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#1

A Future Plan for Geopotential Determination and Height Datum Unification

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Abstract

Advances in high-precision optical clocks and high-stability time-frequency transfer technique poineer a novel relativistic geodesy to directly determine the gepotential differences from gravitational frequency shifts. Here we systematically review the physical thoery, observation methods, error sources, and progresses in optical-clock-based geopotential studies. At technical implementation level, optical-fiber time-frequency transfer, transportable optical-clock comparisons, satellite two-way and common-view links, and GNSS time-frequency transfer are summarized. Both characteristics and limitations for the aforementioned methods are systematically evaluated and commented in terms of measurement accuracy, spatial coverage, operational continuity, and practical applicability. In regions equiped with terrestrial optical-fiber infrastructure, fiber-linked optical clocks provide the best-accuracy determination of geopotential differences to date. Transportable optical combined with satellite time-frequency links provide a unique and independent solution to determine geopotential and height datum across oceans, mountains, and continents. This solution avoids the intrinsically cumulative errors in long-distance spirit leveling. It is crucial to rigorously discern and refine the corrections for clock systematic frequency shifts, transfer-link noise, satellite orbital and velocity effects, atmospheric delays, tidal perturbations, environmental mass redistribution, and temporal variations in the gravity field. Only then can the centimeter-level height datum unification be achieved. A common geopotential reference must also be adopted to ensure the conversion of geopotential differences into physical heights consistently. Looking ahead, a coordinated space-based observing system comprising geostationary and near-polar-orbiting satellites may enable continuous space-to-ground optical-clock comparisons and global coverage, thereby providing independent and reliable support for the realization of a unified global height reference system.

In the last section, we proposes an integrated technical framework for regional and global height datum unification. A coordinated space-based observing system comprising geostationary and near-polar-orbiting satellites ccould enable continuous space-to-ground optical-clock comparisons and global coverage, providing independent and reliable solution for the realization of a unified global height reference system.

Keywords: Height-datum unification, Geopotential determination, Relativistic geodesy, Optical atomic clock, Time-frequency transfer, ,

#2

Terrestrial gravimetry for groundwater-storage monitoring and infrastructure safety in irrigated alluvial plains

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Abstract

Groundwater depletion in intensively irrigated alluvial plains can induce land subsidence and threaten critical infrastructure, including high-speed railways. Satellite gravimetry is effective for regional-scale water-storage monitoring, but its spatial resolution is insufficient to resolve groundwater variations near individual railway sections, pumping centers, or recharge facilities. We develop a terrestrial-gravity approach to detect groundwater-storage changes at these smaller spatial scales and demonstrate it along the Taiwan High Speed Rail (THSR) corridor in Yunlin, western Taiwan and southern Taiwan. Repeated relative gravity surveys were conducted at five sites located in areas of significant land subsidence and high infrastructure concern. The observations were referenced to the Hsinchu gravity station using a CG-6 gravimeter, with campaign uncertainties of approximately 3–8 μGal. Between October 2025 and April 2026, the measured gravity changes indicate net groundwater-storage losses equivalent to approximately 65–128 m^3 within the assumed local sensitivity area around individual observation sites. These signals occurred during an exceptionally dry period, when cumulative rainfall before April was only 26.5 mm. The gravity observations can be integrated with railway deformation records, leveling, GNSS, InSAR, rainfall, and groundwater-level data to distinguish seasonal water-storage variations from longer-term aquifer compaction and loss of storage capacity. Our results show that terrestrial gravimetry provides a non-invasive means of monitoring groundwater mass changes where observation wells are unavailable or cannot be installed near sensitive infrastructure. The approach complements conventional deformation and hydrological measurements and can support the identification of groundwater-stress zones, evaluation of recharge effectiveness, and subsidence-risk assessment. This framework is directly relevant to irrigated basins in other areas with intensive agricultural water use, groundwater abstraction, and transport infrastructure.

Keywords: terrestrial gravimetry; groundwater storage; land subsidence; high-speed rail; irrigation

#3

What do we need to trust high-precision GNSS more?

