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Abstract Book

Session M1: Applications in Earth Sciences and Infrastructure

Conveners: Laura Sánchez, Richard Gross

ID: M1 - o1 | Essential Geodetic Variables (EGVs) – Status and the way forward

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The definition of Essential Geodetic Variables (EGVs) is a key activity of IAG's Global Geodetic Observing System (GGOS). EGVs are specific measurements, observations or parameters that are critical for understanding, monitoring and predicting changes in the Earth system, to provide actionable information in supporting scientific research, decision-making and sustainable development in terms of environmental and socio-economic needs. The EGVs are considered as a powerful tool to address pressing challenges such as monitoring sea level rise and climate change effects, understanding Earth system dynamics, supporting disaster risk reduction, and to underpin the availability of sustainable geodetic services and infrastructure. In addition, EGVs raise awareness of geodesy and its fundamental products, encourage scientists and observing systems to place more emphasis on these variables, stimulate the commitments of funding agencies to support the provision of these variables, to enable cross-disciplinary research, and to facilitate interoperability between science and evidence-based policies. Establishing a comprehensive and widely accepted catalogue of EGVs, accompanied by well-defined requirements and stewardship, is critical to realizing these benefits and meeting the growing demands on geodetic science in a rapidly changing world. This contribution presents the progress made by GGOS in defining a catalogue of EGVs and identifies the next steps needed to establish them in the geoscience community. To demonstrate the relation between EGVs of different levels and some related products, the determination of global reference frames and Earth Orientation Parameters (EOP) is shown as an example. Finally, the strategy to define EGV requirements is explained and the roadmap towards their ultimate implementation is presented.

ID: M1 - o2 | Towards a mature Global Geodesy Supply Chain

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Geodetic products, including reference frames among others, are fundamental to numerous socio-economic sectors that rely on accurate timestamped geolocated data (e.g., telecommunications, finance, disaster management). Their importance in supporting the Sustainable Development Goals was formally recognised by the United Nations General Assembly in 2015 through the adoption of Resolution 69/266, titled "A Global Geodetic Reference Frame for Sustainable Development". These geodetic products are developed through a Global Geodesy Supply Chain (GGSC), which encompasses the full life cycle of geodetic data – from initial measurements to distribution of geodetic products to end-users. The GGSC includes ground-based observatories (e.g., VLBI, SLR, GNSS, gravimeters), combination and correlation centres, data centres, analysis centres, as well as operational services (e.g., human resources, technical support, management) to ensure efficient functioning of the geodetic infrastructure. Although several challenges within the GGSC have already been identified – such as aging infrastructure, underfunding, or insufficient recognition of the importance of geodesy by policymakers – no comprehensive qualitative or quantitative analysis of the entire GGSC has been conducted to date. Here we present a first-of-its-kind holistic assessment of GGSC maturity – defined as the developed state of the supply chain that enables the production and delivery of geodetic products with the required properties (e.g.,

accuracy, robustness, integrity) to fully meet end-user needs. We adopt several maturity assessment frameworks, widely employed in business architecture, to develop a tailored framework for evaluating GGSC maturity. The assessment covers six domains (i.e., engagement and collaboration, governance and strategy, data management, data products and software, asset and infrastructure management, innovation and development) evaluated across four maturity dimensions (i.e., people, processes, technology, and data). Overall, the current GGSC demonstrates moderate maturity levels across all four dimensions, raising a critical question: Is this level of GGSC maturity sufficient to ensure efficient GGSC functioning and fully meet the end-users needs? The GGSC maturity assessment aligns with the First Joint Development Plan for Global Geodesy and emphasises the need for coordinated actions to strengthen the GGSC. In the future, this work will be further extended with sensitivity studies to model the uncertainty propagation along the GGSC and evaluate its impact on the quality of geodetic products, thereby supporting evidence-based policymaking.

ID: M1 - o3 | From Reference Frames to Technological Benefits: Applications through the refined reference frames in the ESA's E-NAFF Project

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All coordinates are meaningless if they are not expressed in a defined reference frame, as the accuracy of a reference frame realization has a direct relation to the quality of resultant coordinates. The E-NAFF project, carried out for ESA, aims to explore the needs for accurate reference frames across industry, environmental monitoring, and society, as well as to investigate the future potential and limitations of improved realizations of the International Terrestrial Reference Frame (ITRF). Current realizations of the ITRF are consistent to a few millimeter level, with differences in origin, scale, and orientation of ITRF2014, ITRF2020, and ITRF2020-u2024 not exceeding 5 mm. Even though this level of stability suffices for most geodetic applications, inconsistent treatment of ITRF realizations or the omission of periodic and post-seismic effects can result in substantial discrepancies. Therefore, strict and uniform application of terrestrial and vertical reference frames remains unavoidable, particularly in high-precision geodetic and engineering applications where the highest accuracy is required. Although reference frames are not market products per se, they represent an unavoidable intermediate component required to obtain the final products, e.g., georeferenced coordinates used in numerous market applications. Reference frame accuracy and stability support the whole GNSS and Earth Observation (EO) infrastructures and have a direct influence on the quality and reliability of satellite-based services. Integration of GNSS and EO data within a consistent global reference framework ensures reliable, interoperable positioning and georeferencing, and therefore, translates reference frame accuracy into real societal, commercial, and scientific benefit. The E-NAFF project focuses on assessing the impact of ITRF realizations in the three main domains: environmental monitoring and agriculture, industry, and real-time GNSS services employed, e.g., for airborne laser scanning or autonomous mobility. It aims to determine where improved geodetic reference frames are essential and where their refinement can deliver the highest societal and economic benefits. Special emphasis has been given to the identification of existing gaps and limitations in the realization and dissemination of ITRF against operational and industrial needs and its evaluation towards enabling environmental and agricultural monitoring. The E-NAFF project combines an assessment of the state of the art in reference frame realization with consultation and validation actions with selected stakeholders. This synergy ensures that the results of the study reflect real-world requirements and expectations from scientific, industrial, and societal communities. The results will be consolidated and converted into

recommendations for future development, aligned with ESA's strategic objectives and facilitating the GENESIS mission and related international programs.

ID: M1 - o4 | Climatic Impacts on Earth Orientation Parameters

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Time-variable Earth orientation parameters (EOP) connect global terrestrial reference frames realized by geodetic markers and/or instruments on the ground with celestial reference frames anchored in inertial space. Despite being sensitive to residual errors arising from the combination of multiple space geodetic techniques that each have substantially evolved during past decades, EOP also contain valuable information on a wide range of geophysical signals that are characterized by large-scale mass transport processes on Earth. In this contribution, we will focus on the climatic impacts on both polar motion and changes in the Length-of-Day by using latest effective angular momentum (EAM) functions from global reanalyses and/or unconstrained model simulations of atmosphere, oceans and the terrestrial hydrosphere. In particular, we will present new simulations with the global hydrological model OS LISFLOOD which covers all land areas of the Earth with a spatial resolution of 1/20°. Daily hydrological EAM from different OS LISFLOOD experiments available from 1962 until present day will be contrasted against the latest realization of the EOP C04 series consistent with ITRF2020 and other publicly available EOP time-series. We will in particular focus on sub-seasonal-to-interannual variations in EOP that are related to large-scale climate modes in the interactively coupled Earth system, and will discuss present-day status of opportunities and limitations for the utilization of EOP in the climate sciences.

ID: M1 - o5 | Surface loading deformation in GNSS: testing the hydrological model OS LISFLOOD

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Time-dependent mass variations of near-surface geophysical fluids in the atmosphere, the oceans and the continental hydrosphere lead to significant and systematic load-induced deformations of the Earth's crust. Based on station coordinate time series derived from geophysical models it is possible to assess the impact of time-dependent mass variations on the Earth's surface geometry and, thus, to assess the impact of uncorrected deformations on GNSS-derived station positions and terrestrial reference frame parameters. Model-based deformation products publicly available from GFZ contain vertical and horizontal crust deformations imposed by surface loading of geophysical fluids in atmosphere, oceans and the continental hydrosphere with a spatial resolution of 0.5° and a temporal sampling of down to 3 hours. Recently, a change from the Land Surface Discharge Model (LSDM) to the open-source rainfall-runoff-routing model OS LISFLOOD for the computation of the hydrologic loading was tested. Compared to LSDM, OS LISFLOOD shows a better representation of mass-induced surface deformations in many regions, especially in the interannual frequency domain. Based on ten years of reprocessed GNSS observations from more than 150 GNSS stations the impact of surface deformation corrections on station coordinate time series are investigated. The main focus of this contribution is the assessment of the new OS LISFLOOD model. In the first part of this contribution, we discuss the impact of surface loadings on the local and regional scale based on the GNSS stations processed in PPP mode. Here the focus is especially on areas known for large annual surface deformations. The second part concentrates on the impact of surface loading deformations on operational products derived in IGS-like rapid and final processing time series.

ID: M1 - o6 | Deformation Modelling of the receiving unit of a VLBI radio telescope

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Gravitational deformations of the receiving unit of VLBI radio telescopes systematically affect the receiving properties and cause biases in the derived products. As this deformation is unique for each radio telescope, the International VLBI Service for Geodesy and Astrometry (IVS) recommends investigations of gravitational deformation to provide correction models for VLBI data on the observation level; a challenging task for the JWG Metrology of Space Geodetic Infrastructure. Since the 1980s correction models are known and applied, that degrade the spatial problem to a two-dimensional problem, considering only homologous deformation and only taking into account three main deformation patterns. More recent studies contradict the assumption of uniform deformation and reveal more complex deformations. Therefore, identifying and modelling all relevant deformation patterns require more sophisticated analysis techniques. This contribution presents an innovative approach for modelling signal path variations using Zernike polynomials. In contrast to the conventional approach, the entire receiving structure is modelled spatially, and the analysis is not restricted to homologous deformation scenarios. Results from the analysis of the receiving unit of the 26-meter radio telescope at the Mount Pleasant Radio Observatory in Hobart, Tasmania, Australia, demonstrate the benefit of the new approach.

ID: M1 - p1 | Contribution of Geodesy to Earth System monitoring: The role of the Global Geodetic Observing System GGOS

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The Global Geodetic Observing System (GGOS) represents the coordinated response of the international geodetic community, under the auspices of the International Association of Geodesy (IAG), to the need for continuous monitoring of the Earth system. As geodesy's contribution to the Global Earth Observation System of Systems (GEOSS), GGOS provides the essential reference frames for all position-dependent observations that form the basis for most Earth observations. It measures changes in the Earth's shape, gravity field and rotation over time and space. Based on the scientific services of the IAG (IGS, IVS, ILRS, IDS, IERS, IGFS, ISG, PSMSL, IGETS, IDEMS, ICGEM, BGI), GGOS provides operational Earth observation using space- and ground-based geodetic techniques. A key objective is to create an integrated framework that moves beyond technique-specific products to combined, comprehensive datasets and products that allow consistent modelling and interpretation of Earth system processes. This integration is essential for a coherent monitoring system that improves our understanding of global change and its environmental and societal impacts. Achieving this requires strong international and multidisciplinary collaboration, focusing on (1) Aligning geodetic observation techniques, services and analysis methods to ensure consistency of data standards, conventions, models and parameters; (2) Integrating geometric, gravimetric and Earth rotation observations to jointly estimate and model key Earth system parameters; (3) Identify scientific and societal needs that

can be addressed by geodetic products, while defining accuracy, time resolution and consistency requirements; (4) Identify and address service gaps with strategic solutions; (5) Increase the visibility of geodesy by improving the accessibility of geodetic observations, information and products to a wide range of users. This contribution highlights recent achievements, ongoing initiatives and key challenges for the future.

ID: M1 - p2 | A Portal for Monitoring GNSS Data Quality in the Distributed EPOS-GNSS E-Infrastructure

Fikri Bamahry; Dr. Juliette Legrand PhD; Dr. Carine Bruyninx; Andras Fabian; Dr. Eric Pottiaux

Royal Observatory of Belgium, Belgium

The European Plate Observing System (EPOS) is a research platform that offers multidisciplinary data and services for advancing Solid Earth research. The Global Navigation Satellite Systems (GNSS) component of EPOS (EPOS-GNSS) ensures that the EPOS platform provides access to GNSS data, metadata, and products from as many as possible permanently tracking GNSS stations across Europe. These efforts are made in collaboration with the European Reference Frame (EUREF) community. Currently, EPOS and EUREF are working together to make all daily RINEX data from EUREF stations discoverable through EPOS. This is achieved through a dedicated EPOS data node, one of the twelve distributed data nodes, connected to a central EPOS-GNSS Data Gateway. To support the continuous and long-term assessment of GNSS data quality, the Royal Observatory of Belgium has developed the EPOS-GNSS Data Quality Monitoring Service (DQMS), accessible at https://gnssquality-epos.oma.be. This poster presents the functionality of the DQMS portal, which monitors the availability and quality of daily GNSS data from more than 1,900 stations integrated within the EPOS-GNSS e-infrastructure. Currently, 447 of these stations are EUREF stations, but this will be extended to 511 stations. A comprehensive set of Data Quality Indicators (DQIs)—including the ratio of observed versus expected observations, number of missing epochs, number of tracked satellites, maximum number of observations, number of cycle slips, and code-based multipath values—is visualized online to identify potential degradations in EPOS-GNSS station performance. This poster further demonstrates how degraded tracking at low-elevation angles, an increased number of cycle slips, and higher multipath values can degrade the quality of GNSS position time series. We also highlight how undocumented changes in the elevation cut-off angle can introduce apparent jumps in the GNSS position time series; identifying such changes through the DQIs helps GNSS analysts to correctly interpret these artifacts. Through these examples, we will show that the DQI plots provided in the DQMS portal are valuable tools for GNSS data analysis that support both geophysical research and the maintenance of geodetic reference frames.

ID: M1 - p3 | The M^{3}G Service: Managing GNSS Metadata to Support Geodetic Reference Frames in Europe

Andras Fabian; Dr. Carine Bruyninx; Anna Miglio; Dr. Juliette Legrand PhD

Royal Observatory of Belgium, Belgium

Accurate and traceable documentation of GNSS station configuration is essential for maintaining and providing access to geodetic reference frames. The M^{3}G (Metadata Management and Distribution System for Multiple GNSS Networks) service (https://10.24414/ROB-GNSS-M3G), developed and operated by the Royal Observatory of Belgium (ROB), provides a centralized platform for managing standardized and validated GNSS station metadata in support of European and global reference frame activities. Originally established within the EUREF and EPOS frameworks, M^{3}G now supports multiple organizations and networks, with more than 150 registered GNSS agencies uploading their station information and keeping it up-to-date. M3G provides an interactive UI and a RESTful API for uploading, validating and retrieving GNSS station

metadata, handling both IGS-style site log format and GeodesyML. M^3G ensures consistent, high-quality, and FAIR (Findable, Accessible, Interoperable, Reusable) metadata describing GNSS stations, including those contributing to the European Terrestrial Reference System (ETRS89). Automated validation routines ensure that the uploaded metadata meet internal consistency rules and GNSS standards, while persistent resolvable identifiers are assigned to enhance data traceability and citation. M^3G's metadata records include detailed station identifiers (9-character IDs, coordinates, installation dates), change logs of equipment and environmental modifications, station pictures, information on data licensing and stakeholder responsibilities, data access details, and network affiliations. By harmonizing this information across European GNSS networks and making it accessible, M^3G supports long-term monitoring of station configuration changes — critical for ensuring reference frame stability and reproducibility. M^3G is free to use and accessible online, promoting open, standardized, and reusable metadata. Here we describe the architecture and functionalities of the M^3G service and its role in strengthening Europe's contribution to the maintenance of global geodetic reference frames.

ID: M1 - p4 | Isolating the common mode error from the European GPS displacements

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In the Global Positioning System (GPS) displacements, systematic errors and unmodelled effects are observed as a common mode error (CME), the isolation of which from displacements seems to be crucial for obtaining reliable velocities and their errors. We use a set of European GPS displacements recorded at 4,443 permanent stations provided by the Nevada Geodetic Laboratory (NGL) and, in the first step, we compare them comprehensively with non-tidal atmospheric (NTAL), hydrospheric (HYDL), and oceanic (NTOL) loading models provided by the GFZ Helmholtz Centre for Geosciences to obtain a consistent picture of GPS sensitivity to loadings over Europe. We note that the correlation between GPS displacements and loading models is significant, but depends on the region. Next, we determine the CME using the probabilistic Principal Component Analysis (pPCA) method. We divide GPS stations regionally. The division depends on the parameters of the stochastic part of the time series. We note a significant correlation between the NTAL model and the CME values, which indicates that in Europe, most of the CME error is generated by the unmodeled NTAL effect. Finally, we estimate the values of velocities of GPS permanent stations together with their errors after removing the CME values.

ID: M1 - p5 | Assessing the evolution of position time series derived from satellite Doppler measurements

Prof. Dr. Janusz Bogusz[1]; Dr. Anna Klos[1]; Dr. Guilhem Moreaux[2]; Dr. Artur Lenczuk[1]

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DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) is a satellite tracking system based on the Doppler effect, with beacons distributed evenly around the world. They collect data from a set of available satellites that have evolved over the years of the system's operation, i.e., from 1992 to the present. Along with the evolution of satellites, there has also been technological progress in the field of individual beacons and the processing of DORIS observations. All this results in an increase in the applicability of DORIS measurements. In this research, we discuss the technological evolution of the system over the years. We examine its impact on parameters determined from weekly position time series aligned to the latest version of the International Terrestrial Reference Frame (ITRF2020) with regard to their use in geodynamic analysis. As the system continues to be upgraded, i.e., from the "network densification" phase, through "network renovation", to the "modernization era", seasonal variations and nonlinear characteristics are investigated, along with uncertainty assessment using preferred noise model.

The research concludes with a discussion of the current accuracy of determining linear velocities using the DORIS system, for example for geodynamic studies or annual oscillation amplitudes for hydrogeodesy.

ID: M1 - p6 | Review of IERS Conventions Chapter 1 for Numerical Standards and IERS Conventional Values

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Chapter 1 of the IERS Conventions (v1.3.0) "General definitions and numerical standards" contains two tables: Table 1.1 (IERS numerical standards) and Table 1.2 (Parameters of the Geodetic Reference System (GRS80). Many of the constants listed in the IERS numerical standards table are candidates to be updated based on recent IAG, IUGG, IAU resolutions and widely accepted usage of these values by the community. However, before finalizing any updates based on widely accepted usage, the Chapter 1 authors have identified a list of expected applications by IERS and other components that might be affected by any changes in values. This list of proposed changes and expected usages is presented in this poster. In addition, some of the constants listed in Table 1.2 have differing values from that listed in Table 1.1, which may confuse users. We ask users and various IERS and other services and components to review the information provided and contact the IERS Conventions with their suggestions, recommendations and concerns before the expected publication date of the next IERS Conventions update (v2.0.0), scheduled for release in late 2026.

Session M2: Defining Lunar Space: Frames, Time Systems and Interoperability
Conveners: Maria Karbon, Mingyue Zhang

ID: M2 - o1 | From Roundtable to Roadmap: Progress on Lunar Standards and Interoperability

Dr. Susan Stewart PhD[1]; Prof. Agnes Fienga PhD[2]

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We present the current status of lunar reference frame, geodetic, and timing standards, building directly on the outcome of the International Astronomical Union (IAU) Symposium 401 roundtable on the Role of Standards and Standards Organizations (LaPlata, 2025). Key outcomes include the need for integration across celestial, lunar, and terrestrial frames, time scales, and ephemerides, fostering cross-disciplinary collaboration to formalize interoperability. Participants also highlighted ambiguity in lunar standards governance, advocating for an "organization of organizations" approach, and emphasized the importance of unified standards work coordinated within existing IAU/IAG ecosystems. Finally, the roundtable underscored the necessity of separating standards bodies from operational mission centers to maintain authoritative conventions, and recognized that well-chartered working groups can issue standards, not solely through full resolutions. The IAU actively supports standardizing foundational lunar parameters, having made progress with the recommendation of a Lunar Celestial Reference System (LCRS) and continued discussions regarding lunar surface frames through IAG WG 3.1.1 on Lunar Reference Frame. By focusing on ongoing progress and remaining open standardization needs, this presentation offers a concrete, standards-first pathway that preserves the essential boundary between authoritative conventions and mission operations, while simultaneously delivering the crucial products required by the lunar community.

