method enables the generation of STDs at any point within the network area, provided that its 3D cartesian coordinates and the same coordinates of the satellites in view are known.

By leveraging the AITD model the ZTD can be predicted in any target location. The STDs can be then obtained by projecting this ZTD into the required slant directions using a mapping function, such as the Vienna Mapping Functions 3 (VMF3). This strategy provides an effective link between zenith and slant delays, but it relies on auxiliary NWP data required by the mapping function.

The refinement presented here addresses this limitation by introducing a GNSS-only data-driven model. A neural network was trained to reproduce a residual component of the slant delays with respect to rough slant delays obtained by geometrically projecting the AITD-predicted zenith delays along the corresponding satellite directions.

The objective is to achieve a prediction accuracy comparable to that of the VMF3-based formulation while reducing the dependence on external atmospheric model data.

The proposed approach was assessed through a Leave-One-Out (LOO) validation using 24 stations of the SPIN3 GNSS permanent network located in northern Italy.

Reference ZTDs and STDs were obtained through the PPP processing strategy implemented in the BREVA software developed by GReD srl.

The RMSE of the differences between the predicted and the actual STDs of all the SPIN3 stations was computed by considering both the proposed GNSS-only method and the AITD-VMF3 approach, showing that the proposed method can replace the VMF3 based one with comparable accuracy.

This study represents an incremental development of the AITD framework: it preserves the original strategy for GNSS-based ZTD map generation while extending its applicability towards high-temporal-resolution prediction of slant tropospheric delays from permanent GNSS networks.

9:20am - 9:40am

High-Resolution GNSS-TEC Characterization of Ionospheric Disturbances Induced by Natural Hazards

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Earthquakes and tsunamigenic events generate atmospheric acoustic and gravity waves that can propagate upward and perturb the ionospheric plasma. These disturbances can be detected through GNSS-derived Total Electron Content

(TEC) measurements, providing a powerful tool to investigate lithosphere–atmosphere–ionosphere coupling, improve understanding of hazard dynamics, and support real-time tsunami monitoring.

A striking example is the 2022 Hunga Tonga–Hunga Ha‘apai eruption. The event generated a strong atmospheric pressure wave (Lamb wave) that produced unexpectedly large ionospheric signatures, revealing important gaps in our understanding of wave–ionosphere coupling. We observe time delays of approximately 12–20 minutes between the passage of the atmospheric disturbance and the ionospheric response, providing new insight into the temporal dynamics of the coupling process. In addition, the same event generated an air–sea response in the form of a non-seismic tsunami, highlighting limitations of classical tsunami early warning systems for non-seismic sources, while also demonstrating the added value of ionospheric sensing for more comprehensive detection strategies.

To systematically extract and analyze these signals, we developed a deep-learning framework for the automatic detection of tsunami-related ionospheric disturbances using real-time GNSS-TEC observations. The approach combines VARION-based TEC estimates, Gramian Angular Difference Fields (GADF), and convolutional neural networks (CNNs). Trained on several major Pacific earthquakes and validated on independent events, the model achieves an F1-score of 91.7% and a recall of 84.6%, demonstrating strong generalization capability and robustness in real-time conditions. Ongoing developments aim to extend this framework beyond detection toward the classification and attribution of traveling ionospheric disturbances (TIDs) generated by different physical mechanisms, including earthquakes, volcanic eruptions, atmospheric forcing, and space-weather activity. Discriminating between these sources remains a major challenge for both scientific interpretation and operational applications.

To operationalize these advances, the ALTRUIST (total variomeTry foR tsUnamI hazard eStimaTion) project was initiated. It integrates real-time ground-motion estimation (VADASE) and ionospheric TEC monitoring (VARION) within a unified multi-GNSS processing chain, providing a scalable testbed for high-rate, multi-layer observations of natural hazards.

Overall, this work highlights GNSS-TEC as a powerful tool for high-resolution probing of ionospheric variability and atmosphere–ionosphere coupling, enabling improved understanding of rapid geophysical processes and hazard dynamics.