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Abstract

High-precision GNSS has become a fundamental tool for Earth science, supporting studies of atmospheric processes, crustal deformation, and earthquake cycles. As geophysical research increasingly relies on centimeter- to millimeter-level positioning, a critical question arises: How much can we trust GNSS-derived signals? This presentation addresses the concept of GNSS trustworthiness for Earth science applications. Unlike navigation-oriented integrity, scientific applications require confidence not only in positioning accuracy but also in the authenticity of weak geophysical signals. We first examine the major sources of uncertainty from both the satellite side, including precise product errors and day-boundary discontinuities, and the user side, such as multipath effects and ambiguity resolution reliability. We then present a comprehensive framework that combines multi-constellation, all-frequency GNSS observations, multi-analysis-center product combination, cross-day product alignment, and machine-learning-based reliability assessment. Finally, we introduce reliable precise satellite products, open-source positioning software, and emerging reliability standards that transform GNSS reliability from an implicit assumption into a measurable and quantifiable property, enabling more trustworthy scientific discoveries.

#4

Seismogeodesy and Earthquake-Cycle Processes in the Northwestern Himalayas, Pakistan

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Abstract

The northwestern Himalayas of Pakistan represent one of the most tectonically active segments of the India–Eurasia continental collision zone, where active thrust and strike-slip faults accommodate ongoing plate convergence and generate significant seismic hazards. This study applies an integrated seismogeodetic framework to investigate earthquake-cycle processes, fault coupling, and strain accumulation across the region. The analysis combines continuous Global Navigation Satellite System (GNSS) observations, multi-temporal Interferometric Synthetic Aperture Radar (InSAR) time-series, regional earthquake catalogues, and broadband seismic waveform data to characterize deformation over multiple spatial and temporal scales. The results reveal pronounced lateral variations in fault coupling and deformation. Geodetic inversions indicate that the Main Himalayan Thrust is strongly locked beneath the eastern Kashmir segment, whereas the basal detachment beneath the Potwar Plateau and Salt Range exhibits weak coupling consistent with aseismic creep. InSAR observations identify significant strain partitioning along the Kalabagh Fault, where the northern and southern segments display creeping rates of approximately 4.2–4.8 mm/yr, while the central segment remains locked. Joint GNSS and InSAR analyses further identify zones of elevated interseismic strain accumulation within the Indus Kohistan Seismic Zone. Integration of high-rate GNSS and seismic waveforms improves coseismic rupture characterization, whereas post seismic InSAR observations distinguish shallow after slip from deeper viscoelastic relaxation. These findings demonstrate that combining geodetic and seismological observations provides a comprehensive view of the regional earthquake cycle and improves understanding of fault segmentation, strain accumulation, and deformation mechanisms in the northwestern Himalayas. The resulting seismogeodetic framework offers valuable constraints for tectonic modelling and contributes to improved seismic hazard assessment and disaster

Keywords: Seismogeodesy, Northwestern Himalayas Pakistan, Seismic Hazard Assessment

#5

Multi-source Geophysical Observations and Engineering Geological Interpretation for Hazard Mitigation: Case Studies from Yunnan-Xizang Tectonic Belt and Tianshan Orogenic Belt

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Abstract

Near-surface structure in the 0–1000 m depth range remains poorly resolved in most regional geophysical models of orogenic belts. While satellite gravimetry, InSAR and regional seismic arrays provide robust constraints at km to lithospheric scales, the shallow crust, where fault zones propagate, geohazards nucleate, and petrophysical properties change most rapidly, is typically parameterized crudely or omitted entirely in large-scale inversions. However, precise near-surface structural models can provide crucial guidance for underground engineering projects, particularly tunnel construction. This work describes a multi-scale imaging workflow developed to address this gap and presents results from two contrasting orogenic settings in western China.

The approach combines three nested observation scales. At the regional scale, a hexacopter- or UAV-mounted transient electromagnetic (TEM) system maps resistivity to depths of 10–500 m, depending on site accessibility. Instead of applying post-hoc static corrections, we incorporate the digital elevation model directly into an unstructured tetrahedral finite-element mesh for 3D forward modelling and inversion, an approach consistent with previous studies in airborne EM showing that the flat-ground assumption can introduce apparent resistivity artefacts exceeding 30% over rugged topography (Sasaki and Nakazato, 2003; Zhang et al., 2016). At the intermediate scale, two-dimensional wide-line active-source reflection seismics and controlled-source magnetotelluric (MT) profiles provide velocity and resistivity data to ~1 km depth. At the tunnel scale, ground-penetrating radar and seismic ahead-prospecting deliver meter-scale resolution to 150 m ahead of the excavation face, using directly exposed strata as ground-truth data.

Our inversion scheme couples surface resistivity and in-tunnel velocity via cross-gradient structural constraints (Gallardo and Meju, 2003, 2004), enforcing geometric consistency between property boundaries without assuming a petrophysical relationship. The process begins with surface seismic and electromagnetic profiles to

build a 3D resistivity model, from which anomaly boundaries are extracted. These boundaries guide a spatially varying regularization matrix for in-tunnel velocity inversion. A relaxation mechanism monitors data residuals and adaptively adjusts prior constraint weights, preventing over-constraint when surface and tunnel observations conflict. As the tunnel advances, mapped geology at the face updates model parameters in real time, forming a dynamically updated digital twin.