ID: M2 - o2 | Propositions of recommendations on Lunar reference systems and frames by the IAG WG 1.3 and synergy with IAU

Prof. Dr. Agnes Fienga[1]; Krzysztof Sosnica[2]; Nicolas Rambaux[3]; Dmitry Pavlov[4]; Sergei Klioner[5]; Susan G. Stewart[6]; Erwan Mazarico[7]; Dr. Maria Karbon[8]; Jurgen Mueller[9]; Pascale Defraigne[10]; Robert Heinkelmann[11]; Trevor W. Gardner[12]; Javier Ventura-Traveset[13]; Richard Swinden[14]; Cheryl J. Gramling[15]; Luciano Iess[16]; JS Ping[17]; Masaya Murata[18]; Suzana Okamoto[18]; Stephen M. Merkowitz[7]; Vishnu Viswanathan[7]; Nicholas R Makley[12]; Pierre Waller[19]

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Since 2022, IAG JWG 1.1.3 has been working to define lunar reference systems and frames, in coordination with the IAU and the BIPM. In this presentation, we will review the characteristics of the ITRS and ITRF, and explain how the Moon's situation differs from that of the Earth. We will review the progress made in providing clear definitions for users of the ILRS (International Lunar Reference System) and its realization, the ILRF (International Lunar Reference Frame). We will present the properties that should be employed to define the lunar-fixed reference system, and propose an initial version of the ILRF obtained by combining three reference lunar ephemerides. We will also provide updates on the ongoing discussions between the IAU WG on Cartography and Rotational Elements and the IAG WG 1.1.3 regarding the definition of the lunar-fixed reference system and its realization. Finally, we will consider possible future developments for the ILRF, in particular. In the context of the ESA Novamoon mission.

ID: M2 - o3 | International Lunar Reference Frame (ILRF) – the first combined reference frame realization for the Moon

Prof. Krzysztof Sośnica PhD[1]; Prof. Agnes Fienga PhD[2]; Dr. Dmitry Pavlov PhD[3]; Dr. Nicolas Rambaux[4]; Dr. Radosław Zajdel PhD[5]

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All future lunar missions require a well-defined lunar reference system and its realization in the form of a lunar reference frame to ensure consistent products for positioning, navigation, cartography, and timing. We propose a definition for the origin, orientation, and scale of the Lunar Reference System (LRS), along with the first numerical realization of the International Lunar Reference Frame (ILRF). The LRS is defined with its origin at the lunar center of mass (lunocenter) in the Principal Axis (PA) system, co-rotating with the Moon and fixed to its surface. The ILRF realization is derived using variance component estimation applied to three lunar ephemerides solutions – DE430, INPOP21a, and EPM2021 – for the series of lunar center-of-mass positions

and rotational Euler angles (precession, nutation, and proper rotation). The solution spans the period covered by Lunar Laser Ranging (LLR) data, from 1970 through 2052, including extrapolated ILRF realizations for future missions. The combined ILRF achieves a mean positional error of 17.6 cm for the 2010–2030 interval, with 15.3 cm attributable to the origin and 8.6 cm to the orientation realization. The dominant source of origin error arises from the limited geometry of the retroreflector network, leading to a strong correlation between the scale and the X-component of the lunocenter in the PA frame. The mean transformation errors between the ILRF and other PA-based reference frame realizations are at the 3 cm level, while the transformation to the Mean Earth (ME) frame based on the DE421 solution yields errors of 5.2 cm and 9.5 cm for the 7-parameter and simplified 3-parameter transformations, respectively. Accordingly, the ILRF represents the first combined realization of the LRS, achieving decimeter-level accuracy, which is sufficient for most current and near-future lunar missions. Future ILRF realizations can attain even higher accuracy through improved lunar geodetic infrastructure, such as additional LLR retroreflectors and stations, active surface transponders, and lunar orbiters with high-precision orbit determination.

ID: M2 - o4 | Computing Ephemerides in a Lunar Reference Frame

Dr. Meredith Elrod PhD[1]; Dr. Susan Stewart[2]

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For decades, the ephemerides of the Earth, Moon, and other solar system bodies have been computed with respect to the Earth or the Solar System Barycenter and verified through Earth-based observations or telemetry from planetary probes. The increased missions and framework designed due to the return of human missions to the Moon, make computing ephemerides from the lunar perspective a key factor for the next steps of space exploration. With the IAU resolution 2024 Resolution II defining the lunar coordinate system (LCRS) and coordinate time (TCL), it is now beneficial to define a quasi-inertial frame within the LCRS centered at the moon, analogous to the geocentric frames in GCRS, a body-centered fixed frame, and a lunar geoid. Through the production of the observational data of stellar and planetary objects in terms of right ascension and declination (which need Ra = 0 and Dec = 0 defined for the Moon) using this defined Lunarcentric quasi inertial reference frame (e.g. ILRF), we can enable enhanced and coordinated observations, star tracking, and navigation between multiple international missions the lunar orbit and on the surface. In addition, we find using a body-fixed lunar reference frame (e.g., ILRF_PA/ILRF_ME etc.) to compute celestial navigation using stars and planets, analogous to techniques developed on the Earth (i.e. azimuth and altitude, or similar lunar surface sky chart, etc.). In order to compute such a useful tool (e.g. general sky chart analogous to the Nautical Almanac), a potential surface (i.e. lunar geoid) and defined latitude longitude point of interest (az/alt) or, a surface time (i.e. TL) will need to be defined. In this paper we will present potential tools designed for the lunar body: observational positions of key navigational tools for the quasi-inertial Lunarcentric frame and for the body fixed Lunarcentric frame.

ID: M2 - o5 | Lunar Laser Ranging for the Space-Time Reference Systems on Earth and Moon

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Lunar Laser Ranging (LLR) has measured the Earth–Moon distance continuously for over 55 years. It benefits from higher-precision observations in the past years, improved data coverage over lunar reflectors and orbit as well as upgraded ground instrumentation. Recently, the new NGLR-1 reflector has been successfully tracked by multiple stations, further densifying the network on the Moon. LLR contributes to realizing terrestrial and selenocentric reference systems. On the

Earth side, it can determine Earth Orientation Parameters (EOP)—including nutation coefficients, ΔUT1, and polar motion. Although present results still trail other space-geodetic techniques, LLR remains the only technique besides VLBI that delivers ΔUT1 and nutation values with some good accuracy, thus providing an important cross-check on VLBI results. On the lunar side, LLR can estimate the parameters related to the lunar orientation, rotation, and its interior. We also assessed a combined concept with Differential LLR (DLLR) and found that joint solutions can substantially improve parameter estimation. Looking ahead to lunar navigation and the planned deployment of new instruments such as lunar surface clocks, the need for an independent lunar time scale is growing. LLR can support precise Earth-Moon time links and synchronization. A dedicated study has been completed and demonstrated this potential.

ID: M2 - o6 | Centimeter-Accurate One-Way Laser Ranging Anywhere in the Solar System — Case Studies of Lunar and Martian Landings

Dr. Drazen Svehla[1]; Prof. Dr. Markus Rothacher[2]; Prof. Dr. Ivan Prochazka[3]; Prof. Dr. Josef Blažej[3]; Dr. Ronald Holzwarth[4]; Dr. Simone Dell'Agnello[5]

[1] ; [2] ETH Zurich, Switzerland; [3] Czech Technical University in Prague, Czech Republic; [4] Menlo Systems GmbH, Switzerland; [5] LNF-INFN, Italia

We proposed the ACES ELT laser receiver (launched onboard ISS on 21.4.2025) with 1-cm-diameter receiving optics for cm-accurate one-way laser ranging to Mars orbiter and Mars lander as well as laser ranging from Mars orbiter to rovers onboard Mars (Perseverance, Rosalind Franklin). The two-way on the orbiter is just used to observe time-drift once a day or over a shorter period of time, of the small Rb clock (2.5 L) that is used for one-way laser ranging. We have also officially proposed a similar setup for the Moon landing, based solely on the one-way laser ranging from Earth. In this concept, onboard corner-cube reflectors are used to estimate the time drift of the clock connected to a laser receiver and to enable one-way laser ranging. With or without the full transponder option, the proposed setup allows centimeter-level accuracy one-way laser ranging anywhere in the Solar System, relying entirely on an onboard stable clock in combination with a laser receiver that time-tags the laser pulses received from ILRS stations on Earth. This setup enables highly accurate scientific missions on Mars and the Moon—such as for gravity and altimetry mapping—and supports the realization of precise reference frames for both Mars and Moon, considering the recent deployment of multiple small laser retro-reflectors on their surfaces that cannot be observed from the Earth.

Session M3: Recent Developments in Regional Reference Frames
Conveners: Fernand Bale, Christof Völksen

ID: M3 - o1 | EUREF Study Group on alternatives to ETRS89. Status of work

Dr Xavier Collilieux[1]; Zuheir Altamimi; Dimitrios Ampatzidis; Andrzej Araszkiewicz; Karoline Arnfinnsdatter Skaar; Esther Azcue Infanzón; Carine Bruyninx; Alessandro Caporali; Rolf Dach; Chris Danezis; Michail Gianniou; Ambrus Kenyeres; Karine Kollo; Christopher Kotsakis; Pasi Häkli; Lennard Huisman; Dr. Juliette Legrand PhD; Gunter Liebsch; Martin Lidberg; Ivars Liepiņš; Tomasz Liwosz; Benjamin Männel; Rosa Pacione; Markku Poutanen; Lars Prange; Martina Sacher; Joachim Schwabe; Wolfgang Söhne; João Agria Torres; Jeffrey Verbeurgt; Brice Virly; Dr. Christof Völksen; Anastasiia Walenta; Lin Wang; Joachim Zurutuza

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The European Terrestrial Reference System 89 (ETRS89) was adopted in 1990 in Florence, Italy, following the EUREF Resolution 1. It is defined in such a way that it coincides with ITRS at epoch 1989.0 and is fixed to the stable part of the Eurasian tectonic plate. 12 realizations ETRFxx have

been published to date, the most recent being ETRF2020. Since its establishment, most European countries have aligned their national reference frame with respect to an ETRS89 realization complying with the INSPIRE Directive. The objective of the "EUREF Study Group on alternatives to ETRS89" is to investigate if ETRS89 is still in line with user needs and to propose an alternative definition of the system if it is relevant. This presentation will show the status of work of the study group, and focus in particular on: (1) an analysis of the displacements on the continental scale and current strategies used by countries to handle them in their national realizations, (2) an inventory of the strategies adopted in other regions of the world to define the regional Terrestrial Reference System and Frames, (3) a discussion on ETRS89 alternatives specifying their advantages and drawbacks.

ID: M3 - o2 | The EUREF Reference Frame Solution based on EPN-repro 3: Methodology, Results, and Quality Assessment

Dr. Juliette Legrand PhD; Dr. Carine Bruyninx PhD; Fikri Bamahry

Royal Observatory of Belgium, Belgium

The primary objective of the EUREF Permanent Network (EPN) is to provide consistent access to the European Terrestrial Reference System 1989 (ETRS89), the standard precise GNSS coordinate system across Europe and the core product of EUREF, the IAG (International Association of Geodesy) Reference Frame Sub-Commission for Europe. To maintain and realize the ETRS89, EUREF regularly publishes multi-year station coordinates and velocities for the EPN sites, collectively referred to as the EUREF Reference Frame Solution. This solution is available in the latest realizations of the International Terrestrial Reference System (ITRS) and ETRS89. This solution, updated every 15 weeks, serves as the official reference for densifying the International Terrestrial Reference Frame (ITRF) in Europe. In addition to the reference frame solution, EUREF provides a station classification designed to help users identify the most reliable reference stations from the EUREF reference frame solution. In 2025, EUREF completed its third reprocessing of EPN data including a significant number of new historical data. A new reference frame solution based on this reprocessing is being finalized and is scheduled for release by the end of 2025. This presentation will outline the methodology and results of the new EUREF Reference Frame Solution, assess its quality, and describe the associated station classification system. The latter supports both users in selecting optimal reference stations within a region and station managers in monitoring the performance and stability of their GNSS sites.

ID: M3 - o3 | NGL-NA25 – A New GPS Position Time-Series Solution for North America

Corné Kreemer [1]; Geoffrey Blewitt; William C. Hammond; Donald F. Argus; Kevin M. Gaastra

[1] University of Nevada – Reno, USA

We present GPS position time-series for all stations processed across the North America continent by the Nevada Geodetic Laboratory (NGL) between 1995-2025 (inclusive). These time-series are relative to a net-rotation of an internally-deforming North American plate and local-to-regional non-seasonal common-mode errors removed. All RINEX data are processed in the IGS20 reference frame using GipsyX-2.3's precise point positioning approach. We remove predicted displacements from non-tidal oceanic and atmospheric loading. The effect of seasonal geocenter motion has also been removed from the NEU position time-series using the ITRF2020 model. The removal of this seasonal model brings the reference frame from CM to CF and this helps the interpretation of NGL-NA25 time-series in terms of regional-to-local sources of periodic deformation, such as hydrological loading. To further reduce the noise in the time-series, for each station we remove non-seasonal common-mode noise constructed from a weighted median stack of residual time-series of nearby long-running stations (using a Delaunay triangulation scheme). To minimize the effect of transient deformation in the residual time-series, we correct those related to postseismic

relaxation or water level variations in large lakes. We place the time-series in a reference frame that minimizes the rotation of the North American plate. However, because the plate deforms internally due to Glacial Isostatic Adjustment, we estimate the plate rotation following one of two approaches. We model the spatial variation of strain and rotation rate and then either estimate an area-weighted rotation vector for the "intraplate" portion of the plate, or we obtain a rotation vector that minimizes the direction of residual intraplate velocities with respect to the gradient in the dilatational strain rate field underneath the former icesheet. Both approaches give similar results and show far-field intraplate motion of up to ~1.5-2.5 mm/yr towards the former icesheet, and near-field outward motion top at 1 mm/yr in Labrador. The intraplate deformation model is estimated using the robust MELD algorithm. For this model, we a priori remove the horizontal response to the ongoing mass removal in Greenland using GRACE/GRACE-FO data. We present our strain rate model, time-series examples, and the 3D velocity field.

ID: M3 - o4 | Evaluating the impact of a Reference Frame update in Spain: Considerations for transitioning beyond ETRF2000

Esther Azcue Infanzón[1]; José Antonio Sánchez-Sobrino[1]; Modesto Blanco[2]; Miguel González-Hidalgo[1]; David Gómez[3]; Joel Grau Bellet[3]; Joaquín Zurutuza[4]; Dr. Santiago Belda[5]; Prof. Dr. Marta Folgueira[6]

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An overview of recent efforts to evaluate the impact of a potential update to the official geodetic reference frame in Spain is presented in this contribution. The latest European realizations of ETRS89, such as ETRF2014 and ETRF2020, offer improved stability and precision for high-accuracy positioning applications. However, they differ significantly, by up to several centimeters, from ETRF2000, which remains the most widely used realization across Europe. In response to this, the EUREF Subcommission is consulting national institutions to assess the implications of a transition and ensure compatibility across European geodetic infrastructures. In Spain, a dedicated Working Group defines a common reference framework in ETRF2000 for all public GNSS networks, excluding the Canary Islands. This collaborative effort brought together national and regional agencies to process data from all permanent GNSS stations, resulting in a unified solution that includes precise coordinates, velocities, time series, and discontinuities. The latest realization of the national frame will be presented. Importantly, the current reference system in Spain is legally defined by Royal Decree 1071/2007 of July 27, 2007. Any significant change to the official frame - such as adopting ETRF2020, which differs from ETRF2000 by several centimeters - would require a revision of this legal framework. This raises a broader debate on the appropriateness of maintaining the current definition versus transitioning to a more modern realization, and the potential impact on users and geospatial applications.

ID: M3 - o5 | ADELA Project: Products, tools, and operational guidelines for the use of kinematic reference frames in the SIRGAS region

Dr. José Antonio Tarrío Mosquera PhD[1]; Marcelo Caverlotti

[1] Universidad of Santiago de Chile, Chile

Seismically active regions such as the Pacific Ring of Fire represent one of the greatest challenges to the stability and long-term consistency of geodetic reference frames. Large earthquakes and their associated post-seismic deformation produce non-linear surface displacements that invalidate the assumption of positional stability that defines static datums. The ADELA Project (Analysis of Deformation beyond Los Andes) addresses this issue by developing an operational kinematic reference infrastructure within the SIRGAS reference frame, capable of maintaining

geodetic traceability through time in tectonically deforming regions of Las Américas. ADELA establishes a fully operational production chain that links scientific GNSS processing, semi-automated quality control, deformation modeling, and the standardized dissemination of products. It aims to transform the concept of time-dependent reference frames into an operational continental service. For Chile's case, the system delivers four key product lines: (1) semi-annual coordinate updates for regional and national GNSS networks aligned with ITRF and SIRGAS-CON; (2) Post-Seismic Displacement (PSD) products, automatically triggered after earthquakes of magnitude ≥ 6.0; (3) epoch-change utilities and time-dependent deformation models, accessible through web and desktop applications; and (4) standardized metadata catalogues, fully compatible with IERS, IGS, SIRGAS, and ISO standards. Within this structure, REDGEOMIN functions as the Chilean implementation of ADELA, acting as a national densification of SIRGAS for mining purposes and serving as the operational testbed for all procedures. REDGEOMIN provides the GNSS infrastructure and processing environment through which ADELA's kinematic solutions, deformation fields, and coordinate updates are validated before integration with the continent. The PSD workflow forms the operational backbone of ADELA. Following any major earthquake, the process is initiated with IGS rapid products, enabling the generation of preliminary displacement and coordinate updates within 72 hours. These rapid results are then refined using IGS final products, which combine residual-velocity estimation, reprocessing of GNSS time series, and deformation interpolation for survey marks using Thin Plate Spline (TPS) algorithms. This two-stage strategy ensures both rapid response and long-term consistency of the kinematic reference frame. All ADELA-REDGEOMIN products are harmonized in a geodetic library registered in the ISO Geodetic Registry (codes 1292–1298), which defines the national dynamic datum and its coordinate reference systems (geocentric, geographic 2D/3D, and UTM). This ensures interoperability with GNSS software, GIS platforms, and spatial data infrastructures, adhering to the FAIR principles (Findable, Accessible, Interoperable, Reusable). Updated coordinates, displacements, and deformation grids are released through the ADELA portals, maintaining complete traceability to the ITRF through SIRGAS-CON. Each affected station is reassigned to a new epoch or deformation model, ensuring coherence with the continental reference frame. The integration of ADELA into SIRGAS offers a reproducible governance model for operational kinematic reference frames in deforming regions. By combining scheduled semi-annual updates, automatic post-seismic triggers, quantitative quality control, and open-access dissemination, ADELA bridges the gap between research and public service. It provides a continental roadmap for the transition from static to, at the very least, kinematic reference systems, thereby reinforcing geodetic resilience, risk management, and spatial governance throughout the SIRGAS region, according to geodetic UN Resolutions.

ID: M3 - o6 | The 2023 Turkish Earthquakes: Impact on Israel's CORS Network

Prof. Gilad Even-Tzur

Technion - Israel Institute of Technology, Israel

This study investigates the impact of the February 6, 2023, M7.8 and M7.6 earthquakes in Turkey on Israel's national Continuously Operating Reference Stations (CORS) network. The seismic epicenters were located approximately 500 km to 900 km from the network, making this a crucial case study of far-field crustal deformation. We analyzed the effects on 16 CORS stations across Israel, observing both coseismic displacements and subsequent postseismic deformations. Our findings reveal significant permanent changes—on the order of several centimeters—in station location, both in absolute terms and relative to one another. As anticipated, stations closer to the epicenters experienced a more pronounced displacement compared to those farther south. Since the Israeli geodetic datum is defined as a semi-dynamic datum, it requires periodic updates to account for crustal movement. The observed deformation necessitates a thorough assessment of the site location changes and their magnitude. The results of this study are critical for guiding the corrective actions required to accurately update and maintain the national semi-dynamic datum.