9:40am - 10:00am

Shipborne GNSS-derived Precipitable Water Vapor tracking and validation along the Amerigo Vespucci world tour (2023–2025)

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The Italian Navy’s Amerigo Vespucci ship world tour 2023-2025 offers a unique and remarkable laboratory for multidisciplinary environmental observations over the global oceans where direct measurements are still extremely limited. Among the different research activities carried out onboard by the Sea Study Center of Genoa University, Precipitable Water Vapor (PWV) assessments contribute to the progress of the knowledge of marine atmospheric processes. In this study, the PWV derived from a Global Navigation Satellite System (GNSS) receiver installed on the iconic ship is compared with the hourly PWV derived from the ERA5 reanalysis dataset. The goal is to assess the ability of GNSS observations acquired in a dynamic marine environment to sense atmospheric moisture variability and to evaluate its consistency with a widely used numerical reanalysis dataset. The GNSS-derived PWV time series showed large temporal variability during the observation period, which indicates rapid changes of the atmospheric moisture over the ocean. In contrast, ERA5 PWV exhibited a smoother temporal evolution because of its model-based assimilation framework and coarser spatial representation. Overall, ERA5 can reproduce the large-scale temporal behavior of PWV over the marine environment while shipborne GNSS observations can provide higher frequency information and more sensitivity to localized atmospheric processes. The results show the feasibility of using shipborne GNSS systems onboard Amerigo Vespucci for continuous monitoring of atmospheric water vapor over the oceans as a moving observatory. Differences between the two datasets may arise from the spatial and temporal smoothing inherent in reanalysis products, the influence of mesoscale meteorological phenomena that are not fully resolved by ERA5, the uncertainties associated with ship motion and the GNSS processing. Assessing the coherence of shipborne GNSS-derived PWV and ERA5 data is a crucial step in view of a future possible assimilation in numerical weather prediction models. Indeed, the integration of shipborne GNSS PWV with ERA5 and other atmospheric datasets is promising for the improvement of marine meteorology, numerical weather prediction and climate studies, particularly for data-sparse oceanic regions.

10:00am - 10:20am

Generation of the first national-scale Precipitable Water Vapor (PWV) Maps in Italy based on the New ASI Fiducial GNSS Network

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Precipitable Water Vapor (PWV) is a key atmospheric parameter for the analysis of meteorological processes, extreme weather events, and potential atmosphere-lithosphere interactions. This work presents the development of the first national-scale PWV maps for Italy coming from GNSS observations, based on the New ASI (Italian Space Agency) Fiducial GNSS Network, achieved through the proprietary processing procedure developed by the Geomatics Laboratory of the University of Genoa, called G4M (GNSS for Meteorology). The PWV distribution is obtained from Zenith Total Delay (ZTD) and near-surface atmospheric pressure (P) and temperature (T) observations. The G4M procedure has been upgraded in its workflow introducing several methodological and technological innovations, to manage the Italian national extension. A major step was to design a DataBase (DB) scheme to receive, examine and manage data coming from both the GNSS and meteorological observations networks. First, ZTD estimates provided by the EUREF infrastructure for stations belonging to the new ASI Fiducial GNSS Network were incorporated and stored in the DB to support operational PWV estimation at national scale. Then, the near-surface atmospheric P and T observations coming from the MeteoNetwork (MNW) observations network were preliminary validated against reference NOAA datasets for the 2023–2025 period and subsequently organized within the same dedicated DB. The assessment of the spatial resolution achievable by PWV maps was conducted based on the geometry and density of both the MMN and ASI's GNSS networks. Several intense meteorological events were analyzed to investigate the spatial correlation length of PWV fields, highlighting a dependence on the characteristic scale of the atmospheric phenomena under study. These analyses provide valuable information for defining the optimal mapping resolution and for evaluating the representativeness of the generated PWV fields. Regarding the temporal resolution, PWV maps are evaluated in respect of the ZTD and P, T acquisition rates. Finally, the entire processing chain has been automated to support future near-real-time applications, enabling access to advanced PWV mapping capabilities by non-expert users. The resulting national PWV maps constitute a new observational product for Italy, supporting the investigation of severe weather events and providing a basis for future studies on the relationship between PWV field anomalies and seismic activity.

This research project is funded by the Italian Space Agency under Implementing Agreement No. 2024-25-HH.0, “Monitoraggio dello stato troposferico a livello nazionale e precursori sismici a partire dai dati della nuova rete fiduciale nazionale GNSS dell’ASI” (CUP: F33D24000060001).