ID: M3 - p1 | Germany-wide GNSS measurement campaign 2021. Introduction of the new implementation of the official spatial reference system ETRS89/DREF91(R2025)

Tetyana Romanyuk MSc[1]; Ole Roggenbuck[1]; Dr. Axel Ruelke[1]; Dr. Bernd Krickel[2]; Andreas Bruenner[3]; Ralf Daebel[4]; Hans-Georg Dick[5]; Dr. Barbara Goerres[6]; Bjoern Mehlitz[7]; Werner Pape[8]; André Sieland; Dr. Wolfgang Soehne[1]; Laura Vassmer[4]; Dr. Lin Wang[1]

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The integrated geodetic spatial reference system for Germany is implemented using stable GGP („Geodätische Grundnetzpunkte" (geodetic control points) and permanently secured through regular monitoring and verification. The geodetic spatial reference system is largely provided by the SAPOS® satellite positioning service of the federal states of Germany. To determine the geometric component of the spatial reference (3D coordinates), the AdV (Working Group of the Surveying Authorities of the States of the Federal Republic of Germany) conducted its first nationwide GNSS measurement campaign in 2008. Observations of the GGP framework network were evaluated together with observations from SAPOS®, GREF (Integrated Geodetic Reference Network of the Federal Government) and selected EPN (European Permanent Network) and IGS (International GNSS Service) stations. The coordinates determined were introduced as realization R2016 for the official reference system ETRS89/DREF91. A second measurement campaign took place in 2021. The results from the 2021 GNSS measurement campaign were processed and evaluated by two analysis centers (LGLN (State Office for Geoinformation and Surveying of Lower Saxony) and BKG (Federal Agency for Cartography and Geodesy)) in three network stages. In order to capture the influences of the calibration methods as accurately as possible, all three network stages were processed using robot and chamber calibrations (with priority on individual multi-GNSS calibrations). The results from the analysis centers were afterwards combined. The combined final result for the entire network (GGP and reference stations) with robot calibrations was introduced as the new R2025 implementation of the official spatial reference on July 1, 2025. This poster provides an overview of the various evaluation phases and highlights the most important findings.

ID: M3 - p2 | Swiss Terrestrial Reference Frame CHTRF2022

Lars Prange[1]; Daniel Ineichen; Simon Lutz; Stefan Schaer; Arturo Villiger

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The Swiss coordinate reference frame CHTRF forms the basis for the georeferencing of official geodata in Switzerland. It is maintained by the Federal Office of Topography (swisstopo). We provide information about the latest version, CHTRF2022. This includes an overview of the underlying station network, monitoring, access, and applications of the national reference frame. The resulting horizontal and vertical velocity field, which is dominated by alpine uplift, is shown. We address the sometimes diverging requirements of different user groups and applications. Finally, we provide an outlook on developments planned for the near future.

ID: M3 - p3 | Updating Canada's 3D GNSS-derived velocity field and deformation model

Karen M. Simon; Jason Bond; Mohammad Ali Goudarzi; Michael Craymer

Canadian Geodetic Survey, Natural Resources Canada, Canada

A national scale crustal velocity model has accompanied realizations of the Canadian Spatial Reference System (CSRS) since 2009. The velocity model enables the propagation of coordinates to different reference epochs and also supports scientific studies of lithospheric deformation and sea-level change. This work presents the most recent updates to the model and its constraining velocity field as well as discusses ongoing improvements and applications. Specifically, a GNSS dataset that includes sites from continuously observing stations throughout Canada, repeated, high-accuracy Canadian campaign data, as well as continuous GNSS data from Alaska, the northern contiguous United States, and Greenland is reprocessed to the end of 2024. The updated velocity field for Canada incorporates more stations relative to the previous version, and is determined using IGS repro3 products, processing standards and models and the Bernese GNSS Software 5.4. The resulting velocity field is used as a primary constraint for the velocity model, while predictions from glacial isostatic adjustment and elastic deformation models provide a secondary constraint to supplement regions such as northern Canada where data are sparser. The updates to the velocity field and model coincide with the implementation of the new North American Terrestrial Reference Frame of 2022 (NATRF2022), which is being planned to be adopted in Canada and the United States in 2026 and will replace the North American Datum of 1983 (NAD83). Differences between the velocity model in NAD83 and NATRF2022 are shown and demonstrate that residual velocities present in NAD83 are significantly reduced in NATRF2022 using new Euler pole parameters determined for the North American plate. Finally, an application of the model is discussed wherein a subset of campaign data from the total GNSS dataset is analysed to determine the overall influence of individual stations on the velocity model prediction. Such applications of the velocity model can help to inform site selection in future campaign surveys and identify potential regions to target for network densification.

ID: M3 - p4 | EUREF and 35 years with the ETRS89

Dr. Martin Lidberg PhD[1]; Dr. Wolfgang Söhne; Dr. Karin Kollo; Dr. Carine Bruyninx; Prof. Dr. Alessandro Caporali; Prof. Dr. Rolf Dach; Dr. Lennard Huisman; Dr. Juliette Legrand PhD; Dr. Tomasz Liwosz; Dr. Christof Voelksen; Prof. Dr. Zuheir Altamimi; Prof. Dr. Markku Poutanen; Dr. Ambrus Kenyeres; Dr. Rosa Pacione; Dr. Joaquin Zurutusa; Dr. Benjamin Männel; Dr. Joachim Schwabe; Dr. Andrzej Araszkeiewicz; Dr. Xavier Collileux; Dr. Tobias Bauer

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EUREF (IAG sub-commission 1.3a for Europe) was founded in 1987 at the IUGG General Assembly in Vancouver, and the European terrestrial Reference System 89, ETRS89, was adopted at the EUREF Symposia 1990 in Firenze. EUREF primary mission is to define, realize and maintain the ETRS89 and the European Vertical Reference System (EVRS) for scientific and practical purposes in Europe. These systems have been recognized at high political level in Europe by the European Union and are mandatory for exchange of geodata governed under the INSPIRE directive. To note is that practically all countries in Europe has a national realization of the ETRS89 that has been endorsed by EUREF. Realization and maintenance of the ETRS89 is primarily done through the EUREF Permanent GNSS Network (EPN), while the physical height system EVRS is realized through common adjustment of the Unified European Levelling Network (UELN). All contributions to EUREF are provided on a voluntary "best effort" basis, with more than 100 European bodies (agencies/research institutes) involved. EPN consists of more than 400 continuously operating GNSS stations, supported by Data and Analysis Centers and a Central Bureau. The backbone EPN has been complemented with additional national CORS networks. The dense European network (EPND) incorporates ten times more stations as the core EPN. In the presentation we will discuss

de development the last 35 years and the current and future challenges regarding continental scale geodetic infrastructure and the contribution from EUREF. Since the processing strategy for analyzing GNSS networks has developed during the more than 3 decades of the EPN (new ITRFs, new GNSS antenna phase center variation models, PCVs, etc.), the complete re-processing if the EPN is sometimes needed. The EPN-Repro3 is about to be completed but will be reported in detain in another presentation. We will also mention the development of a European Height Reference Surface, models for crustal deformations, and discuss the realization of the emerging International Height Reference System (IHRS) in Europe. Finally, we will touch upon the role of EUREF in the organizational landscape where the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) Subcommittee on Geodesy, UN GGIM: Europe, the UN Global Geodetic Centre of Excellence, and the European Plate Observing System (EPOS) are important partners.

ID: M3 - p5 | DrukRef23: Establishing an ITRF-Aligned Reference Frame for Bhutan in the Himalayan Deformation Zone

Dr. Rui Fernandes[1]; Chokila Chokila[2]; Gonçalo Henriques[3]; Fernando Geraldes[1]; Gyeltshen Jamphel[2]; Dorji Pema[2]; Pedro Almeida[1]

[1] University of Beira Interior, Portugal; [2] National Land Commission Secretariat, Bhutan; [3] MIRASpaco, Lda, Portugal

Bhutan lies within the Himalayan orogen formed by the convergence of the Indian and Eurasian plates. GNSS observations show a persistent north–south component of crustal shortening of about 5–6 mm/yr across Bhutan. Static frames become increasingly inconsistent in such deforming settings particularly when the original definition relies on limited or heterogeneous control. DrukRef03, while geocentric, was defined in 2003 from a small set of campaign stations and lacked robust materialisation, which prompted the recent establishment of a new national frame, DrukRef23. The DrukNet continuous national GNSS network materialised DrukRef23, expanded from the original six sites to sixteen by 2024 to provide national coverage. The datum was computed directly in ITRF2020 and expressed at the reference epoch 2023.5. Processing used GipsyX with the PPP strategy over a 15-day interval to form daily station solutions; each day was aligned to ITRF2020 via a seven-parameter Helmert transformation to a global set of IGS reference stations. Daily solutions were combined per site using weighted averaging to obtain the published coordinates at epoch 2023.5. Adopting the new frame required migrating the existing geoinformation from DrukRef03 to DrukRef23 so the older frame can be retired from operations. Analyses of paired coordinates show that differences reflect both long-term tectonic deformation and heterogeneous errors accumulated in control over many years, so a single Helmert parameter set was inadequate. Consequently, a national NTv2 transformation was estimated in 2024–2025. The NTv2 model is derived from CORS-controlled observations, with iterative outlier screening, and encoded on a 10" grid to capture the spatial variation at country scale; tests report sub-decimetre horizontal accuracy. This contribution sets out the tectonic context and the reference-frame implications for Bhutan, details the datum definition and computation of DrukRef23 tied to ITRF2020 at epoch 2023.5, and reports the national transformation grid enabling the systematic migration from DrukRef03. DrukRef23 is a static, fixed-epoch frame by design; a time-dependent realisation is recognised as the logical next step for Bhutan but is deferred for practical reasons at present. The current solution provides a robust basis for positioning until a later generation frame incorporates velocities at the national scale.

ID: M3 - p6 | Impact of the changes of absolute individual calibration models on the regional GNSS Networks: a comparative case study with a permanent German Network

Dr. Lin Wang PhD[1]; Sebastian Knappe[1]; Tetyana Romanyuk[1]; Axel Rülke[1]; Gunter Liebsch[1]; Eric Buchta[1]; Hans-Georg Dick[2]; Irene Feldmeth[2]; Uwe Hensel[3]; Huishu Li[2]; Falko John[4]; Christian Rentsch[5]; Ole Roggenbuck[1]; Wolfgang Söhne[1]

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The German national reference frame network DREF-Online is used as a backbone to realize and monitor the datum realization of the German National Reference System ETRS89/DREF91. It consists of 110 active GNSS German reference stations operated by BKG and the surveying authorities of the German Laender. The latest realization of ETRS89/DREF91 (R2025) was introduced as the official reference frame in Germany on July 1st, 2025. This realization is based on the recent national survey campaign and further detailed in Romanyuk et al. (2025). One of the major modeling differences compared to IGS20 is the selection of the antenna calibration model: the available individual absolute robot antenna calibration models have been preferred over type mean robot antenna calibration models for the determination of ETRS89/DREF91 (R2025). This differs from analyses within IGS or EUREF, where type-mean robot antenna models are in use. Most of the German reference network antennas are calibrated individually, either with robot calibrations, chamber calibrations, or with both. In our study, we present the impacts of the antenna calibrations on the reference frame realization and the related products. We analyze and interpret the differences between the absolute individual antenna calibration models and the type mean calibration models of different sources among selected antennas from the German reference station network. We also present the deviations of individual antennas from the type mean calibrations of the popular antenna types used in Germany. Furthermore, with a designed and consistent reprocessing of DREF-Online network, we evaluate the impacts of the antenna calibration models on the coordinates and reference frame product level.

ID: M3 - p7 | The EPN-Repro3 Campaign: Homogeneous Reprocessing of GNSS Data Since 1996 for an Improved Regional Reference Realisation in Europe

Dr. Christof Völksen[1]; Tomasz Liwosz[2]; Dr. Juliette Legrand PhD[3]; Martin Lidberg[4]; Andrzej Araszkiewicz[5]; Carine Bruyninx[3]; Miguel Gonzales Hidalgo[6]; Martin Imrišek[7]; Tina Kempe[4]; Benjamin Männel[8]; Rosa Pacione[9]; Juraj Papco[10]; Lin Wang[11]; Sandor Tóth[12]; Joaquín Zurutuza[13]

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The EUREF Permanent Network (EPN), operational since 1996, realizes the European Terrestrial Reference System (ETRS89). The ETRS89 is a regional geodetic reference system for Europe, fixed to the stable part of the Eurasian tectonic plate, and based on the global International Terrestrial Reference System (ITRS). Today, the EPN includes around 400 GNSS stations across almost all of Europe. Since the EPN's inception, successive modernizations, including improvements in computation standards, the introduction of new satellite navigation systems (like GLONASS and Galileo), and advances in receiver and antenna technology, have affected the homogeneous nature of the position time series. To maintain and improve the realisation of the ETRS89, EUREF

decided, similar to the IGS, to reprocess all available GNSS data since 1996 in a standardized way (EPN-Repro3). This campaign involves twelve Analysis Centres (ACs), each computing a sub-network and providing daily SINEX solutions for combination. A key difference from previous work is the switch from individual antenna calibrations to type mean calibrations. This change aligns with the IGS and addresses the lack of full frequency spectrum calibrations for Galileo and Beidou in many individual antenna calibrations. The presentation first details the results from the individual ACs and the combination of their daily solutions. This foundational output then allows the Reference Frame Coordinator to generate a multi-year position and velocity solution aligned to the IGS20, which ultimately defines the latest terrestrial reference frame realisation.

Session T1: Earth Orientation Parameters

Conveners: Xavier Collilieux, Nicholas Stamatakos

ID: T1 - o1 | A Coming Wave of New Astronomical Standards: Adoption and Impact

Dr. Andrew Kopf PhD

United States Naval Observatory, USA

This presentation will highlight the upcoming wave of new international standards for reference frames, time, and associated constants that are expected to be established over the next approximately five years, their impact to the global community, and ongoing efforts to prepare for their incorporation. A number of organizations with close ties to the IAG are preparing to affirm new reference frame and time standards that will have broad ranging impacts. Expected this year are the new report from the IAU's Working Group on Cartographic Coordinates and Rotational Elements (WGCCRE) and the newest IERS Conventions, both of which will establish multiple new standard values related to planetary parameters and rotation values. Multiple redefined time standards will follow in 2027 and beyond, along with official lunar reference frame and time definitions. Efforts to capture these and other standards in almanacs and online references is an ongoing process. The IAU has not formally updated fundamental constants since the 2009/2012 resolutions, though there is active work within Commission A3 to do so. Several constants or best estimates have seen improved measurements, including multiple solar system mass ratios and perhaps most notably the gravitational constant. Coordination is also ongoing with the IERS to rectify the updated numerical standards in the new conventions with existing IAU values. New planetary parameters influence the calculation of precise ephemerides, while a new definition of UTC will result in growing deviations in data tables due to the long-used UT1 = UTC approximation steadily becoming less consistent. Properly capturing these changes in reference tools is critical to users who rely on them for navigation or observation, and will take on a whole new importance as global exploration of the Moon ramps up to include long-term human presence. Recent and upcoming work in these areas will be presented.

ID: T1 - o2 | How to bring precession and nutation models closer to CPO observations in the short term

Prof. Jose M. Ferrandiz PhD[1]; Prof. Alberto Escapa[2]; Dr. Maria Karbon[1]; Dr. Santiago Belda[1]

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Over the last decade, the International Astronomical Union (IAU) and the International Association of Geodesy (IAG) have organised successive Joint Working Groups (JWGs) to improve the theories and models of the Earth's rotation. Their reports revealed inconsistencies and obsolescence of the standard theories and models, and some of underlying concepts, and led to

the 2019 IAG and 2021 IAU Resolutions encouraging their improvement in terms of accuracy, consistency, and better adaptation to present knowledge of the actual Earth. The current IAU/IAG JWG on Consistent Improvement of Earth's Rotation Theory (CIERT) is addressing this problem with a particular focus on the theories of precession and nutation (PN). Improving consistency requires that all components of theories and analyses of observational data refer to and use identical reference frames, basic and ancillary Earth models and parameters. Regarding precession, it has become clear from the work reported by different research groups that revising the rates and offsets of the observed Celestial pole offsets (CPO) is an urgent need to reduce the WRMS of all kinds of CPO time series. Therefore, it is one of the main topics that must be considered in the ongoing update of the IERS Conventions. In addition, the revision of the values of some second-order components of IAU2006, though has no direct effect on the precession model itself, affects the H_{d} value and thus indirectly the nutations amplitudes to a non-negligible extent. As the linear model for the J_2 variation adopted in the development of IAU2006 is no longer valid, the challenge of updating the precession theory to a more realistic model arose, which would require modifying coefficients beyond the linear ones. Just at the moment of submitting this abstract, Liu and Huang communicated the availability of a solution to this problem. Their preliminary results suggest that the subsequent modification of the quadratic and cubic powers of time could help to reduce the observed upwards curvature of dX in recent years. Regarding the block of planetary nutations, there is strong evidence in favour of no longer neglecting the non-rigid contributions that have been ignored so far. The simplest way to implement this is to use the available corrections arising from an analytical solution, which can be enhanced with around five empirical corrections to increase the WRMS reduction. However, replacing the whole block of rigid planetary nutations with non-rigid ones would be a goal beyond the short term. As for the lunisolar nutations, it has been shown that the direct fit of corrections to the amplitudes of about ten periods allows reducing the WRMS of VLBI solutions in a significantly larger amount than other approaches such as indirect fits through some earth parameters or accumulation of new, theoretically derived corrections. Based on the tests performed so far, applying all the previous corrections would enable the definition of modified CPOs, with a WRMS of 120 micro arcseconds or less across the entire observation series. Finally, using convenient free core nutation (FCN) models would reduce the unexplained variability by a quarter.

ID: T1 - o3 | Temporal Evolution of the Free Core Nutation Quality Factor from VLBI Celestial Pole Offsets

Dr. Santiago Belda[1]; Dr. Maria Karbon[1]; José M. Ferrándiz[1]; Lucía D. Del Nido Herranz; Alberto Escapa[2]; Clara Pérez[3]; Esther Azcue Infanzón[3]

[1] IVS Analysis Center - UAVAC, Dpt. Applied Mathematics, Escuela Politécnica Superior II, University of Alicante, Spain; [2] Dept. Aerospace Engineering, University of León, Spain; [3] National Geographic Institute of Spain, Madrid, Spain

The Free Core Nutation (FCN) represents the most prominent free rotational mode of the Earth, arising from the differential rotation between the fluid outer core and the solid mantle. Its amplitude and phase are well observed in long-term VLBI Celestial Pole Offset (CPO) series. While the FCN frequency and amplitude modulation have been extensively studied, the temporal behavior of its dissipation — quantified by the quality factor Q— remains less constrained. In this work, we investigate the time evolution of the FCN Q-factor using recent CPO series spanning 1984–2025. The analysis is based on a sliding-window exponential decay model fitted simultaneously to the dXand dYcomponents of the CPO, ensuring consistent damping across both components. These tests confirm that the proposed approach can reliably retrieve Q values within the 10^4 to 10^5 range typical of FCN estimates. Application to VLBI observations suggests a globally stable but weakly variable Q(t), possibly related to long-term changes in the core–mantle coupling. These results contribute to refining the dynamical description of the FCN and provide

new insights into the physical dissipation processes at the core–mantle boundary, supporting improved empirical and theoretical Earth rotation models.

ID: T1 - o4 | Validation of New Earth Rotation Models for the IERS Conventions Update

Dr. Maria Karbon[1]; on behalf of JWG IAG 3.1

[1] Universidad de Alicante, Spain

An international effort is underway to revise geodetic reference systems to meet the millisecond-of-arc accuracy required by GGOS for Earth System Monitoring. Our working group is structured into two components: Theory and Observations. While the theoretical team develops an extended Earth rotation model—recomputing the precession-nutation solution and trying to refine the separation of nutation and polar motion for improved Free Core Nutation (FCN) modeling—this presentation focuses on the results of the observational validation. The observational analysis systematically fits the new models to VLBI data, with complementary checks using SLR and GNSS orbit determination. This multi-technique evaluation quantifies residual errors, verifies theoretical consistency, and confirms that the new formulations are accurately represented in operational analysis packages. These results form a key input to the evaluation and acceptance of the revised models for the next IERS Conventions update, ensuring that future geodetic standards are both theoretically consistent and empirically validated. We gratefully acknowledge the collaboration of all contributors whose efforts make this progress possible.

ID: T1 - o5 | Estimation of the Earth angular rotation velocity with geodetic VLBI

Dr. Oleg Titov PhD

Phase&Rate, Australia

Very Long Baseline Interferometry (VLBI) measures two standard observables: group delay and fringe frequency (delay rate). The delay rate is an effective tool for direct estimation of the instantaneous Earth angular rotation velocity which is not accessible with other space geodetic techniques. It aims to estimate the magnitude of the Earth angular rotation velocity using almost 33-year set of VLBI data and, in addition, to obtain daily estimates of X and Y angles linking the Celestial Instantaneous Pole (CIP) and the International Celestial Reference System (ICRS) pole. I used the plain least squares method to analyse the delay rate data because the phase variations affecting the time delay results do not spoil this delay rate data. Three components of the Earth rotation vector are estimated on daily basis with a formal error of 1 prad/s or 10^{-8} in relative units. Using the newly obtained values one could obtain the Earth angular rotation velocity directly, rather than by converting the length-of-day.