10:20am - 10:40am

Assessment of correlation length and GNSS-derived PWV mapping across Italy under different meteorological scenarios

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This study investigates the spatial correlation length of Precipitable Water Vapor (PWV) as a measure of atmospheric moisture variability and as a key parameter for defining the effective spatial resolution of national-scale PWV maps. Indeed, estimating the PWV correlation length is therefore essential for determining the spatial representativeness and resolution of PWV mapping products. The proprietary procedure called G4M (GNSS for Meteorology) has been developed by the Geomatics Laboratory of the University of Genoa to produce 2D PWV maps starting from GNSS and meteorological sensors observations. The GNSS stations within the New ASI (Italian Space Agency) Fiducial GNSS Network and the meteorological sensors belonging to MeteoNetWork (MNW), a citizen-science meteorological observation network, are the sources of GNSS and meteorological data, respectively. Several case studies involving significant meteorological events over Italy are analyzed. These events span a wide range of spatial scales, from local convective systems to large-scale synoptic conditions. The objective is to assess whether the PWV correlation length

depends on the characteristic scale of the atmospheric phenomenon and to quantify its variability before, during, and after significant weather events. Furthermore, PWV maps generated through the proprietary G4M procedure will be compared with the corresponding PWV fields derived from the ERA5 reanalysis dataset, providing an initial evaluation of the consistency and reliability of the GNSS-based products. Preliminary results indicate that the resulting PWV maps provide an initial nationwide representation of atmospheric PWV conditions, supporting the identification of potentially critical areas that may require more detailed meteorological investigations and contributing to the optimization of future high-resolution GNSS meteorology applications over Italy.

This research project is funded by the Italian Space Agency under Implementing Agreement No. 2024-25-HH.0, “Monitoraggio dello stato troposferico a livello nazionale e precursori sismici a partire dai dati della nuova rete fiduciale nazionale GNSS dell’ASI” (CUP: F33D24000060001).

10:40am - 11:00am

Analysis of atmospheric water vapor variability associated with seismic activity: first experiences starting from ASI’s national GNSS fiducial network

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Recent seismic activity in Italy has renewed interest in multidisciplinary approaches aimed at investigating interactions between geophysical and atmospheric processes. In this context, GNSS-derived Precipitable Water Vapor (PWV) represents a promising parameter for studying atmosphere–geosphere coupling through the analysis of atmospheric water vapor variability associated with seismic activity. This study presents a preliminary framework for investigating potential relationships between PWV variability and seismic activity through the integration of seismic and GNSS observations across Italy. Previous studies suggest links between earthquake-induced energy release, atmospheric temperature variations, and consequent increases in PWV. Furthermore, several investigations have explored whether microearthquakes may be associated with subtle thermal anomalies that could precede larger seismic events. Seismic events with magnitude greater than or equal to 4.0 occurring between December 2024 and April 2026 were selected from the catalog of the Istituto Nazionale di Geofisica e Vulcanologia (INGV). Initial analyses focused on the Campi Flegrei area because of the shallow depth of the recorded earthquakes and the ongoing bradyseismic crisis, making it a suitable case study for preliminary investigations. The seismic domain associated with each event was constrained using data from the Italian National Accelerometric Network (RAN). Peak Ground Acceleration (PGA) values recorded by RAN stations were used to delineate the area affected by seismic shaking. GNSS stations belonging to the national reference network operated by the Italian Space Agency (ASI) and located within the identified seismic domain were subsequently selected for PWV analysis. GNSS data acquisition and the characterization of PWV spatiotemporal variability are currently being performed using G4M (GNSS for Meteorology), a proprietary procedure developed by the Geomatics Laboratory of the University of Genoa. The methodology aims to (1) generate national-scale PWV maps and (2) investigate potential correlations between seismic events and PWV anomalies using observations collected by the ASI National GNSS Reference Network. The proposed integrated RAN–GNSS approach provides a physically constrained framework for investigating temporal and spatial relationships between seismic activity and atmospheric water vapor variability at local and national scales. The ongoing research may contribute to a better understanding of atmosphere–geosphere interactions and support the development of multiparametric monitoring strategies for seismically active regions.