ID: T1 - o6 | Short-term Earth Orientation Parameter Prediction: Present-Day Accuracy and *Future Directions*

Dr. Henryk Dobslaw[1]; Justyna Śliwińska-Bronowicz[2]; Jolanta Nastula[3]; Maciej Michalczak[4]; Marcin Ligas[4]; Malgorzata Winska[5]; Robert Dill[1]

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Accurate knowledge of Earth orientation parameters (EOP) is critically important for a wide range of operational tasks associated with spacecraft navigation, ground-based astronomy, and even satellite-based navigation on Earth. Since geodetic observations are usually only available with some delay, short-term predictions are utilized for many of those tasks. The second EOP Prediction Comparison Campaign organized by CBK PAN and GFZ under the auspices of IERS has rigorously compared the accuracy of various internationally available prediction algorithms for

all five EOP. Based on additional data collected during the currently running post-operational phase of the campaign, we will discuss emerging opportunities to further improve the prediction of EOP by utilizing both improved forecasts of geophysical excitations and improved prediction algorithms based on data science methods and artificial intelligence approaches.

ID: T1 – p1 | Reconstruction of the instantaneous Earth rotation vector

Christian Bizouard[1]; Dr. Oleg Titov PhD[2]

[1] IERS Earth Orientation Center, France; [2] Phase&Rate, Australia

Processing of modern astro-geodetic observation have tended to neglect the instantaneous rotation vector components for the benefit of the rotation transformation R between terrestrial and celestial reference systems. Current practice is to adjust that transformation by small angles, or related quantities, called Earth Orientation Parameters (EOP). However, laser ring gyro and recent processing of VLBI delay rates rehabilitate the components of the the rotation vector as quantities directly related to the observations. In order to compare these two kind of parameters it is worthy to reconstruct the instantaneous rotation vector components within the CRS or the TRS using kinematic relation mixing R and its time derivative. Whereas this issue has been addressed for the polar motion (Gross, 1992 ; Brzezinki and Capitaine 1993), the complete derivation faces numerical instability due to the time derivative of R. Here we propose a solution based upon quaternion of rotation derived by Bizouard and Cheng (2023). Finally our method is successfully applied to the reconstruction of rotation vector components derived by Titov (2025).

Session T2: Terrestrial Reference Frames and Combination
Conveners: Xavier Collilieux, Linda Geisser

ID: T2 - o1 | The ILRS ASC operational product portfolio – status and plans

Dr.-Ing. Mathis Bloßfeld[1]; Dr. Cinzia Luceri[2]; David Sarrocco[2]; Antonio Basoni[2]; Frank G. Lemoine[3]; Keith Evans[4]

[1] Deutsches Geodätisches Forschungsinstitut (DGFI-TUM), Technical University of Munich, Germany; [2] e-GEOS/ASI, Italia; [3] NASA Goddard Space Flight Center, USA; [4] UMBC JCET, USA

The Analysis Standing Committee (ASC) of the International Laser Ranging Service (ILRS) operationally computes TRF and EOP solutions on different temporal timescales. These solutions are based on a combination of input solutions (and normal equation systems) of up to 8 different Analysis Centers (ACs), each computed from observations up to five different satellites, namely LAGEOS-1/2, Etalon-1/2, and Lares-2. Along with the above-mentioned products, the stability and quality of each ILRS network station is monitored by the SSEM-X (Station-Systematic Error Monitoring product - eXtended) product. This product comprises long-term mean range biases (RBs) for many ILRS stations (provided via the ILRS Data Handling File) to the users and is based on weekly combined RB estimates. The ILRS ASC also maintains an SLR-specific solution of the ITRF2020, the SLRF2020. In addition, the ILRS ASC also provides weekly combined orbits of the five processed satellites. The ILRS ASC product portfolio is also planned to be extended by weekly/monthly combined low-degree spherical harmonic coefficients of the Earth gravity field. This presentation provides an overview of the current ILRS product portfolio and provides insights into the future ASC plans regarding the incorporation of new satellites, new ACs, etc. Finally, the presentation will provide information on how SLR observations to colocation satellite platforms (like Jason, Sentinel or Genesis) will be handled for the TRF computation.

ID: T2 - o2 | Status of ITRF2020 Updates and Future Outlook

Dr. Zuheir Altamimi PhD Habilitation[1]; Paul Rebischung; Xavier Collilieux; Laurent Métivier; Julien Barnéoud; Kristel Chanard; Maylis De la Serve

[1] IGN-IPGP, France

The International Terrestrial Reference Frame (ITRF) is the foundation for Earth science and operational geodesy applications. It is built on international cooperation over more than three decades for the benefit of countries, regions and global geodesy. Substantial improvements have been constantly made in the data analysis strategy, at the level of both individual geodetic techniques, as well as the ITRF combination, with the aim to improve the ITRF accuracy and reliability. Motivated by a number of reasons that will be exposed in this paper, the ITRS Center decided to regularly (yearly) update the ITRF2020, with a first update (ITRF2020-u2023) released in December 2024, a second update (ITRF2020-u2024) released in September 2025 and a third update foreseen in 2026. Results of these updates will be presented and discussed, 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 when adding extended data from the four techniques: VLBI, SLR, GNSS and DORIS. Future plans and perspectives regarding the ITRF2020 updates and consequences for the most demanding user needs conclude the presentation.

ID: T2 - o3 | DTRF2020 and its updates

Dr. Manuela Seitz; Dr.-Ing. Mathis Bloßfeld; Julian Zeitlhöfler; Dr. Detlef Angermann; Matthias Reber PhD; Jacob Klug

Deutsches Geodätisches Forschungsinstitut (DGFI-TUM), Technical University of Munich, Germany

The International Terrestrial Reference System (ITRS) is realized through the International Terrestrial Reference Frame (ITRF). As one of the three ITRS Combination Centers (CC) of the International Earth Rotation and Reference Systems Service (IERS), DGFI-TUM assumes responsibility for the calculation of an independent ITRF solution, the DTRF. This solution is derived from a combination of the normal equation time series of four geodetic space techniques, namely Global Navigation Satellite Systems (GNSS), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Satellite Laser Ranging (SLR), and Very Long Baseline Interferometry (VLBI). The ITRS CC at IGN, which traditionally provides the official ITRF solution on behalf of the IERS, has proposed to deviate from the practice of publishing a new ITRF solution every five to six years. Instead, annual updates to the ITRF solution shall be calculated. This approach aims to reduce computational effort while extending the interval between two ITRFs whose input data series are fully reprocessed, and at the same time increasing the accuracy of the ITRF. DTRF2020 was computed from consistently reprocessed input data provided by the international technique services. Its updates, DTRF2020-u2023 and DTRF2020-u2024, incorporate extended input series covering 2021–2023 and 2024, respectively. The accuracy of current ITRS realizations remains limited by several factors, affecting both the accuracy and the long-term stability. This presentation outlines the processing strategy of DTRF2020 and its updates and discusses challenges in ITRS realization caused by numerous discontinuities—of both geophysical and instrumental origin—and by inconsistencies between consistently reprocessed input series and their extensions due to model changes or varying Analysis Center contributions. Comparing the solutions provides a good measure of the DTRF accuracy. We will discuss the accuracy of state-of-the-art TRF realizations and the potentials for improving ITRF solutions by both the Genesis mission and improving the ITRF's long-term stability, necessary to transfer the higher accuracies reached by Genesis to pre-Genesis timespans.

ID: T2 - o4 | Consistent estimation of EOP and TRF on a weekly inter-technique combined datum

Lizhen Lian; Simeng Zhang; Dr. Chengli Huang

Shanghai Astronomical Observatory, Chinese Academy of Sciences, China

Earth orientation parameters (EOP) and terrestrial reference frame (TRF) are two components of spatial reference systems and closely related to each other, and ensuring their self-consistency is a matter of concern and one objective of the IAU/IAG joint Working Group on Consistent Improvement of The Earth's Rotation Theory (JWG CIERT). To this end, we take the four intra-technique combined solutions within VLBI, GNSS, SLR, and DORIS techniques as well as local ties data as input, and utilize the coordinates of each technique's station and the covariance information of their EOP determination, and finally we realize an inter-technique combined datum at the level of solutions, from which we also get the estimations of the coordinates of stations of each technology under this combined datum, the Helmert transformation parameters between the frames of each technology and this integrated reference frame, as well as the combined EOP which is consistent with this integrated terrestrial reference frame, all of the above are on a weekly basis at the solution level. Finally, the precision of these results can be evaluated by referring to ITRF2020 and IERS EOP 20 C04, and will be presented here.

ID: T2 - o5 | Impact of common clock and common target on intra- and inter-technique combination for global Terrestrial Reference Frames (TRF)

Anton Reinhold[1]; Prof. Dr. Susanne Glaser[1]; Jacob Klug[2]; Dr. Manuela Seitz[2]

[1] University of Bonn, Germany; [2] Deutsches Geodätisches Forschungsinstitut (DGFI-TUM), Technical University of Munich, Germany

The accuracy and long-term stability of global Terrestrial Reference Frames (TRFs) are crucial for many scientific applications. The global TRFs are currently determined by a combination of the four main space geodetic techniques, namely Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) by using local-ties on the co-location sites. The Global Geodetic Observing System (GGOS) has set 1 mm accuracy and 1 mm/decade long-term stability as important goals for current and future TRFs. To achieve these goals, an innovative combining strategy for the space geodetic techniques has been introduced, namely a common target (CT) and a common clock (CC), which serve as a reference point and time frame for all techniques, respectively. This study focuses on simulation studies to investigate the potential impact of combining of the techniques at a CT and a CC on the global TRF. Initially, extensive software modifications were made to introduce a CC for GPS, enabling an intra-technique combination at the Geodetic Observatory Wettzell (GOW) as a starting point, as well as at additional fundamental sites. To implement the inter-technique combination between GPS and VLBI on a CC, a new clock parameterization is being developed for both techniques. Furthermore, a combination at a CT at GOW was simulated between GPS, VLBI and SLR. To evaluate the impact of the novel combination strategy on the TRF, a reference solution of GPS, VLBI and SLR data over a 7-year time span was simulated based on real data and global TRF solutions were set up for each combination. The impact on the TRF solutions was then evaluated with respect to the estimated station coordinates and Earth Orientation Parameters (EOPs).

ID: T2 - o6 | Impacts of Time-correlated Noise Modelling on GNSS Terrestrial Reference Frame via Square Root Information Filter

Na Wei[1]; Dr. Yanlin Li[1]; Guo Chen[1]; Chuang Shi[2]; Jingnan Liu[1]

[1] Wuhan University, China; [2] Beihang University, China

Realizing a Terrestrial Reference Frame (TRF) with an accuracy of 1 mm and a long-term stability of 0.1 mm/yr has long been a goal in the field of geodesy. To improve TRF accuracy, selecting an appropriate stochastic model to describe the nonlinear coordinate variations of geodetic stations is essential. However, the commonly used Random Walk (RW) model in filtering is not optimal for modelling time-correlated noise in Global Navigation Satellite System (GNSS) coordinates. In this study, we used the first-order autoregressive (AR[1]) process instead of RW to model GNSS time-correlated noise and implemented a GNSS TRF solution aligned to ITRF2020, via the Square Root Information Filter (SRIF). We found that as the AR[1] model used in this study has a higher cut-off frequency than the RW model, allowing it to retain a larger portion of the input flicker noise. Consequently, the GNSS time-correlated noise modelled by AR[1] more closely approximates flicker noise than that modelled by RW process. By modelling time-correlated noise with AR[1], the median RMS of coordinate residuals is reduced to 0.3 and 2.0 mm in the horizontal and up components, respectively. Moreover, the AR[1] model can capture short-term correlations in time-correlated noise parameters, thereby enhancing the accuracy of short-term (approximately 11 weeks) TRF coordinate predictions. These results demonstrate the potential of incorporating time-correlated noise by AR[1] in GNSS data assimilation, with implications for both multi-technique TRF and regional GNSS TRF realizations.

ID: T2 - p1 | Symmetric least squares solution for spatial coordinate transformations with small rotation angles – moved to oral presentation ID: T3 - o5

Prof. Dr. Rüdiger Lehmann[1]; Michael Lösler[2]

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Parameters for the transformation between reference frames are often obtained by least squares estimation from control points, also known as identical or homologous points. The solution is most simple in the case that the uncertainty leading to discrepancies between the coordinate sets is fully assigned to the target frame. However, in most practical applications the uncertainty should be split between source frame and target frame, as both systems are derived from measurements. In some cases, this splitting does not alter the solution, but in many cases it does. We investigate the effect of (not) splitting the uncertainty for the case of a six-parameter spatial rigid transformation consisting of translations and rotations with small rotation angles. A formula is derived for the distortion of the rotation angle caused by this effect. Numerical results give an indication, when the effect is important and when it can be neglected.

ID: T2 - p2 | Novel approach for the combination of GNSS and VLBI clock parameters

Jacob Klug[1]; Manuela Seitz[1]; Anton Reinhold[2]; Susanne Glaser[2]; Jari Widczisk[3]; Benjamin Männel[3]

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The International Terrestrial Reference Frame (ITRF) serves as the foundation for applications in geodesy, navigation, and Earth sciences. It is computed and released by the International Earth Rotation and Reference Systems Service (IERS) and is a combination of the solution time series of four geodetic space techniques: Global Navigation Satellite System (GNSS), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Satellite Laser Ranging (SLR), and Very Long Baseline Interferometry (VLBI). The combination of techniques is based on local ties, station velocities, and Earth orientation parameters (EOP). The implementation of local ties

remains a major challenge in calculating the ITRF. Until now, the clock parameters of instruments related to one common clock have not been taken into account in the combination approach. We present a novel approach that creates a common time frame for different techniques. To achieve this, the definition of the reference clock is of the utmost importance. Hence, we introduce a mean stable reference clock (MSRC), which is derived from the mean value of all stable clocks. This reduces variability and minimizes the influence of the reference clock on the estimated station clock parameters. Another challenge is the different clock parametrization of the geodetic space techniques. The current strategy applies epoch-wise estimation of highly time-resolved clock offsets for GNSS, while VLBI uses session-wise offset, drift, and quadratic terms, together with piecewise linear continuous clock parameters. The temporal resolution differs between 5 minutes for GNSS and 1 hour for VLBI. The presented approach of establishing a homogeneous time frame for the ITRF may be the next step toward achieving the Global Geodetic Observing System (GGOS) goal for ITRF of 1 mm accuracy and 0.1 mm/yr stability.

ID: T2 – p3 | Multi-technique geocenter motion combination for consistent reference frame realizations

Adrian Nowak[1]; Dr. Tomasz Kur[1]; Dr. Radosław Zajdel[2]; Prof. Krzysztof Sośnica[1]

[1] Wrocław University of Environmental and Life Sciences, Poland; [2] Geodetic Observatory Pecný (GOP), Czech Republic

The accurate determination of the Earth's geocenter motion remains a fundamental challenge for ensuring the consistency of global terrestrial reference frames and for interpreting large-scale mass transport processes. Currently, the geocenter motion gains in importance as it is considered one of the factors limiting our ability to achieve millimeter-level gravity field models. Moreover, the techniques that provide information about geocenter motion differ significantly in magnitude. The primary objective of this research is to lay the foundation for developing a geocenter motion combination framework that compares and integrates estimates from various space geodetic techniques (GNSS, SLR, DORIS) and expected changes from the geophysical fluid models into a combined model. The analysis spans over two decades of data. The evaluation process includes identifying data gaps, assessment of inter-technique systematics, and the magnitude of intra-technique discrepancies, e.g., by the example of the GNSS-based geocenter series from the third International GNSS Service reprocessing campaign. We investigate the impact of different combination approaches, with primary focus on variance component estimation, on the stability and physical consistency of the resulting geocenter products. Particular attention is paid to the relative contributions and weights of specific solutions. We explore combination strategies by assessing differences in amplitude, phase, and spectral behavior across geocenter motion products, highlighting the challenges posed by differing observation principles and systematic errors. This research is a preparatory stage for the combination and comparison campaign focused on geocenter motion and other low-degree gravity field coefficients. In this stage, the impact of space geodesy techniques on the stability of combined geocenter products is assessed using available time series and weight analysis. These findings contribute to the ongoing efforts to develop next-generation combined reference frame realizations with improved origin definition and inter-technique consistency.

Session T3: Position Time Series and Height Reference Frames
Conveners: Xavier Collilieux, Manuela Seitz

ID: T3 - o1 | Geocenter estimates from 10 years of multi-mission LEO GNSS tracking

Peter Steigenberger[1]; Dr. Bingbing Duan[2]; Oliver Montenbruck[3]

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Geocenter motion (GCM) is the relative motion of the center of mass of the Earth w.r.t. the center of figure of the solid Earth. It can be estimated from space-geodetic observations of Earth-orbiting satellites. However, geocenter estimates from the precise orbit determination of Global Navigation Satellite System (GNSS) satellites are hampered by deficiencies in solar radiation pressure modeling, the high altitude of these satellites, as well as the lacking separability of GCM-related orbit changes and clock offset estimates. Satellites in low Earth orbit (LEO) have a higher sensitivity to the geocenter motion due to their lower orbital altitude. We present the results of a homogeneous reprocessing of 10 years of LEO data (2015-2024) with thoroughly revised LEO antenna and radiation pressure models based on 13 satellites. These include GRACE and GRACE Follow-on, Jason-2 and -3, Sentinel-3A/3B/6A, Swarm-A/B/C, and TerraSAR-X with orbit heights between 340 and 1340 km. The orbit determination is based on a reduced-dynamic approach using precise point positioning with ambiguity resolution utilizing the reprocessed GNSS orbit, clock, and bias products of the Center for Orbit Determination in Europe (CODE). The consistency of the geocenter estimates is evaluated by comparing the results from the different LEO missions. A combined time series is obtained and validated with geocenter estimates from Satellite Laser Ranging (SLR). This series is also evaluated with geocenter motion obtained from ECMWF reanalysis (ERA-5) atmosphere and hydrology as well as TUGO-m ocean. Finally, annual and semi-annual amplitudes and phases are compared to the ITRF2020 geocenter model as well as other geophysical and space-geodetic models.

ID: T3 - o2 | What do we Need from Future Geophysical Loading Models, and How Can They be Incorporated into Future Global Reference Frame Realizations?

Dr. Jeff Freymueller

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Geophysical loading signals are a substantial source of variability in geodetic position time series. Considerable work has been done in comparing models and observations for higher-frequency variations (days to seasonal), but hydrologic signals include multi-year timescales as well. While overall long-term trends, including for example trends induced by GIA, are captured in the estimated station velocities, changes in the trends must be approximated by estimating multiple consecutive velocities for a station. Because such changes, caused e.g. by today's ice melt, shifts in the hydrological regime, or groundwater extraction, often occur regionally or across wider areas, multiple stations can be affected by the segmentation of the time series. This, in turn, limits the long-term stability of the reference frame. Because hydrological mass transport in particular is subject to continual change, we need to disentangle the hydrologic signals from other signals, including its contribution to the long-term trends. This poses several challenges for reference frame realization, and will require careful definitions (for example, how we define "zero variation"?) if we are to remove any component of the loading deformation via models. Specifically, if a given signal causes both a long-term trend and changes in that trend, can we (and should we?) remove the changes in trend without removing the long-term trend as well? Removing the entire loading signal might change the datum definition of the frame, but removing only the variations from the trend presumes that we somehow know the "true" long-term trend.

Here I examine case studies from North America and Central Asia that illustrate the extent of hydrologic mass variability over a range of timescales, and discuss how well existing models capture that variability. Even where seasonal (~annual periodic) signals dominate, the hydrologic variability often is significant over a range of timescales from sub-seasonal to inter-annual.

ID: T3 - o3 | Estimation of a Continuous Spatio-Temporal Vertical Displacement Model From GNSS Position Time Series

Jan Martin Brockmann; Lukas Jendges; Prof. Dr.-Ing. Susanne Glaser

University of Bonn, Germany

Thanks to the continuous operation of stations equipped with Global Navigation Satellite Systems (GNSS) receivers, long-term time series of the station positions with at least a daily temporal resolution are available for scientific analysis. Due to the improved accuracy and advanced analysis techniques, the observed displacements can be linked to geophysical signals in the Earth system. As a practical example, vertical displacements can be related to changes in the terrestrial water storage or its trends to glacial isostatic adjustment and then used to validate or improve geophysical models. Unfortunately, although the GNSS network is dense in many regions, the GNSS observed/derived station positions are irregular sampled in space and time and of inhomogeneous quality. In addition to different noise levels, the position time series contain outliers and systematic errors, like jumps (e.g. caused by equipment change, antenna issues, etc.). In case the observed station positions are used for the validation or improvement of geophysical background models (for instance glacial isostatic adjustment models or loading models), a spatial and temporal gridding procedure is required. As the systematic errors, outliers and irregular signals caused by Earthquakes heavily influence the analysis, especially the estimation of linear trends, these have to be carefully considered in the analysis. In this contribution, a continuous spatio-temporal model, originally developed for the estimation of the mean sea surface, is utilized to continuously represent the vertical deformations based on GNSS station position time series. Spatial and temporal basis functions are combined to estimate the scaling coefficients of the continuous function jointly from all irregularly sampled observations in the domain of interest. Special focus is on the detection of jumps and station-specific anomalies. For this purpose, the least-squares residuals from the joint adjustment are screened, to identify outliers, anomalies and new jump locations. The proposed spatio-temporal approach is extended towards co-estimating the jumps and iteratively introducing new station-specific jump locations. It is expected that the joint spatial and temporal analysis strongly supports the detection of jumps, as observations from neighboring stations will help to identify station specific anomalies. The parametrization of the function is chosen in a way, that for instance trends and seasonal amplitudes can be determined continuously in the domain of interest as well. To test the performance of the proposed procedure, it is applied to GNSS position time series processed by the Nevada Geodetic Laboratory for a study region in Europe over at least a ten years time span.

ID: T3 - o4 | A Hybrid Automated Method for Discontinuity Detection in Geodetic Time Series toward Improved TRF Realization

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The construction of the Terrestrial Reference Frame (TRF) critically depends on the precise analysis of geodetic time series derived from VLBI, SLR, GNSS, and DORIS. A key step in the TRF pre-analysis is the identification of discontinuities in these time series, typically resulting from equipment changes, antenna displacements, or seismic events, etc. Currently, discontinuity detection is largely performed through manual visual inspection supported by auxiliary metadata. Although reliable, this procedure is time-consuming, subjective, and difficult to scale to the

continuously expanding global dataset. This study aims to develop a robust, accurate, and automatic method for discontinuity detection in geodetic time series. We propose a Hybrid Automated Detection (HAD) method based on Detection–Identification–Adaptation (DIA) method and a stochastic noise model, incorporating the Sequential T-test Analysis of Regime Shifts (STARS) algorithm to enhance discontinuity detection capability. This proposed method will be trained and validated using historical multi-technique geodetic time series with well-documented, manually identified discontinuities. The expected outcome is a highly automated tool for discontinuity detection in the TRF pre-analysis.

ID: T3 - o5 | The Impact of Gravity on Different Height Systems: A Case Study in Indonesia
– Withdrawn –

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This study investigates the influence of gravity variations on different height systems through the integration of Global Navigation Satellite System (GNSS) observations, precise geometric leveling, and gravimetric measurements. While the theoretical impact of gravity on height determination is well established, empirical quantification of these effects across regions with significant topographic variation remains limited, particularly within the Indonesian Geospatial Reference framework. The research aims to bridge this gap by examining how gravity variations affect the relationship among geometric, normal, and orthometric height systems under Indonesia's unique geophysical conditions. Field measurements were conducted across several Indonesian cities, including Makassar, Manado, Ketapang, Balikpapan, Semarang, and Bali, encompassing an elevation range of approximately 500 to 1,000 meters. GNSS data were processed within the Indonesian Geospatial Reference System 2013 (SRGI2013) to obtain precise geodetic coordinates. Geometric leveling was utilized to derive height differences with high precision, while gravimetric observations, which refer to the International Gravity Standardization Network 1971 (IGSN71), were employed to account for spatial gravity variations. These combined datasets facilitated the analysis of the relationship between gravity field irregularities and vertical reference systems tied to regional mean sea level. The results reveal that discrepancies between geometric and normal-orthometric heights become more distinct with increasing elevation but generally remain within the millimeter range. At higher altitudes, gravity's effect is more pronounced, with differences between geometric and gravity-related heights (normal and orthometric) reaching approximately 10 centimeters at the highest observation points. Additionally, the comparison between normal and orthometric heights indicates a systematic increase in their divergence along the leveling line from about 5 millimeters at lower elevations to over 1 centimeter at the uppermost section. This trend reflects the theoretical expectation that gravity-induced potential variations become increasingly significant with elevation. Furthermore, the study verifies the theoretical relationship between the geoid–quasigeoid separation and topographic elevation, demonstrating a clear tendency for greater divergence in regions of higher relief. Two computational approaches were applied to assess the internal consistency of height determination: one based on adjustment within the geopotential domain, and another involving direct adjustment in the target height system with applied height corrections. Both approaches yielded nearly identical outcomes, with discrepancies limited to tenths of a millimeter—affirming their mutual consistency and precision. Overall, this research enhances the empirical understanding of the interplay between gravity and height systems in Indonesia. The findings emphasize the importance of incorporating gravity field information in vertical reference determination, especially in regions characterized by significant elevation variation. The study contributes valuable insights toward improving the accuracy, consistency, and unification of national height reference systems within the broader geodetic infrastructure.

ID: T3 - o6 | Clock Networks for Realising a Global Height Reference System

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A globally consistent height reference system is vital for monitoring physical heights and enabling diverse geodetic applications. In practice, it shall be realised through the International Height Reference Frame (IHRF). Using clock networks, regional and national height systems can be unified in a novel and unique way to form the IHRF. In this study, we simulate the unification process for two regions - Europe and Brazil - using such a clock-based approach. An a priori height system is selected and subdivided into multiple local height systems (LHS), with complex error parameters introduced (including vertical offsets and systematic tilts) to simulate real-world discrepancies. A closed-loop simulation is performed using a joint adjustment that includes optical clock observations, enabling the estimation of the error parameters and the unified heights. High-performance optical clocks, with fractional frequency uncertainties between 10^{-17} and 10^{-18}, are assumed. Multiple sites in each LHS are selected as possible clock locations, arranged in a reduced link configuration consisting of master clocks and local clocks. Clock connections are modelled using optical fibre links for local connections and free-space links for inter-LHS master connections. Realistic simulation of clock observations accounts for various error sources in the measurement and analysis process, including clock noise, tidal correction errors, and link uncertainties. The impact of the clock distribution is analysed, and an optimal configuration is identified that minimises the standard deviations of the estimated error parameters and improves the overall unification accuracy. Additionally, the study examines the robustness of the unification under conditions such as the presence of outliers and temporal correlations between common clock observations. The results demonstrate that, under optimal conditions and with clock uncertainties at the 10^{-18} level, a unification accuracy of 1-2 cm is achievable. Furthermore, the resulting unified heights can be related to the global geoid with an uncertainty of approximately 3 cm.

ID: T3 - p1 | Statistical significance of non-tidal loading corrections on GNSS station positions

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Signals of non-tidal loading (NTL) displacements of the Earth's crust, caused by mass variations in the atmosphere, ocean and local hydrology, can be observed in Global Navigation Satellite System (GNSS) station position time series. Such displacements are readily available from various models, based on a variety of geophysical data and modeling choices, but, following the IERS 2010 convention recommendations, these effects are not included in ITRF2020 as the latest realization of the ITRS. Since then, further models of the NTL were published and improved, allowing for a more accurate representation of these signals. Bringing the theory of NTL effects and GNSS station position time series together enables to correct the GNSS data for these effects, resulting in more stable and reliable station positions. Vice versa, the dense, global network of GNSS stations helps in the validation of models containing such effects, e.g. hydrology. Together, these applications support the exploration of geophysical processes in detail. In this study, we work towards a high accuracy processing of raw GNSS observations of globally distributed stations to yield a consistent network estimate, to study the NTL effects in detail. Solutions generated with and without the correction for NTL effects allow for the application of statistical testing methods. The estimation of autoregressive processes from the time series data gives reliable covariance information, which forms the basis for trustworthy results of these statistical tests. Here, we test for significant changes in various parameters between both realizations and quantify the differences, aiming to reduce previously unmodeled rest signals.

ID: T3 – p2 | Geodetic Observations and Geopotential Determination for BEV's Optical Clock

Franz Blauensteiner; Hubert Butta; Anna Eigner; Dr. Jürgen Fredriksson; Martin Haslinger; Dr. Andreas Hellerschmied; Thomas Lercher; Tristan Lielacher; Dr. David Mayer; Sviatoslav Pavlov; Dr. Anastasiia Walenta; Ernst Zahn

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In October 2025 a new optical clock was installed Federal Office of Metrology and Surveying in Vienna. To correct for the relativistic redshift of the clock's frequency the geopotential at the clock's position has to be known accurately. This report outlines the geodetic observations and the geopotential determination carried out by Department G1 at BEV in support of the optical clocks deployed in Vienna. The measurement campaign encompassed GNSS-based position determination, as well as local trigonometrical and levelling surveys. A new GNSS reference station was installed on the roof of the building to enable the connection to the international reference frame. A series of local trigonometrical and levelling surveys facilitated the connection between global and local reference frames, ultimately providing precise coordinates of the optical clock reference point in the ITRS. Finally, the geopotential was determined by locally modelling the gravity field using a compute-remove-restore method and terrestrial gravity data. This work is required for accurately applying the relativistic redshift correction, thereby supporting the reliable synchronization and operation of the new timekeeping system.

Session T4: Genesis and Space Ties

Conveners: Krzysztof Sósnica, Kyriakos Balidakis

ID: T4 - o1 | ESA combined processing for Genesis

Jean-Christophe Berton[1]; Ivan Sermanoukian[2]; Francesco Gini[1]; Dr. Tim Springer[3]; Michiel Otten[3]; Florian Dilssner[3]; Volker Mayer[4]; Birgit Traiser[4]; Sara Bruni[3]; Erik Schoenemann[1]; Frank Zimmermann[1]; Sara Gidlund[5]

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Genesis is ESA's future mission that will contribute to the improvement of the Earth reference frame with a target accuracy of 1 mm and a long-term stability of 0.1 mm/year, providing a coordinate system for the most demanding scientific applications on our planet. The baseline for the Genesis satellite is to combine all four major space-geodetic techniques: Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR), Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) and Very-Long-Baseline Interferometry (VLBI). The synchronisation and cross-calibration of these instruments are key to determine the inherent biases of each technique, allowing for a coherent combination of the relevant observations resulting in an improved accuracy of the orbit determination, which is a requirement for the accurate Reference Frame derivation. In preparation for this mission, which is expected to be launched in 2028, the Navigation Support Office of the European Space Agency is responsible for the Precise Orbit Determination (POD) of the GNSS and Genesis satellites. Hence, the Office is preparing the necessary tools to be ready to combine all these techniques on the observation level in a coherent manner. Ongoing studies have demonstrated the performance improvement achieved by the Combination On the Observation Level (COOL) in the orbit determination system through the inclusion of both Medium Earth Orbits (MEO) and Low Earth Orbiting (LEO) satellites, along with the inclusion of SLR observations to both MEO and LEO satellites into the POD processing. Additionally, SLR targets such as LAGEOS and LARES-2 have been combined in the multi-technique processing. To further improve its precise navigation capabilities and better

support the Global Geodetic Observing System (GGOS) goals as well as the upcoming Genesis mission, the Navigation Support Office has been reviewing its ESA Precise Navigation System (EPNS)-based processing setup. Additional observations and techniques are being added step by step, carefully analysing their impact on and benefits for the COOL solution. Exploiting its newly developed GNSS processing system CHAMP, this combined processing will enable the identification and quantification of the effects of the multi-technique, multi-satellite co-processing on all constellations parameters and satellites products. A detailed description of the roadmap that the Navigation Support Office is applying for the Genesis mission will be presented and the latest analysis results of the Combination On the Observation Level, considering GNSS, SLR and DORIS together with Sentinel satellites flying these techniques will be discussed.

ID: T4 - o2 | Orbit Combination at Normal Equation Level

Prof. Dr. Urs Hugentobler[1]; Dr.-Ing. Mathis Bloßfeld[2]; Dr. Bingbing Duan[1]; Dr. Kyriakos Balidakis[3]; Dr. Daniela Thaller[3]; Dr. Helene Wolf[4]; Prof. Dr. Johannes Böhm[4]

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The upcoming ESA Genesis mission will provide space ties between all space geodetic techniques and support the consistent realization of a highly accurate and long-term stable terrestrial reference frame as the metrological basis for monitoring processes in the system Earth. All four space geodetic techniques will contribute to the precise orbit determination of the Genesis satellite. Currently, all the orbit combination strategies are performed at product level. A consistent combination of contributions by individual techniques, however, requires the handling of orbit parameters in the normal equation combination as it is already well established for station coordinates and Earth rotation parameters. Orbits are represented by initial state vector parameters, including position and velocity vectors at an initial epoch as well as additional empirical parameters. Using the initial state vector, satellite orbits can be reconstructed by numerical integration of the equations of motion. The interpretation of the initial state vector thus is strictly linked to the underlying force model. Stacking of initial state vectors is thus only allowed when all contributing solutions use identical force models and orbit parameterizations. In this contribution, we present a methodology for combining satellite orbits at the normal equation level, even when individual contributions originate from different techniques, different software packages or use different force models. We present the mathematical procedure, the additionally required information in SINEX files, and the performance based on simulated and real data. The proposed method is generally applicable and can be also used for the combination of GNSS, SLR and LEO satellite orbits from different analysis centers.

ID: T4 - o3 | Genesis contribution to SLR-based geodetic parameters

Dr. Tomasz Kur PhD; Joanna Najder; Prof. Dr. Krzysztof Sośnica

Wrocław University of Environmental and Life Sciences, Poland

Satellite Laser Ranging (SLR) is a fundamental space geodetic technique essential for the realization of the International Terrestrial Reference Frame (ITRF), providing critical information on the geocenter and scale of the ITRF. The upcoming European Space Agency (ESA) mission Genesis will, for the first time, co-locate all four fundamental space geodetic techniques - SLR, GNSS, DORIS, and VLBI - onboard a single satellite, offering a unique opportunity to strengthen global geodetic infrastructure. This study investigates the potential contribution of Genesis to SLR-based geodetic parameters, focusing on geocenter coordinates (GCC), Earth rotation parameters (ERP), and low-degree zonal coefficients of the Earth's gravity field ($C_{2,0}$, $C_{3,0}$, $C_{4,0}$). We analyze various orbit configurations proposed for Genesis, including the ESA baseline orbit

(altitude 6,000 km, inclination 95°) and alternative scenarios with different altitudes, inclinations, and eccentricities. Two orbit determination strategies are considered: (1) estimating the Genesis orbit from SLR observations, and (2) fixing the orbit to GNSS-based solutions. Extensive simulations were conducted including Genesis alongside the existing geodetic satellites - LAGEOS 1/2 and LARES 1/2 - over one year of simulated SLR observations from 20 high-performing stations. The results show that Genesis significantly enhances geodetic parameter estimation, especially for the Z component of GCC, which benefits from high-inclination orbits and GNSS-based orbit determination. For the ESA-proposed orbit, the median formal error in Z can be reduced below 1 mm, fulfilling GGOS goals for reference frame stability. For ERP, Genesis improves the formal errors of polar motion and UT1-UTC estimates by up to 35% compared to current SLR constellations, with the best results obtained for high-altitude, retrograde orbits. Gravity field coefficients also benefit from Genesis, with improvements up to 80% for C4,0 in the eccentric orbit configuration. Overall, the orbit parameters of Genesis strongly influence the number and geometry of SLR observations, affecting the quality of derived geodetic products. The combination of SLR with GNSS-based orbit determination offers the greatest improvements, particularly for Z component of GCC and UT1-UTC. These results demonstrate that Genesis will be a critical mission for advancing the accuracy of global geodetic parameters and improving the long-term stability of the ITRF.

ID: T4 - o4 | Combination of GENESIS observations with the other Earth's Laser Ranged satellites for Optimal Estimation of Geocenter

Dr. Francesco Vespe

Agenzia Spaziale Italiana, Italy

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.

ID: T4 - o5 | Preparing for VLBI with ESA's Genesis satellite

Prof. Dr. Rüdiger Haas PhD

Chalmers University of Technology, Sweden

The European Space Agency (ESA) currently prepares on the Genesis mission. Genesis is a so-called co-location satellite that should contribute to the improvement of the International Terrestrial Reference Frame (ITRF). The idea is to combine the four space geodetic techniques Very Long Baseline Interferometry (VLBI), Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR) and Doppler Orbitography and Radio Positioning Integrated by Satellite (DORIS) on one single spacecraft that is orbiting Earth. The Genesis satellite is planned to be launched in 2028 and have a life time of at least 2 years. In order to work on the goals of the Genesis mission, ESA has set up a Genesis Science Exploitation Team (GSET). GSET involves four technique-specific working groups (WGs), one each for VLBI, GNSS, SLR and DORIS, as well as one working group for the ITRF and combinations. The technique- specific WGs have the task to advise and support ESA for all aspects of the Genesis mission, including assistance in calibration, processing and validation of Genesis data, and the exchange information with the international

science community. ESA GSET Working Group 3 (WG-3) focusses on the VLBI aspects of Genesis. Currently discussed topics are the VLBI transmitter and transmitting antenna, compatability with normal operations of the International VLBI Service for Geodesy and Astrometry (IVS), and the IVS product generation. Other important aspects for WG-3 are optimal scheduling, end-to-end simulations, and eventually also test observations of Genesis. This presentation is on behalf of ESA GSET WG-3 (VLBI) and gives an overview on the current status of the work performed in the working group.

ID: T4 - o6 | Potential of VLBI for Orbital and Solar Radiation Pressure Parameter Estimation

Dr. Helene Wolf[1]; Prof. Dr. Urs Hugentobler[2]; Prof. Dr. Johannes Böhm[1]

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The Genesis mission, scheduled for launch by the European Space Agency (ESA) in 2028, will carry a dedicated VLBI (Very Long Baseline Interferometry) transmitter. This mission represents a significant advancement, as it will enable direct VLBI observations of a satellite, opening new possibilities for satellite orbit modelling based on VLBI data and potentially improving the accuracy and consistency of orbit determination across different space-geodetic techniques. In this study, the potential of VLBI to estimate the six orbital elements together with nine solar radiation pressure (SRP)–related dynamical parameters is investigated using simulated VLBI observations. The analysis employs partial derivatives with respect to the dynamical parameters obtained from the ORBGEN module of the Bernese GNSS Software. The SRP-induced accelerations are decomposed into three orthogonal directions: (a) along the satellite to the Sun direction, (b) along the satellite's solar panel axis, and (c) along the direction completing the right-handed coordinate system. Accordingly, the accelerations are parameterized by three components in each direction, resulting in a total of nine SRP parameters. Furthermore, the study examines the impact of geocentre estimation on the determination of both the orbital elements and the SRP parameters, providing insight into the interplay between global reference frame parameters and satellite dynamics.

ID: T4 - p1 | Precise Orbit Determination with Satellite VLBI

Dr. Jungang Wang[1]; Dr. Kyriakos Balidakis[2]; Prof. Dr. Robert Heinkelmann[3]; Prof. Dr. Maorong Ge[4]; Prof. Dr. Harald Schuh[1]

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To meet the Terrestrial Reference Frame (TRF) requirements set by the Global Geodetic Observing System (GGOS), namely 1 mm accuracy and 0.1 mm/year stability, a rigorous combination of the four space geodetic techniques is essential. Currently, such combinations rely mainly on station coordinate and Earth Orientation Parameters (EOP) ties, while additional atmospheric and clock ties have the potential to further enhance the integration. A particularly promising strategy involves equipping Low Earth Orbiters (LEO) with instruments from all four techniques, enabling direct co-location in space. At present, several LEO satellites carry Global Navigation Satellite System (GNSS), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) receivers, and/or Satellite Laser Ranging (SLR) reflectors. Adding a VLBI transmitter onboard a LEO would complete the set, enabling true space ties between all four ITRF techniques and strengthening multi-technique integration, an approach also pursued by ESA's Genesis mission. In this study, we simulate a VLBI transmitter onboard a LEO satellite and schedule 24-hour VLBI sessions involving approximately eleven VGOS stations observing both active galactic nuclei (AGN) and the LEO. Our simulations demonstrate that satellite VLBI can achieve satellite orbit accuracies at the centimeter level and enable the estimation of geocenter coordinates with a

precision of about 1 mm. However, both orbit and geocenter estimates are highly sensitive to the dynamic orbit modeling. For instance, when empirical accelerations are estimated once per revolution (approximately four hours for a Genesis-like orbit) rather than once per day, the error of geocenter estimates doubles (from 2 to 4 mm), and that of satellite orbit increases even more significantly. This accuracy degradation is mainly caused by the poor observation geometry resulting from the limited ground station distribution. It can be mitigated by increasing the number of participating stations or by optimizing the spatial distribution of observations. The benefits of satellite VLBI for EOP estimation are less pronounced. Primarily, because the AGN observations provide a much stronger contribution. Finally, we investigate the impact of different satellite orbits (e.g. simulating various inclinations) and scheduling strategies on orbit determination and geocenter coordinate estimation, and we explore the potential benefits of incorporating atmospheric and clock ties in satellite VLBI.