This research project is funded by the Italian Space Agency under Implementing Agreement No. 2024-25-HH.0, “Monitoraggio dello stato troposferico a livello nazionale e precursori sismici a partire dai dati della nuova rete fiduciale nazionale GNSS dell’ASI” (CUP: F33D24000060001).

Friday, 11/Sept/2026, 11:20am - 12:50pm

S10: New altimetry missions

Session Chair: **Prof. Lucie Rolland**

Session Chair: **Prof. Mattia Crespi**

11:20am - 11:50am

Tsunami monitoring with space altimetry: new perspectives from SWOT

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Satellite radar altimetry has long demonstrated its value for observing tsunamis in the open ocean, but conventional nadir altimeters provide only one-dimensional measurements along their ground tracks. The SWOT mission represents a major advance by delivering the first two-dimensional observations of sea surface height at high spatial resolution.

Following the first SWOT observation of the 2023 Loyalty Islands tsunami, the mission has also imaged the tsunamis generated by the 2 May 2025 Mw 7.4 Drake Passage earthquake and the 29 July 2025 Mw 8.8 Kamchatka earthquake. In each case, SWOT's KaRIn instrument resolved the two-dimensional tsunami wave field, providing unprecedented observations of wavefront geometry and propagation.

This presentation reviews these first tsunami observations from SWOT and discusses their implications for tsunami science. Comparisons with numerical simulations highlight the potential of wide-swath altimetry to improve tsunami source characterization, validate propagation models, and complement existing observations from conventional altimetry, GNSS ionospheric sensing, seismic networks, and tide gauges. These first results illustrate the new opportunities offered by SWOT for advancing tsunami monitoring and future early-warning capabilities.

11:50am - 12:10pm

Evaluation of ICESat-2 LiDAR Altimetry for Sea Surface Height Applications

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ICESat-2 photon-counting LiDAR altimetry represents a promising source of sea surface height (SSH) observations, particularly in coastal and semi-enclosed basins where conventional radar altimetry may be limited by reduced spatial resolution and land contamination effects. The Mediterranean Sea, characterised by relatively small sea-level gradients and complex coastal dynamics, provides a challenging environment for evaluating emerging altimetric approaches.

In this study, ICESat-2 SSH data collected over the Ligurian Sea between 2018 and 2024 were processed through a dedicated Python workflow including photon extraction, quality control, spatial averaging, and tidal correction. More than 3900 satellite passes were initially considered and subsequently filtered to generate a quality-controlled dataset suitable for oceanographic applications. Seasonal and annual SSH maps were produced and compared with independent observations from in situ data and the Genoa tide gauge. Results show that ICESat-2 successfully reproduces the seasonal variability of sea level, with good agreement with in situ observations (correlation = 0.82; RMSE = 0.04 m). Seasonal patterns were consistent with the expected steric and atmospheric contributions, showing lower SSH values in winter and higher values during summer. However, absolute SSH fields exhibited spatial gradients larger than expected from the known regional circulation, suggesting residual uncertainties associated with geoid modelling, atmospheric pressure effects, and heterogeneous spatial coverage. The study highlights the potential of ICESat-2 as a complementary tool for investigating seasonal sea-level variability in the Mediterranean Sea and supporting regional oceanographic analyses. As a continuation of this work, the proposed methodology is currently being extended to additional case studies, including Arctic environments, to assess its applicability across different oceanographic settings.

12:10pm - 12:30pm

Impact of EGM2008 Geoid Model on Lake Surface Orthometric Heights Observed by SWOT and ICESat-2 Altimetry

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It is a fundamental principle of geodesy that a water surface at rest conforms to the local gravity field potential; thus, a lake surface, free from hydrological and atmospheric perturbations, materializes an equipotential surface. However, these surfaces do not maintain constant orthometric heights due to the non-parallelism of equipotential surfaces (driven by Earth's rotation) and local density variations between the surface and the geoid. Consequently, orthometric heights inherently vary across a lake's latitudinal extent.

This study builds on top the considerations and conclusions highlighted by Sneew et al. [1] and benefits from the present technological advances. In details, it investigates lakes that are wide, deep, and situated at high elevations, such as Lake Michigan and Lake Titicaca, to maximize these theoretical orthometric height variations and assess their detectability via the Surface Water and Ocean Topography (SWOT) mission, with validation from ICESat-2. SWOT's high-resolution interferometry, referenced to the EGM2008 gravitational model and corrected for atmospheric and tidal effects, provides a unique lens into these subtle gradients.

Preliminary analyses reveal spatial orthometric height variations of approximately 90 cm, consistently detected by both SWOT and ICESat-2 in both Michigan and Titicaca Lake. While the sensors show strong agreement, the observed profiles vastly exceed theoretical expectations, which predict variations of only ~5 cm for a basin like Lake Michigan. While dynamic processes (e.g., wind-driven setup, seiches, and long-period oscillations) contribute to water surface variability, they do not fully account for this magnitude of discrepancy.

Critically, this persistent 90 cm pattern seems pointing toward systematic inconsistencies in the EGM2008 geoid model, which is the most commonly used global geoid model for the altimetric sensors. In regions with complex topography or sparse data, such as the Andes, EGM2008 relies on fill-in gravity anomalies generated via Residual Terrain Model (RTM) forward modeling. This technique can introduce decimeter-level biases in geoid height, which are subsequently propagated into the satellite-derived orthometric heights. Our findings suggest that the "observed" spatial variations may be less a reflection of true water surface dynamics and more a manifestation of the inherent limitations and lack of high-accuracy terrestrial gravity data within the global geoid models currently used by altimetry missions.

References:

[1] Sneeuw, N., Berge-Nguyen, M., Cretaux, J.-F., 2024. Physical heights of inland lakes. J. T. Freymueller, L. S´anchez (eds), X Hotine-Marussi Symposium on Mathematical Geodesy, Springer International Publishing, 19–25.

12:30pm - 12:50pm

Estimating water level changes with SAR amplitude altimetry: the case study of lake trasimeno, Italy

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Traditionally, on-site water monitoring has been confined to large reservoirs in developed regions. However, as water scarcity worsens, tracking smaller, remote basins has become crucial. To address this gap, remote sensing effectively supplements or replaces traditional gauge stations. While radar altimetry is widely used for this purpose, conventional sensors are often limited by their large footprints.

As an alternative, Synthetic Aperture Radar (SAR) imagery offers traditional interferometric approaches that leverage phase signals to track water level variations. However, these methods are constrained by the low coherence of open water, which complicates phase unwrapping. The advanced SWOT mission significantly improves spatial limitations with a new interferometric technique, but its revisit time restricts continuous monitoring. Unlike interferometry, amplitude-based SAR techniques analyse backscatter differences along the shoreline, but they face a different constraint since they rely on highly accurate digital elevation models.

In this study, we propose a novel methodology to estimate water level changes using SAR amplitude data without requiring any a priori morphological information. The approach exploits the geometric relationship between the horizontal shoreline shifts (and the related variations in the sensor-to-target distance (Δd)) and the water level changes (Δh), which are linked by the local coastal slope (i) under the assumption that the local coastal morphology can be piecewise approximated by planes. By integrating this measured distance with the satellite's viewing geometry (e.g.,

azimuth and local incidence angle), we formulated the observation equation linking the Δd values to the unknowns Δh and i for each coastal zone, giving redundancy to the system.

We implemented the workflow using the SAM3 algorithm to generate water masks from SAR images coregistered with the pyGMTSAR library. The boundaries of these masks identify optimal locations for extracting image patches, which are then matched across different epochs to measure distance displacements Δd . These displacements are fed into a least-squares approach and combining the measured shifts with known geometric parameters, the model simultaneously estimates the water level variations Δh between epochs and the specific slope i of each coastal segment.

The methodology was tested on Lake Trasimeno (Umbria, Italy) using a stack of Sentinel-1 (S1) Single Look Complex (SLC) images (IW mode, VV+VH polarization) acquired in 2022 and 2023 from both ascending and descending orbits. Compared to in-situ gauge data, our estimates achieved high accuracy with median error of 5 cm and an NMAD of 3 cm, demonstrating the method's strong potential even with medium-resolution S1 imagery. Ongoing work focuses on optimizing the algorithm's performance and validating it across new case studies, leveraging its independence from basin size and SAR sensor type.