ID: T4 - p2 | SLR simulations for improved geodetic parameters in light of the Genesis mission

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The accuracy and stability of global terrestrial reference frames relies on the contributions of the main space geodetic techniques: Very Long Baseline Interferometry (VLBI), Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). Each technique is subject to a particular set of strengths and weaknesses that determine which geodetic parameters can be estimated by which technique with sufficient reliability for reference system realization. This study looks ahead to a future SLR network with 20 new stations planned to be in operation by 2028 to determine the impact of this expanded network on a subset of SLR-derived geodetic parameters. SLR station performance is highly variable, depending mainly on local weather conditions and technical capabilities. To reflect this variability, the simulated performance of the 20 new SLR stations takes into account local cloud cover and technical capabilities with the goal of simulating a realistic number of observations depending on the geographic location. In 2028, the European Space Agency (ESA) will launch the Genesis mission as the first space-based co-location of the main space geodetic techniques in an effort to address and overcome challenges that have hindered an accurate and stable realization of the International Terrestrial Reference System (ITRS) thus far, such as technique-specific systematic error sources and inconsistent terrestrial tie measurements. Thus, another goal of this simulation is to assess the capabilities of an expanded SLR network in light of the new Genesis mission. This simulation study investigates various scenarios to ensure the greatest possible improvement in geodetic parameter estimation by SLR.

ID: T4 - p3 | Improving GNSS-derived geocenter motion using SLR observations

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Estimating geocenter motion from GNSS alone is problematic, primarily because orbit-modeling errors produce spurious draconitic signals—especially in the Z component—making the GNSS-derived center of mass ambiguous. In GNSS processing, satellites are referenced to a notional apparent center of mass rather than Earth's true center of mass, which undermines the physical meaning of geocenter estimates. We introduce a hybrid approach that fuses GNSS microwave observations with Satellite Laser Ranging (SLR) data to Galileo, GLONASS, and the two LAGEOS satellites. We systematically test combinations of GNSS, SLR@GNSS, and SLR@LAGEOS to assess how each contributes to geocenter recovery. Our key findings include that (1) SLR to GNSS

observations alone are insufficient to suppress draconitic contamination in the geocenter series; the GNSS-only and GNSS + SLR@GNSS solutions remain dominated by the same spurious Z signals. (2) Combination of GNSS and SLR@LAGEOS observations improves results: the 3rd harmonic of the draconitic year (~117 days) is reduced by a factor of ~4, and the annual Z amplitude falls from ~8 mm (GNSS-only) to ~4 mm, aligning the GNSS solution closely with the LAGEOS-based geocenter. (3) In combined solutions, the formal uncertainties in X and Y geocenter components drop from ~0.9 mm to ~0.5 mm, and the Z component uncertainty is reduced by ~40–46%. (4) Full co-location (i.e., SLR on GNSS + LAGEOS) is not strictly necessary. (5) Even without SLR tracking of GNSS satellites, simply combining GNSS microwave data with LAGEOS SLR observations yields a well-defined geocenter origin with suppressed draconitic artifacts. In summary, fusing GNSS with LAGEOS-based SLR provides a practical and effective route to embed a physically meaningful geocenter in GNSS solutions—reducing noise and spurious signals without needing complete spatial co-location of all systems.

ID: T4 - p4 | VLBI satellite scheduling with VieSched++

Matthias Schartner; Benedikt Soja

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Very Long Baseline Interferometry (VLBI) relies on a network of radio telescopes conducting synchronized observations of celestial radio sources. A crucial component of every VLBI experiment is the observing plan, known as schedule, which defines the sequence and timing of observations. Creating an optimal schedule can be seen as a complex optimization problem: given a telescope network configuration and a specific time frame, the goal is to determine the sequence of observations that maximizes scientific return. This task is handled by specialized software packages such as VieSched++. With the upcoming launch of geodetic satellite missions such as Genesis, it has become increasingly important to incorporate satellite observations into the VLBI scheduling process. In this contribution, we present recent enhancements to VieSched++, further improving VLBI satellite scheduling support. Beyond implementing orbit propagation for telescope pointing, which was already implemented in the past, we introduce developments that account for varying signal strengths based on transmitter antenna gain patterns, as well as considerations of technological compatibility throughout the VLBI observation pipeline.

ID: T4 - p5 | Three Decades of DORIS Zenith Tropospheric Delay: A Global, Homogenized Comparison CNES/CLS IDS vs IGS Time-Series (1993–2024) using the GINS software

Vikash Kumar[1]; Prof. Alexandre Couhert[2]; Prof. Hugues Cadeville[3]; Prof. Adrien Mezerette[3]; Prof. Petr Stepanek[4]; Prof. Nagarajan Balasubramanian[1]; Prof. Onkar Dikshit[1]; Prof. Alvaro Santamaria[5]

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We address the need for accurate neutral-atmosphere corrections for space-geodetic observations by building and evaluating a global record of zenith tropospheric delay (ZTD). Our workflow extends the proven homogenization strategy used to build the 1993–2008 DORIS precipitable water vapor (PWV) data set, where equipment-change biases were corrected and the resulting series showed very high agreement with GPS (Bock et al., 2014) and reanalyses to the full three-decade interval, updating mapping functions and ancillary models as appropriate.

Our data set spans 31 years from (1993-2024) and leverages DORIS processing with CNES' GINS software. Validation will rely on co-located IDS (DORIS) and IGS (GNSS) station solutions from the respective CNES/CLS Analysis Centers (AC), comparing ZTD at matched epochs while accounting for height/distance differences and known technique specifics (e.g., estimation intervals, gradients). The workflow combines modern dry/wet mapping functions, estimation of ZWD and horizontal gradients, and practical homogenization to mitigate equipment and process changes through time. Using DORIS and IGS co-locations, we quantify random scatter and systematic offsets between techniques, produce global maps and site-wise time series, and assess seasonal to multi-decadal variability. Building on earlier findings that DORIS achieves mm-level multi-day precision and robust long-term stability after homogenization, we expect the extended record to support climate-scale water-vapor monitoring, and through better tropospheric modelling over oceanic regions.

ID: T4 - p6 | Progress on DORIS Clock Correction Strategies from the IDS Working Group

Adrien Mezerette[1]; Hugues Capdeville[1]; Théo Gravalon[1]; Jean-Michel Lemoine[2]; John Moyard[2]; Flavien Mercier[2]; Alexandre Couhert[2]; Guilhem Moreaux[1]; Patrick Schreiner[3]; Anton Reinhold[3]; Mara Guaini[4]; Barath Gunasekaran[4]; Urs Hugentobler[4]; Carlos Fernández Martín[5]

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The DORIS Ultra-Stable Oscillators (USO) on board altimeter satellites are perturbed when crossing the South Atlantic Anomaly (SAA), where they exhibit rapid variations in oscillator frequency and, consequently, phase measurements. SAA-induced USO perturbations affect derived products such as station positioning in the SAA region and, to a lesser extent, precise orbit positioning. Fortunately, recent satellites such as Sentinel-3A/-3B, and Sentinel-6 MF are equipped, in addition to the DORIS receiver, with a GNSS receiver connected to the same DORIS USO. It is then possible to correct the clock of DORIS observations using estimated GNSS clock corrections. The IDS Clock Working Group aims at exploring this possibility for current DORIS satellites and in preparation for the next Genesis mission. Some results of the working group will be presented in terms of characterization of the DORIS USO frequency excursions in relation with the Earth's radiative environment, correction of the DORIS clock through the link with the GNSS receiver, impact of the corrected clock on satellite and station positioning, expected radiative environment at the altitude of the future European geodetic mission Genesis.

ID: T4 - p7 | Assessing the Potential of Co-location in Space for Global Reference Frame Realisation Using End-to-End Simulations

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Future multi-technique missions such as Genesis aim to establish co-location of space-geodetic techniques directly on a single satellite platform to improve the consistency and stability of the terrestrial reference frame (TRF). To assess the quantitative benefits of such in-space co-location, comprehensive end-to-end simulations are performed using GFZ's in-house software EPOS-OC. This unified processing environment enables the generation of realistic synthetic observations for Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR), and Very Long Baseline Interferometry (VLBI), as well as dynamic precise orbit determination (POD) within a fully consistent multi-technique modelling framework. The simulator is calibrated with real tracking

data of other missions to reproduce representative noise characteristics, data gaps, and observation geometry for each technique. Simulated observations are used to derive single-technique orbit and parameter solutions, from which normal equations are accumulated over a two-year simulation period. These are combined with and without the inclusion of the simulated space-tie satellite, enabling a quantitative assessment of the specific contribution of the space-based co-location to the overall reference frame improvement. The study is performed within project GENESIS-D, funded by the German Space Agency at DLR, and provides a quantitative insight into the achievable gain in reference frame consistency, geocentre determination, and Earth orientation parameters through co-location in space. It is supporting ongoing efforts to meet the TRF accuracy requirements set by the Global Geodetic Observing System (GGOS).

ID: T4 - p8 | Multi-Technique POD Solution for Jason-3 developed at DGFI-TUM

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The Genesis mission, launching in 2028, aims to collocate the four geodetic space techniques within a single satellite platform. To validate multi-technique precise orbit determination (POD) strategies prior to launch, the Jason-3 satellite, carrying three of the four Genesis techniques, serves as a suitable test platform. Within the Genesis-D project, DGFI-TUM is responsible for evaluating Satellite Laser Ranging (SLR) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). Consequently, the validation of a combined SLR/DORIS POD solution is performed using Jason-3 data. The optimal relative weighting between SLR and DORIS observations is investigated through a combined POD (3.5-day arcs) at observation level. Several test computations are performed for a selected and representative time interval ensuring enough SLR observations. A comprehensive evaluation of the obtained relative weights is performed using, both, internal (orbit parameters, stochastic properties, and overlap differences) and external (reference orbit differences) validation. Future work will additionally address the combination at normal equation level. The best technique-specific standard deviations are derived through comparison with SSA and JPL reference orbits, showing 0.2 mm/s for DORIS and 5 cm for SLR.

ID: T4 - p9 | GENESIS-D: a geodetic project from German organizations to support ESA's Genesis mission

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ESA's Genesis mission primarily aims to improve the International Terrestrial Reference Frame (ITRF). Currently, this fundamental product is obtained by a combination of four space-geodetic techniques: Global Navigation Satellite Systems (GNSS), Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and Doppler Orbitography and Radio positioning Integrated by Satellite (DORIS) involving additional tie measurements. The ties that are applied in standard processing are local ties at co-location sites on ground and global ties, i.e. a common series of daily Earth Orientation Parameters (EOP) across the techniques. The celestial reference frame (ICRF) and satellite orbits are not parameterized globally in the adjustment process. Several low Earth orbit (LEO) and some navigation satellites, however, are observed by more than one of the four space-geodetic techniques. If the displacements of the phase centers of each sensor with respect to the center of mass of the satellite are known with high precision, orbit parameters can

be introduced as an additional parameter set common to all techniques. ESA's Genesis mission will realize all four space-geodetic techniques on board of a medium Earth orbiting (MEO) satellite. For the realization of the mission goals, ESA cooperates with the International Association of Geodesy (IAG) and its Scientific Services and established working groups to foster and to oversee the scientific exploitation. Before launch (planned for 2028), realistic simulation studies will be carried out to effectively support the mission goals and to assess the improvement of accuracy of the geodetic parameters, of the ITRF, but also of EOP, ICRF and satellite orbits. In order to address these and other related tasks, a German consortium led by GFZ Helmholtz Centre for Geosciences with the Federal Agency for Cartography and Geodesy (BKG), Frankfurt a. M., and the DGFI-TUM, Munich, as contractors, as well as University of Bonn and GeoBM GmbH as sub-contractors, started in March 2025 to work on the GENESIS-D project funded by the German Space Agency at DLR. First, within this project the various project partners will enable their software to incorporate the technique-specific observations and parameter sets that represent LEO and/or MEO satellites. Then, combinations will be carried out based on detailed simulation and real data scenarios of several or of all four techniques. The most innovative technique onboard the Genesis satellite will be the VLBI transmitter. Accordingly, the optimal scheduling of observations to the satellite and to active galactic nuclei (AGN) for achieving the most accurate and stable geodetic parameters is another key objective. In this presentation, we will present an overview of the project objectives and highlight the key contributions of this scientific network to the successful exploitation of the Genesis mission.

Session W1: Multi-technique Combinations and Co-location in Space
Conveners: Krzysztof Sósnica, Lisa Klemm

ID: W1 - o1 | On the Combination of LAGEOS and Sentinel-6A in Preparation for Exploiting the Genesis Mission

Dr. Kyriakos Balidakis[1]; Luca Weinem[1]; Claudia Flohrer[1]; Daniela Thaller[1]; Dr.-Ing. Alexander Kehm[1]; Daniel König[1]; Ulrich Meyer[2]; Daniel Arnold[2]; Linda Geisser[2]

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ESA's Genesis mission will provide a co-location platform for all four space geodetic techniques that currently contribute to the realization of international terrestrial reference systems, thus strengthening the integration of Earth's geometry, rotation, and gravity field. In anticipation of its launch, several Low-Earth-Orbiting (LEO) satellites represent a co-location in-space already now for the three space-geodetic techniques GNSS, SLR and DORIS. Using such LEOs allows to study potential hurdles in harvesting the full potential of Genesis. In this work, we have chosen the altimetry satellite Sentinel-6A Michael Freilich (S6A) as a proxy for Genesis, and we analyzed the SLR data to S6A together with laser ranges towards LAGEOS-1 and LAGEOS-2. Unlike the two LAGEOS satellites where a single arc is set up per week, we estimate daily arcs for S6A due to the lower altitude and more complicated radiation-pressure modelling. Upon accumulating the daily-arc S6A normal equations (NEQs) to weekly NEQs and stacking them with the LAGEOS-based NEQs we retrieve weekly solutions containing satellite orbits, station coordinates, Earth rotation parameters, the geocenter coordinates, and the range biases. We compare all parameters estimated in the framework of the three solution types, that are (i) LAGEOS-only; (ii) S6A-only; and (iii) LAGEOS+S6A. In addition to the estimated parameters, we investigate the post-fit range residuals. We find the LAGEOS station coordinate repeatability is 2-3 times better than S6A, a fact expected from a single-satellite LEO solution, which we utilized for the relative LAGEOS-S6A weighting. While the S6A residuals are on average 5% larger compared to LAGEOS, we observe a 50% larger variability in the residual levels among different SLR stations., with the S6A residuals being clearly smaller at the high-performing stations. We also find that the six-fold increase in low-

elevation observations to S6A compared to LAGEOS facilitates the decorrelation between range bias and station height, which for LAGEOS is on average 0.93, whereas for S6A is 25% smaller.

ID: W1 - o2 | On the extension of geodetic parameter determination from SLR to spherical satellites by GNSS and SLR observations to non-spherical LEOs

Martin Lasser[1]; Linda Geisser[1]; Ulrich Meyer[1]; Daniel Arnold[1]; Luca Weinem[2]; Daniela Thaller[2]; Rolf Dach[1]; Adrian Jäggi[1]

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At the Astronomical Institute of the University of Bern (AIUB) the Celestial Mechanics Approach is currently employed for two space geodetic techniques, namely Global Navigation Satellite Systems (GNSS) and Satellite Laser Ranging (SLR). Both are not only used for the computation of global solutions but also for precise orbit determination (POD, with GNSS data) and validation (using SLR observations) of Low Earth Orbiting (LEO) satellites. Recent enhancements to the Bernese GNSS Software have enabled the POD of non-spherical LEO satellites equipped with laser retro-reflectors. In this contribution, a SLR-based POD for LEO satellites is presented and compared to the GNSS-based POD. In a next step, the SLR and GNSS observations are combined for the POD process, thereby implementing a space-tie on the LEO satellite. With that, the analyses are expanded by incorporating observations to dedicated spherical SLR satellites. This facilitates an estimation of the underlying SLR station network and geodetic parameters. Data from the Gravity Recovery and Climate Experiment Follow-On (GRACE Follow-On) satellite mission serve as input for the LEO satellite, providing high-quality GNSS tracking data and a sufficient number of SLR observations. The investigation of orbit solutions is conducted through a comparative analysis of internal consistency numbers, such as the root mean square of post-fit residuals, alongside external quality checks utilising the K-band range data from GRACE Follow-On. The geodetic parameters are evaluated with respect to SLR-only solutions and the IERS C04 Earth rotation parameter model as reference.

ID: W1 - o3 | Estimation of LEO antenna phase center offsets and variations towards future LEO/GNSS integrated processing

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Space-based Global Navigation Satellite System (GNSS) observations from Low Earth Orbit (LEO) satellites, characterized by their fast motion, offer significant advantages in global coverage and observation geometry compared to the exclusive use of ground observations. The abundant space observations integrated with ground observation to build a multi-layer system covering ground, LEO, medium, and potentially geosynchronous orbits, which might play an important role in the next International Terrestrial Reference Frame (ITRF) realization, e.g., the upcoming GENESIS mission. Reliable knowledge of LEO antenna phase center offsets (PCOs) and phase variations (PVs) is a prerequisite for LEO-included data processing. However, the manufacturer-provided PCOs and PVs for existing missions may not be accurate since they are often affected by various factors, such as on-orbit thermal deformation and unmodeled spacecraft-specific effects. Therefore, LEO PCOs and PVs should be calibrated precisely, aligning to current ITRF. Unlike the traditional multi-step PCO/PV estimation, e.g., using residual stacking approach to correct LEO PVs with fixed PCOs (Jäggi et al., 2009), we estimate LEO PCOs and PVs simultaneously with flatness and zero-mean constraints via multi-day normal-equation (NEQ) stacking (Duan et al., 2024). The use of flatness and zero-mean conditions not only helps to separate PCOs, PVs, and constant phase ambiguities clearly, but also avoids the use of potentially inconsistent or alternating minimization criteria in the multi-step PCO/PV estimation. In this study, daily NEQ is generated via reduced dynamic approach, including LEO PCO, PV and

orbit parameters. For multi-day NEQ stacking, a random walk noise (RWK) of 0.2 mm is added for PCO parameters between adjacent sessions while a tight constraint is added to PV parameters. We choose a RWK instead of tight constraint because the PCOs may change due to variation of the center of mass. A uniform weighting over an equidistant grid of boresight angles in the pattern minimization is applied after stacking all daily NEQs. In this framework, LEO PCOs and PVs from multiple missions, including GRACE-FO, Swarm-a/b/c, Jason-3, and Sentinel-3/6 are calibrated separately. Finally, an example of LEO/GNSS integrated processing is presented to demonstrate the superiority of using consistent LEO PCOs and PVs.

ID: W1 - o4 | Potential of GPS-SLR space ties onboard LEO satellites for global geodetic parameter determination

Bo Li[1]; Dr. Shiwei Guo PhD[1]; Jingzhu Zhao[1]; Prof. Chuang Shi PhD[1]; Lei Fan PhD

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Global geodetic parameters, such as Geocenter Coordinates (GCCs) and Earth Rotation Parameters (ERPs), are critical for the definition of the International Terrestrial Reference Frame (ITRF) and geophysical studies. Traditional ITRF realization relies heavily on ground-based local ties to combine multiple space geodetic techniques, but these ties suffer from spatial unevenness, high maintenance costs, and infrequent updates. Low Earth Orbit (LEO) satellites equipped with multi-geodetic payloads have emerged as a transformative solution, providing "space ties" that allow inter-technique linkage independent of ground surveys. This study explores the potential of GPS-SLR space ties onboard Swarm LEO satellites for precise parameter determination via observation-level combination. Using ground-based GPS observations from 107 IGS stations, Swarm-borne GPS observations, and SLR-to-Swarm measurements from 36 SLR stations, three solutions (GPS-only, GPS+LEO, GPS+LEO+SLR) were analyzed and compared. Swarm-borne GPS observations markedly improve sensitivity to geocenter motion, decreasing GCC formal errors by about 46.5%, 48.4%, and 36.7% in the X, Y, and Z components, and reducing ERP formal errors by 34.3%, 40.1%, and 31.5% for the X-pole, Y-pole, and LOD, respectively, due to enhanced geometry. Correlation analyses further confirm that Swarm-borne GPS observations effectively decouple the GCC Z-component from GPS orbit model parameters, thereby enhancing solution robustness. The inclusion of SLR-to-Swarm observations yields additional reductions in the horizontal components, improves the temporal stability of geocenter estimates, and further mitigates the β-angle dependence of GCC formal errors in the X and Y components. The annual difference between GPS+LEO+SLR and SLR-60day solutions was 0.6 mm in amplitude and 15° in phase for the GCC Z component. However, due to SLR's insensitivity to Earth rotation and its sparse temporal sampling, its contribution to ERP estimates is limited, yielding only moderate improvements in polar motion bias and standard deviations, especially in the Y component. This study confirms the value of LEO-based GPS-SLR space ties in advancing global geodetic parameter estimation. In the future, a promising direction is the co-location of GNSS and VLBI payloads onboard LEO satellites to address residual ERP limitations.

ID: W1 - o5 | Antenna calibration error propagation in single- and multi-technique TRF solutions

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The GENESIS mission aims to improve the accuracy and stability of the terrestrial reference frame (TRF) by co-locating DORIS, GNSS, SLR and VLBI instruments on the same satellite. A key

objective of the mission is accurate calibration of all onboard antennas to ensure inter-technique consistency. While correlations between antenna calibration and TRF parameters have been analyzed in GNSS solutions, their effects in the other technique solutions or in multi-technique solutions such as those anticipated from GENESIS are not well understood. Using numerical simulations with CNES' GINS/DYNAMO software, we model antenna calibration errors and test different error scenarios for GENESIS and other contributing satellites (DORIS, SLR, and GNSS). We investigate how calibration biases and uncertainties propagate into TRF origin and scale parameters, and evaluate the sensitivity of each technique to these errors. This study provides insights into calibration error propagation mechanisms in current TRF solutions, and characterizes GENESIS' potential to improve TRF parameter determination through its co-location and calibration strategies.

ID: W1 -o6 | FocusPOD: A POD and Geodesy SW Package

Jaime Fernández Sánchez; Miguel Ángel Muñoz; Javier Berzosa; Marc Fernández; Luning Bao

GMV A&D

Since 2021, GMV has been developing FocusPOD, a new Precise Orbit Determination (POD) and Geodesy software package designed to serve as a unified framework for multi-technique space geodesy. Written in modern C++17 and Python3, FocusPOD is built around four core design principles: (1) Object-Oriented Architecture, ensuring modularity, scalability, and efficient handling of large geodetic datasets; (2) Data–Algorithm Separation, enabling consistent use of the same algorithms across multiple observation types; (3) Centralized Data Model, which structures heterogeneous measurements (GNSS, DORIS, SLR, VLBI) in a coherent, relational format; (4) Multi-Use Case Support, allowing expert interactive use as well as automated operations and machine-to-machine interfaces. FocusPOD supports precise orbit determination based on GNSS, DORIS, and SLR measurements for Copernicus Sentinel-3 and Sentinel-6 missions, achieving millimeter-to centimeter-level orbit precision. These capabilities enable cross-validation and bias estimation between techniques, supporting the refinement of reference frames and the study of co-locations in space. In addition, VLBI processing has recently been incorporated, allowing geodetic and astrometric applications such as the joint estimation of Earth Orientation Parameters (EOPs), station coordinates, and celestial source positions, in support of the Galileo Reference Centre (GRC) v2 project from the EUSPA. The software also provides a flexible environment for comprehensive observation simulation, including realistic noise effects and modelling uncertainties, enabling controlled performance assessment and sensitivity analyses across techniques. This contribution presents FocusPOD's multi-technique POD capabilities, demonstrating how the combined use of DORIS, SLR, and GNSS enhances orbit consistency and supports integrated space-based co-location experiments. The results, based on Sentinel-3A and -3B and Sentinel-6 orbit determination and combination, highlight the potential of a unified geodetic processing environment for the Genesis mission and future global reference frame realizations. Ongoing developments include normal equation stacking for TRF-like global solutions and the integration of GNSS network processing within the same software framework.

ID: W1 - p1 | Preliminary analysis of K-band VLBI sessions for the IVS contribution to ITRF2020-u2025 – moved to oral presentation W4 - o5

Shrishail Raut; Dr.-Ing. Alexander Kehm; Dr. Sabine Bachmann; Dr. Kyriakos Balidakis; Lisa Klemm; Sandra Schneider-Leck; Dr. Daniela Thaller

BKG Federal Agency for Cartography and Geodesy, Germany

The International VLBI Service for Geodesy and Astrometry (IVS) Combination Centre (IVS-CC) is operated by the close collaboration between the Federal Agency for Cartography and Geodesy (BKG) and the Deutsches Geodätisches Forschungsinstitut at the Technical University of Munich

(DGFI-TUM). IVS-CC is principally responsible for the generation of official IVS products, such as the realisation of the International Terrestrial Reference System. It is achieved through a combination of the contributions submitted by the IVS Analysis Centres (ACs). As initiated by IVS, IVS-CC plans to provide an update to the International Terrestrial Reference Frame 2020 (ITRF2020), ITRF2020-u2025, based on the ACs' contributions, which will involve a complete reprocessing since 1979. For their generation, the VLBI sessions will consist of S/X-band, VGOS, and K-band, where the ITRF2020-u2025 update will foresee the inclusion of K-band VLBI sessions for the first time. The K-band operates on a much higher frequency of 24 kHz compared to S/X and VGOS. This investigation focuses on the implementation and assessment of K-band VLBI sessions. The 24-hour K-band VLBI sessions have been conducted from May 2002 to the present, encompassing over 200 sessions. The work discusses the combination methodology employed for K-band and details the sessions used as input. We examine the solutions from individual ACs and perform a comparative analysis. We will quantify the benefits of including these K-band VLBI sessions and additionally highlight their limitations.

ID: W1 - p2 | Assessing Range-Dependent Systematic Errors in SLR Data and Their Influence on Height Time Series

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Satellite Laser Ranging (SLR) to geodetic spherical satellites has been a cornerstone of precise geodesy for nearly fifty years, providing essential data for the continuous improvement of the accuracy of the terrestrial reference frame. Over this period, significant advances in ground-station technology have reduced systematic range measurement errors to only a few millimetres at most modern facilities. Motivated by these technological and methodological improvements, particularly those introduced through ILRS initiatives, we have revisited SLR data from several European network stations operating in the early 2000s. These stations employed time-of-flight systems known to exhibit range-dependent biases of up to approximately 10 mm. In 2002, detailed investigations at the UK Space Geodesy Facility (Herstmonceux) quantified these biases using comparisons with a high-precision event timer. However, the corresponding corrections have not been systematically applied in subsequent data processing for ITRF realisations. In this contribution, we revisit that analysis, apply range-dependent corrections to the historical datasets, and assess their impact on station height time series. We demonstrate how the removal of these systematic effects improves the consistency and stability of the geodetic height estimates, contributing to ongoing efforts to enhance the accuracy of global reference frame products.

ID: W1 - p3 | A review of the SLR station performance since the release of ITRF2020

Dr Magdalena Kuzmicz-Cieslak PhD[1]; Alexandre Belli[2]; Frank Lemoine[3]; Keith Evans[1]; Van Husson[4]

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The Analysis Centers (AC's) of the International Laser Ranging Service (ILRS) routinely process SLR data from ILRS tracking stations for the purpose of providing routine solutions for station coordinates and Earth Orientation Parameters (EOP) and contributing to the International Terrestrial Reference Frame (ITRF). The contributions include SINEX files computed on both a daily and a weekly basis. Since 2022, the contributions are based on processing data to five geodetic satellites: LAGEOS-1, LAGEOS-2, LARES-2, Etalon-1, and Etalon-2. As an ILRS analysis center (AC) and as an ILRS combination center (designated as ILRS-B), JCET/NASA GSFC provides

daily and weekly SINEX contributions, and combines the SINEX solutions of the eight ILRS AC's to provide the ILRS-B solution, as a backup to the solution provided by the Italian Space Agency (ASI), ILRS-A. The process of data analysis and combination provides a wealth of data on station performance with time, in terms of station precision, and range bias stability. We review recent ILRS station performance in terms of the following parameters: (1) quality of the performance in the recent ITRF2020 solution extensions; (2) tracking performance by the individual stations, including frequency and geometry of tracking; (3) normal point quality; (4) bias stability (short and long-term). We review the coordinate history for the ILRS core sites, comparing station coordinate solutions of collocated geodetic techniques at these SLR stations.

ID: W1 - p4 | Towards a more accurate DORIS scale: Evaluating modeling and processing Strategies

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The DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) system is one of the four geodetic techniques contributing to the realization of the International Terrestrial Reference Frame (ITRF). While DORIS contributes valuable data to the multi-technique combination, its derived scale has long exhibited a systematic bias compared to other space geodetic techniques. However, this bias has remained remarkably stable in recent years, coinciding with an increase in the number of operational DORIS-equipped satellites, which has improved the overall geometry and robustness of the network. The origin of this scale bias is still under investigation. Two primary sources are considered: (1) Modeling errors, particularly uncertainties in the satellite antenna phase center offsets (PCOs), (2) The parametrization strategies used in the data processing. To address these issues, this study aims to refine the scale estimation by evaluating the sensitivity of reference frame parameters to these factors. First, we assess the impact of a 1 cm error in the satellite antenna PCO on the estimated scale and other reference frame parameters, using a satellite-by-satellite approach. Second, we investigate how different orbital modeling strategies affect the scale, focusing on the estimation frequency of the atmospheric drag coefficient, the configuration of stochastic acceleration parameters, and the solar radiation pressure modeling.

ID: W1 - p5 | PCC-Explorer: An open-source simulator to assess the impact of PCC differences on geodetic parameters

Dr. Johannes Kröger; Amr Fawzy; Tobias Kersten; Steffen Schön

Leibniz University Hannover, Germany

For highly precise positioning with Global Navigation Satellite Systems (GNSS), it is essential to apply Phase Center Corrections (PCC), especially for data processing at reference stations contributing to regional or global reference frames. However, no unique ground truth for calibration values exists, leading to a lack of standardized benchmarks across different calibrations performed by different facilities and methods. To assess the similarity of different calibration results (dPCC), characteristic measures such as absolute mean values or standard deviations can be computed, and graphical comparisons can be performed. These analyses are typically carried out in PCC domain as given by the Antenna Exchange (ANTEX) format. ANTEX files store Phase Center Offsets (PCO) and Phase Center Variations (PCV) on an azimuth–zenith grid per system and frequency. However, the grid-level similarity does not directly reveal the impact on estimated geodetic parameters. Yet for users and network providers it is most relevant to investigate how dPCC affect topocentric coordinate differences, receiver clock errors, and tropospheric parameters — i.e., quantities that directly influence terrestrial reference frame

consistency. In this contribution, we present PCC-Explorer, an open-source, standardized simulation tool written in Python. It quantifies how dPCCs propagate into geodetic parameters at the station level under realistic multi-GNSS conditions. The tool processes ANTEX files, supports all major GNSS and their frequencies, and allows users to specify ionosphere-free linear combinations. It also supports multi-GNSS processing, enabling joint analyses across systems and frequencies. Furthermore, station location and time span, azimuth/elevation masks, observation weighting schemes, and tropospheric mapping functions can be configured by the user. In addition to a variation of the sampling rate, the solution length of interest (e.g., 3 h or 24 h solutions) can be specified. Further options include selecting a geographic location on a map and assessing the impact of dPCC over a user-defined region at a chosen spatial resolution, up to global coverage. Using PCC-Explorer, exemplary results are presented, analyzed and interpreted. Also, the simulated impacts are verified against Precise Point Positioning (PPP) solutions derived from real GNSS data.

ID: W1 - p6 | Understanding Systematic Errors in Datum Transformations: Evaluating the Limits of Rigid Models between Legacy and Global Reference Frames

Dr. Olga Bjelotomić Oršulić PhD[1]; Josip Alpeza[2]; Dr. Sanja Šamanović PhD[1]; Prof. Danko Markovinović PhD[1]

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This paper examines the origin and nature of systematic errors arising in transformations between legacy national datums and modern global reference frames. A locally derived 3D Helmert transformation was analysed and compared with officially adopted transformation parameters, revealing consistent discrepancies that indicate regional distortions and methodological differences. The study critically evaluates the limitations of rigid seven-parameter models in representing deformed historical networks and explores the potential influence of 2D versus 3D modeling approaches that have historically been used in national transformations. Results highlight how conceptual inconsistencies between modelling strategies contribute to systematic errors and reduced reference frame consistency. These findings suggest that systematic errors are not merely numerical discrepancies but are generated from conceptual mismatches between transformation models and the physical reality of legacy geodetic networks. Understanding these limitations is essential for accurately interpreting coordinate differences and ensuring the scientific integrity of reference frame transformations and long-term reference frame stability.

Session W2: Systematic Effects in VLBI
Conveners: Robert Heinkelmann, Thomas Herring

ID: W2 - o1 | Assessing the frame ties between VLBI observations to quasars and Genesis

Dr. Lisa Kern; Dr. Helene Wolf; Prof. Johannes Böhm

TU Wien, Austria

The European Space Agency's (ESA) Genesis mission will integrate multiple space geodetic techniques on a single satellite at an altitude of 6000 km, serving as a dynamic space geodetic observatory. Its primary goal is to significantly enhance the accuracy and stability of Terrestrial Reference Frames (TRFs). A key feature of Genesis is the dedicated Very Long Baseline Interferometry (VLBI) transmitter, which enables observations to the satellite using the existing VGOS antennas and infrastructure. Using the well-established pipeline of software modules provided by the Vienna VLBI and Satellite Software (VieVS), weekly 24-hour VLBI sessions over a five-year period, comprising observations to both quasars and the Genesis satellite, are scheduled

and simulated. The subsequent analysis and derivation of TRFs allow not only for the estimation of a single set of VLBI station positions and velocities from the combined set of observations but also for the simultaneous estimation of positions and velocities from both observation types separately. This enables a comparative analysis between the combined and the separate TRFs, as well as a direct comparison between the satellite-based and quasar-based TRFs.

ID: W2 - o2 | Systematic errors in geodetic VLBI observations

Dr. Ming Hui Xu PhD

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Since 2019, the new generation geodetic VLBI system has started to operate regularly to make geodetic and astrometric observations, currently with a network of 16 to 19 telescopes observing 24 hours once per week. Based on the data analysis of these observations, systematic errors limiting the geodetic accuracy will be discussed in detail. We will also present the recent progress of reducing the impact of these errors.

ID: W2 - o3 | Assessment of performance of first VGOS operational sessions scheduled with source-centric approach

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The new Very Long Baseline Interferometry (VLBI) Global Observing System (VGOS) started regular observations in 2019. In our previous studies, based on the analysis of then available VGOS data, the high potential of the data for the geodetic and astrometric products has been shown. At the same time, possibilities for improvement have been identified. One obvious deficiency of the current VGOS network has been the lack of antennas in the southern hemisphere. Joining of the HARTVGS (South Africa) and YARRA12M (Australia) the VGOS network in the second half of 2024 doubled the number of the southern hemisphere antennas to four. In this paper, we present the improvement in densifying the VGOS celestial reference frame (CRF) in the southern region. Furthermore, our comparison of VGOS-CRF (VIE2024) with ICRF3-SX revealed that 21% sources have normalized angular separation higher than 5 sigma. Assuming that one of the reasons is the different contribution of the source structure delay, sessions allowing for a simultaneous imaging of sources are needed. Therefore, since July 2025 the new source-centric scheduling approach for the operational VGOS sessions (VS) has been tested by the International VLBI Service for Geodesy and Astrometry. In this contribution, we assess the performance of the available VS sessions and evaluate the precision and accuracy of the resulting geodetic parameters with respect to parameters from the established operational VGOS sessions (VO).

ID: W2 - o4 | Developments at the BKG/DGFI-TUM IVS Combination Centre within the framework of the IVS Contribution to ITRF2020-u2025

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The International VLBI Service for Geodesy and Astrometry (IVS) Combination Centre (IVS-CC) provides the official IVS products for reference frames and Earth orientation by combining the contributions of the IVS Analysis Centres (ACs). It is operated in close cooperation between the Federal Agency for Cartography and Geodesy (BKG) and the Deutsches Geodätisches

Forschungsinstitut at the Technical University of Munich (DGFI-TUM). Besides providing the IVS contribution to the official Earth Orientation Parameter (EOP) product C04 of the International Earth Rotation and Reference Systems Service (IERS), an important activity of the IVS-CC is the computation of the IVS contribution to the realisations of the International Terrestrial Reference System. For the 2025 update of the International Terrestrial Reference Frame 2020 (ITRF2020-u2025), the IVS initiated a reprocessing of the full VLBI observation history since 1979. Besides S/X-band and VGOS sessions, for the first time, the IVS decided to include K-band VLBI sessions into the ITRF contribution. Moreover, on an experimental basis, the IVS-CC provides combined normal equations including radio source coordinates as parameters to allow for joint and consistent realisation of terrestrial and celestial reference frames and EOPs as the link between them. This presentation focuses on the developments in the framework of the IVS-CC combination setup for the IVS contribution to ITRF2020-u2025. Starting with an outline of the combination setup, we present validation of input data provided by the contributing ACs and the combined IVS contribution to ITRF2020-u2025. A special focus is put on specifics of the session types from different frequency bands.

ID: W2 - o5 | A New Look at the Parallax Effect

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Accurate positions of extragalactic radio sources are determined using Very Long Baseline Interferometry (VLBI) observations. These positions are used for constructing a quasi-inertial celestial reference system. The current realization of the International Celestial Reference System (ICRS) is the International Celestial Reference Frame 3 (ICRF3, 2018), which includes coordinates for 4,536 radio sources, among which 303 are designated as "defining" sources. To ensure the highest possible accuracy of the ICRF, a precise model of geometric delay is required. This model must take into account various relativistic effects, such as the gravitational deflection of light. Further improvement of this model could significantly enhance the accuracy of future realizations of the ICRF. We have discovered the presence of an annual periodic signal in the positions of extragalactic radio sources. This may indicate a manifestation of the parallax effect. Recently, we have detected the parallax effect in the VLBI observations of quasars over a time span from 1993 to 2025. The mean parallax value for extragalactic sources was found to be significantly negative (-17 μas), in contrast to the expected zero value as defined by the definition and extragalactic nature of quasars. Moreover, this effect exhibits a dipole component (pointing approximately toward RA = 33 deg , Dec = -17 deg) as well as a quadrupole systematic pattern over the celestial sphere. However, unlike classical stellar parallax—where the shape of the parallactic ellipse depends on ecliptic latitude as $e = |\cos \beta|$—no similar dependence is observed here. Furthermore, while classical parallax ellipses (in ecliptic coordinates) follow a canonical orientation, the ellipses associated with this parallactic effect are arbitrarily tilted, with various orientations of their major axes relative to the ecliptic. The origin of this anomalous parallax effect remains unknown. Some theoretical works predict terms similar to parallax in these contexts, supporting the validity of further investigation in this direction as a possible systematic effect which can improve future ICRF.

ID: W2 - o6 | Impact of geophysical modelling on reference frames estimated from VLBI

Dr. Tobias Nilsson

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In Very Long Baseline Interferometry (VLBI) data analysis, a multitude of models are applied to correct for geophysical effects, like atmospheric refraction and geophysical loading. Errors in

these models can affect the VLBI results, for example the estimated terrestrial and celestial reference frames (TRF and CRF) and the Earth Orientation Parameters (EOP). If different models are used when estimating the TRF and the CRF, it can lead to inconsistencies between these frames. In this contribution, the effects of different geophysical models on the VLBI results are investigated. Several different global VLBI solutions are made, using geodetic VLBI data from 1979 to 2025. In each solution, one model is varied and the impacts on the estimated TRF, CRF and EOP are studied. Examples of models investigated are those used for atmospheric refraction, thermal and gravitational deformation of VLBI telescopes, and non-tidal atmospheric, oceanic, and hydrological loading. The results of this work provide information on the impact of different models on the references frames and EOP estimated from VLBI and how the models affect the consistency between the TRF and the CRF.

Session W3: Systematic Effects in GNSS, POD and DORIS
Conveners: Robert Heinkelmann, Thomas Herring

ID: W3 - o1 | Comparison of ITRF2020_u2024 GNSS residuals displacements with environmental loading models

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All geodetic technique observations (DORIS, GNSS, SLR and VLBI) have been processed up to the end of 2024 in order to compute the second update of the International Terrestrial Reference Frame 2020, namely ITRF2020-u2024 (https://itrf.ign.fr/en/solutions/ITRF2020-u2024). Following the IERS conventions, no environmental loading corrections have been applied besides ocean and atmospheric tides. In parallel, the IERS Global Geophysical Fluid Center has provided atmospheric, induced oceanic and hydrological loading estimates for all permanent stations based on the latest ECWMF reanalysis (ERA5) and the barotropic ocean model TUGO-m (http://loading.u-strasbg.fr/ITRF2020/). In this paper, we present a comparison of the ITRF2020- u2024 GNSS residual displacements to environmental loading estimates, because of their higher sampling rate (daily instead of typically weekly for the other techniques). In more details, we show that the ERA5-based reanalyzes are in better agreement with the geodetic observations than the MERRA2 (Modern-Era Retrospective Analysis for Research and Applications, Version 2) reanalysis. We also show the improvement of the ERA5-land, a re-run of the land component of the ECMWF ERA5 climate reanalysis, versus the original ERA5 hydrological component. Finally, we also show that a dynamic ocean response to pressure and wind is more suitable to model high frequency ocean non-tidal loading effects than the classical inverted barometer (IB) approximation.

ID: W3 - o2 | Do the GPS Repositioning Events Degrade the Stability of GNSS Scale Contribution?

Aiswarya Melathakathoottu Gopalakrishnan PhD; Prof. Dr. Rolf Dach; Prof. Dr. Adrian Jäggi

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The International Terrestrial Reference Frame (ITRF) is fundamental for precise positioning, navigation, and Earth science applications. Traditionally, the scale of the ITRF solutions is defined by VLBI (Very Long Baseline Interferometry) and SLR (Satellite Laser Ranging). Global Navigation Satellite Systems (GNSS) have the potential to contribute to the ITRF scale as well: on the one hand, celestial mechanics defines the radius of the GNSS orbits for their center of mass (CoM). The GNSS measurements refer to the antenna phase center which was calibrated before launch and made available to the user community for Galileo and GPS Block IIIA satellites. These calibrated satellites have only been active during the last years of the ITRF solution (the full Galileo constellation was

established in 2019; the first launch of the Block IIIA satellite was in late 2018). Therefore, we need to transfer the scale information back to the beginning of the GNSS solution in the ITRF. This seems to be possible because of the overlapping time intervals of active GNSS satellites. In this context, the GPS constellation is particularly important, as it was the most stable system prior to Galileo. One potential problem in transferring the scale is that the GPS satellites need to perform repositioning events, on average one maneuver per year, to maintain the satellite constellation. This operation is related to fuel consumption which may change the CoM of the satellite. The Center of Orbit Determination in Europe (CODE) acts as one of the analysis centers of the International GNSS Service (IGS) and contributes -- among others -- to the final and reprocessing series with a multi-GNSS solution considering GPS (from 1994), GLONASS (from 2003), and Galileo (from 2012). Since 2004, CODE is estimating the epoch and magnitude of the repositioning events. We can estimate the GPS satellite antenna offsets between the repositioning events and compare their stability with the velocity changes during the satellite maneuvers. If the obtained satellite antenna offsets are stable during the maneuver epochs it means that the scale information can be transferred in time disregarding fuel consumption during the repositioning events. By using different reference frame solutions, we also investigate the dependency of the obtained satellite antenna offsets on the geodetic datum definition of the ground network.

ID: W3 - o3 | Satellite-/block-/plane- and constellation-specific GNSS LOD biases

Florian Seitz[1]; Dr.-Ing. Mathis Bloßfeld[1]; Dr. Bingbing Duan[2]; Urs Hugentobler[2]; Jacob Klug[1]

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Length of Day (LOD) describes variations in the duration of a single Earth rotation relative to the standard 24 hours. It is an important Earth Orientation Parameter (EOP) linking the International Celestial Reference Frame (ICRF) and the International Terrestrial Reference Frame (ITRF). For space geodetic satellite techniques (GNSS, SLR, and DORIS), the estimation of LOD is highly correlated with the precession of the satellite orbital ascending node, which is largely driven by the even low-degree spherical harmonic coefficients of the Earth gravity field (i.e. Earth flattening) and is also sensitive to orbit modeling deficiencies, such as out-of-plane empirical accelerations or solar radiation pressure (SRP). In the case of SLR and DORIS, LOD estimation benefits from combining observations from multiple satellites with clear different orbital inclinations. Due to the different inclinations of the various satellites, SLR- and DORIS-derived LOD estimates are less correlated with other parameters which results in less biased LOD values. For the GNSS technique, GPS, Galileo and BeiDou constellations share the same orbital inclination of about 55 degrees, while GLONASS and QZSS employs an orbital inclination of 65 and 43 degrees, respectively. Given this small varying range of orbital inclination, modelling deficiencies lead to biased GNSS-based LOD estimates. Up to now, this was not handled, or a long-term constant (constellation-independent) bias was determined and applied at NEQ level. In this presentation, we evaluate various LOD solutions computed from different satellites (including different satellite blocks, orbital planes, and constellations) and different SRP models.

ID: W3 - o4 | Improved Attitude Modeling for GPS III Satellites in the Eclipse Season

Dr. Bingbing Duan[1]; Prof. Dr. Oliver Montenbruck[2]; Peter Steigenberger[2]; Prof. Dr. Urs Hugentobler[1]

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GNSS satellites traditionally apply a yaw-steering attitude law to keep the antenna pointing to the Earth while maintaining the solar panel rotation axis perpendicular to the Sun-spacecraft-Earth

plane. During the eclipse season, i.e., in periods with low Sun elevations (β-angles) above the orbital plane, the idealized, nominal yaw-steering typically results in angular rotation rates that exceed the capabilities of the momentum wheels for attitude changes. To cope with this issue, different types of rate-limited yaw-steering laws are applied by GNSS satellite designers during noon- and midnight turns in the eclipse season. Knowledge of the yaw-steering profile is essential for a proper modeling of the antenna phase center offset from the center of mass as well as the phase wind-up and a prerequisite for precise orbit determination and time synchronization (ODTS) as well as precise point positioning (PPP). Over the years, rate-limited yaw models have been disclosed for a variety of GNSS satellite types or derived from observations using a reverse PPP technique. On the other hand, no such model is presently available for the latest generation of GPS satellites, i.e. GPS III, where the application of a reverse PPP is hampered by the near-zero offset of the GNSS antenna from the yaw-axis. In the absence of a dedicated yaw model either a nominal yaw-steering or the yaw-steering model of the GPS IIR and IIR-M satellites built by the same manufacturer is widely assumed for GPS III by analysis centers (ACs) of the International GNSS Service (IGS). As an exception, a non-standard, rate-limited yaw model is applied by the Jet Propulsion Laboratory (JPL). While the underlying algorithm has not been disclosed, attitude quaternions representing the modeled attitude are publicly shared along with JPL's orbit and clock products for the IGS. These indicate a symmetric yaw angle profile during both noon and midnight turns that differs notably from the IIR/IIR-M profile. To assess the quality and realism of the currently adopted GPS attitude models, we investigate the time series of estimated clock offsets in the periods of interest and assess their smoothness during the yaw slews. While the clock products of a given AC have been determined with a specific yaw model, we can account for the impact of phase wind-up in the clock solution and thus compute transformed GPS III clock offset solutions representative of any other yaw model. Throughout the considered test cases, use of the JPL attitude yields a better clock continuity and reduced spikes compared to other models in current use by IGS ACs. To enable a wider use of the JPL attitude model without depending on the post-facto availability of JPL's quaternion product, an analytical model is presented, which closely matches the quaternion-based attitude profiles of GPS III satellites in the eclipse season. The formulation of this yaw model and its properties are discussed and the model is proposed as a common standard for a harmonized OTDS and PPP processing within the IGS.

ID: W3 - o5 | Analysis of different observation-specific signal bias products for ambiguity fixing in precise orbit determination of the Copernicus Sentinel satellites

Dr. Heike Peter[1]; Carlos Fernández[2]; Dr. Tim Springer[1]

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Precise orbit determination (POD) of low Earth orbiters (LEOs) with on-board collected GNSS (Global Navigation Satellite System) data is done using the single-receiver ambiguity resolution technique. For this approach observation-specific signal biases (OSBs) for all GNSS satellites are needed to account for such biases in the processing and allowing for integer ambiguity fixing. Meanwhile many IGS (International GNSS Service) analysis centers (ACs) provide such OSBs together with their classical orbit and clock products. A new combined OSB product is also provided by the IGS Wuhan Combination Center (WCC). Testing these products by applying them for LEO POD is very interesting and relevant, because LEOs are much more sensitive than ground stations to any inconsistencies in the products. We present an analysis of several available OSB products by using them for POD of the Copernicus Sentinel satellites. This includes GPS- and Galileo-based POD. Observation metrics, ambiguity fixing rates and orbit comparisons to the combined orbit of the Copernicus POD Service are shown and analysed. The results are very promising and show a very good consistency between most of the products. However, deficiencies are missing OSBs for the newer GPS (C2L/L2L) or Galileo signals and the necessary GNSS clock interpolation for some of the products. In addition, we analyse if systematic effects map into the results due to the different input products.

ID: W3 - o6 | Expected improvements of the DORIS contribution to the next ITRF realization

Dr. Guilhem Moreaux PhD[1]; Frank Lemoine[2]; Dr. Hugues Capdeville[1]; Dr. Petr Štěpánek[3]; Dr. Michiel Otten[4]; Samuel Nahmani[5]; Arnaud Pollet[5]; Patrick Schreiner[6]

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Since the release of the 2020 realization of the International Terrestrial Reference Frame (ITRF2020), the Analysis Centers (ACs) of the International DORIS Service (IDS) have been engaged in several efforts to improve the processing of the DORIS observations obtained since the launch of the HY2A mission mid-2011. These efforts include (i) improving the orbit and measurement modelling (atmospheric loading effects, satellite surface force modeling...) (ii) reviewing the mitigation strategies of the South Atlantic Anomaly effects on the onboard DORIS Ultra Stable Oscillators (USO's) (iii) individually analyzing the DORIS satellite contributions to geocenter and scale, and (iv) assessing the impact of the latest DORIS satellites (Sentinel-6A, HY2C, HY2D and SWOT) on the IDS products. Among the studies on the SAA mitigation strategies, in the scope of the IDS WG titled "Integrated Clock Correction Strategies for DORIS", the IDS community will take advantage of the connection of the GPS/GNSS and DORIS receivers to the same USO on Sentinel-3A/3B/6A to correct the clock of the DORIS observations. The objective of this study is to present the major DORIS processing evolutions and their impact on the DORIS contribution to the next ITRF realization in terms of origin, scale, station positioning and EOPs.

Session W4: Systematic Effects in SLR and multi-technique Combination

Conveners: Robert Heinkelmann, Thomas Herring

ID: W4 - o1 | The impact of reference frame realization on the determination of Earth's gravity field parameters from SLR

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This study investigates the sensitivity of SLR-derived low-degree gravity field coefficients to the realization of the terrestrial reference frame and the adopted network constraining strategies, based on a 10-year time series of Satellite Laser Ranging (SLR) observations. The analysis focuses on SLR-only gravity field solutions expanded up to degree and order 5, including the additional estimation of the C_{61} and S_{61} spherical harmonic coefficients, derived from observations of the LAGEOS-1/2, LARES-1/2, Starlette, Stella, Ajisai, Larets, and Beacon-C satellites. A set of alternative configurations is examined to quantify the impact of network constraints and the treatment of Earth Rotation Parameters (ERPs). The first group of configurations comprises solutions with fixed station coordinates, no-net-rotation and no-net-translation (NNR + NNT) constraints with estimated degree-1 terms, NNR + NNT with the geocenter estimation using the network shift approach instead of degree-1, and fixed coordinates with and without range bias estimation. These configurations enable the assessment of how different network realizations propagate into the recovered low-degree coefficients and affect the internal consistency of C_{20}, C_{30}, and C_{40}. The second group of configurations examines the impact of ERP handling, specifically whether polar motion and UT1 are estimated or fixed, on the recovery of low-degree gravity field coefficients. In particular, the analysis investigates how fixing or estimating UT1

affects the even zonal terms (C_{20}, C_{40}, C_{60}), while variations in the treatment of polar motion primarily influence the tesseral components (C_{21}, S_{21}, C41, S41). Correlations between ERP and gravity field parameters are analyzed to quantify how imperfect ERP modeling may propagate into the estimated low-degree harmonics. The study aims to provide a quantitative assessment of how reference frame realization and ERP treatment affect the stability and internal consistency of SLR-based gravity field solutions, thereby offering methodological insights for improving the robustness of future SLR-only gravity field models and their role in monitoring long-term mass redistribution within the Earth system.

ID: W4 - o2 | Using the VMF3o Data to detect and correct Barometric errors in ILRS Stations

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The troposphere is a major systematic error source (i.e. mm to cm) in the Satellite Laser Ranging (SLR) space geodetic technique. The atmospheric pressure is critical in computing the SLR tropospheric delay. A barometric error will induce an elevation-dependent bias in the tropospheric correction. Common issues in ILRS barometric measurements will be discussed along with the limiting factors in the absolute accuracy of the measurements. By comparing SLR station's barometric data to Vienna Mapping Functions 3 for optical frequencies (VMF3o) barometric data from Numerical Weather Models (NWM), drifts and discontinuities in ILRS tropospheric measurements can be detected. Comparisons of two of the VMF3o categories (VMF3o_EI and VMF3o_FC) from selected SLR stations along with mitigation and recovery of ILRS barometric errors will be presented.

ID: W4 4- o3 | Assessment of Different ITRF Realizations Using Satellite Laser Ranging

Linda Geisser[1]; Andreja Susnik[2]; Rolf Dach[1]; Daniel Arnold[1]; Adrian Jäggi[1]

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International Terrestrial Reference Frames (ITRFs) are fundamental for Earth system monitoring, satellite orbit determination, and precise positioning. They are regularly realized and provided by the three International Terrestrial Reference System (ITRS) Combination Centres (CCs) of the International Earth Rotation and Reference Systems Service (IERS): the Institut national de l'information géographique et forestière (IGN, France), the Jet Propulsion Laboratory (JPL, NASA, USA), and the Deutsches Geodätisches Forschungsinstitut at the Technical University of Munich (DGFI-TUM, Germany). Each centre applies specific combination methodologies and modeling assumptions, which can lead to subtle differences among ITRF realizations. Within the framework of the IAG–IERS Joint Working Group 1.2.4 on the evaluation of terrestrial reference frames, this study investigates the influence of the three ITRF realizations on Satellite Laser Ranging (SLR) data analysis with a focus on the estimation of Earth Orientation Parameters (EOP). The analysis begins by assessing the effect of the adopted ITRF realization on SLR satellite orbits and post-fit residuals, with station coordinates fixed to their a priori values. Moreover, it is examined how the selection of core SLR stations used for datum definition differs between the ITRF realizations and how these differences affect the frame's origin, scale, and orientation. Finally, state-of-the-art SLR data processing is carried out in which orbit parameters, range biases, EOPs, and station coordinates are jointly estimated. This investigation contributes to a better understanding of the sensitivity of SLR-based products to reference frame definition and station network selection.

ID: W4 - o4 | Assessing the Long-Term Stability of the Recent ITRF2020 Solutions

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For the ITRF2020, multi-technique solutions were produced by the combination centers (CC): Institut National de l'information Géographique et Forestière (IGN, France), Deutsches Geodätisches Forschungsinstitut (DGFI, Germany), and Jet Propulsion Laboratory (JPL, USA). All centers used the same input data - contributions from the International Association of Geodesy (IAG) services related to the four space geodetic techniques: Global Navigation Satellite System (GNSS), Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and Doppler Orbitography by Radiopositioning Integrated on Satellite (DORIS). The resulting Terrestrial Reference Frame (TRF) realizations differ not only in the combination methodologies but also in their treatment of nonlinear station motions. While ITRF2020 estimates periodic signals for all station time series, DTRF2020 applies non-tidal loading models as reduction models. JTRF2020, by contrast, represents a high temporal resolution reference frame time series. Typically, the Helmert transformation parameters for the individual techniques are presented, and the obtained TRF solutions are referred directly back to the respective technique-specific services. However, consistency assessments between the solutions from the ITRS CC across techniques is not done very often. This study investigates the datum consistency and inter-technique contributions among the three latest TRF realizations: ITRF2020, DTRF2020, and JTRF2020. In the first step, we are going to analyse transformation parameters from the four space geodetic techniques across the TRF solutions. Systematic effects from the techniques are expected to be consistently shown in all three TRF solutions. On the other hand, differences may provide insight into the relative strengths and weaknesses of the combination strategies applied by the ITRF CC. The different treatments of the non-linear components are also examined in this context. The Center for Orbit Determination in Europe (CODE) hosts one of the analysis centres of the International GNSS Service (IGS) and has contributed to the reprocessing series for ITRF2020. Using the ITRF2020, DTRF2020, and JTRF2020 realizations as the basis for the datum definition in the GNSS solutions, the resulting global geodetic parameters can be analysed for comparing the long-term consistency of the three ITRF solutions, particularly regarding their distinct handling of nonlinear components.

ID: W4 - o5 | Advancing the Multi-Technique Combination at BKG - Towards a Consistent Estimation of EOP and TRF **– Withdrawn –**

Lisa Klemm; Daniela Thaller; Dr.-Ing. Alexander Kehm; Claudia Flohrer; Daniel König; Sadegh Modiri

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The Federal Agency for Cartography and Geodesy (BKG) continues its efforts in the combined processing of space-geodetic techniques based on datum-free normal equations. The aim is to achieve a consistent and accurate estimation of Earth Orientation Parameters (EOP) and also of the Terrestrial Reference Frame (TRF). The current combination integrates VLBI (Intensive and 24h-Rapid turnaround sessions), GNSS Rapid, and SLR normal equation systems, enabling a rigorous multi-technique combination with common parameters across all techniques. While earlier developments primarily focused on the improvement of the combined EOP series, recent work extends the combination towards a consistent realization of both, i.e., EOP and TRF. This advancement requires addressing various methodological challenges, such as the appropriate treatment of technique-specific datum constraints and the incorporation of local tie measurements at co-location sites. We present the current status of the combination strategy, first results from the extended processing, and an outlook on the next steps towards a fully consistent EOP-TRF estimation.

ID: W4 - o6 | Benchmarks for Assessment of Different Terrestrial Reference Frame Realizations: Insights from the IAG-IERS Joint Working Group 1.2.4

Dr. Sergei Rudenko[1]; Guilhem Moreaux[2]; Andreja Susnik[3]; Dr.-Ing. Mathis Bloßfeld[4]; Manuela Seitz[4]; Dimitrios Ampatzidis[5]; Daniella Thaller[6]; Lisa Klemm[6]; David Sarrocco[7]; Susanne Glaser[8]; Anton Reinhold[8]

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The IAG-IERS Joint Working Group 1.2.4 (JWG1.2.4) focuses on evaluating global and regional Terrestrial Reference System (TRS) realizations, with particular emphasis on identifying and quantifying systematic differences. A key outcome of the working group is the definition of a set of benchmarks for assessing the quality and consistency of reference frames. These benchmarks allow systematic comparisons of ITRS realizations by the ITRS Combination Centres of the IERS, helping to quantify differences in station positions, velocities, and time series behavior. They also provide metrics to assess the impact of geophysical models, such as loading displacements, and the performance of space-geodetic techniques, including precise orbit determination of satellites in various orbital regimes. By applying these benchmarks to current Terrestrial Reference Frame (TRF) realizations, the working group can identify systematic patterns, evaluate stability over time, and support informed interpretation of reference frame solutions. The benchmarks are intended to serve as a practical tool for the broader geodetic and scientific community, offering guidance and objective information to help users assess the quality and consistency of different TRF realizations for high-precision positioning, Earth observation, and geophysical applications. This contribution will present the current set of benchmarks, illustrate their application to the latest TRF realizations, and discuss the insights gained from these analyses.