We applied this workflow to three study areas. In the Ningnan Tunnel, which traverses the western branch of the Xiaojiang Fault System along the eastern margin of Tibet, fault inversion successfully identified seven fault branches, including the F23 structure, and mapped a silicified dolomite zone that reduces rock strength by 40%–60% under unconfined compression. We found that the strength of the silicified zone exhibits a negative logarithmic relationship with resistivity and a negative linear relationship with P-wave velocity. These results add meter-scale structural detail to the existing regional tomography model, which resolves the Xiaojiang Fault System at a horizontal resolution of 2–5 km (Duan et al., 2023; Li et al., 2023). This multiscale focusing strategy was demonstrated in a test section of approximately 700 meters within the 62-kilometer-long Xianglushan Tunnel of the Central Yunnan Water Diversion Project, where a total of six major hidden faults (previously unidentified) were identified, 86% of which were verified during tunneling. In the Tianshan Shengli Tunnel, located at an elevation of 3,000–4,200 meters, airborne TEM surveys were first conducted, followed by in-tunnel radar mapping, which identified six hydrothermal alteration zones with resistivities below 200 Ω·m, whereas unaltered granite exhibited resistivities greater than 1,000 Ω·m. The consistency between aerial and tunnel survey locations exceeded 90% for major anomaly positions, validating the method’s suitability for high-altitude environments where ground surveys are logistically challenging to conduct.

These high-resolution near-surface models provide independent constraints and ground truth for broader geodetic and geodynamic studies. The imaged fault zone architectures, rock property relationships, and uncertainty estimates can serve as prior information for regional gravity, magnetotelluric, and seismic tomography inversions, as well as for interpreting InSAR-observed deformation anomalies. The multi-scale fusion methodology is transferable to other orogenic belts and offers a pathway toward unified inversions that integrate satellite, airborne, and ground-based observations across scales.

#6

Application and prospect of optic frequency signal transfer via fiber

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Optical fiber-based frequency transfer, characterized by low attenuation, high stability, and immunity to environment influences, has emerged as a critical technology for high-precision frequency dissemination. This report provides a systematic review of the development and key technological advances in optical fiber frequency transfer. In phase noise compensation, round-trip phase detection combined with real-time feedback control effectively suppresses phase disturbances induced by temperature variations, mechanical vibrations, and fiber stress. The transfer stability has improved from 10^{-17} to the 10^{-21} level, with transmission distances exceeding 2000 km. The introduction of optical frequency combs enables low-noise down-conversion between optical clock signals and fiber communication bands, facilitating optical clock comparisons. Concurrently, optical clocks have reached fractional uncertainties and instabilities of 5×10^{-19}, enabling millimeter-level height sensitivity and providing the precision foundation for diverse applications of fiber-based frequency transfer. On the application side, based on the general relativity, optical fiber frequency transfer can determine gravity potential differences between two sites, thereby enabling remote centimeter-level physical height transfer and unification of physical height datums. Furthermore, fiber links are highly sensitive to stress/strain, temperature fields, and electromagnetic perturbations, capable of detecting ultra-low-frequency signals in the 0.01–10 Hz band. This capability provides novel data sources for seismic precursor anomaly detection, Earth rotation parameter monitoring, Earth's free oscillation mode identification, and tidal analysis. Optical fiber frequency transfer technology is becoming an essential tool for establishing the next-generation four-dimensional Earth reference framework.

#7

Global surface mass redistribution drives 21st century polar motion excitation

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Abstract

Polar motion evolution is primarily driven by surface mass transport associated with terrestrial water storage, the atmosphere, and oceans, while also being modulated by processes within the solid Earth. Accurately quantifying the contributions of different source terms to polar motion excitation (PME) is essential for reliable reconstruction and prediction. This study integrates both satellite gravity observations from GRACE/FO (2002–2025) and future scenario simulations (2026–2100) to systematically evaluate the excitation effects of global surface mass redistribution on polar motion.

The reconstructed PME signals agree well with International Earth Rotation and Reference Systems Service observations, explaining approximately 94% and 72% of the long-term trends in the χ_1 and χ_2 components, respectively. This confirms that surface mass redistribution effectively captures the long-term behaviour of polar motion. Notably, the PME associated with mountain glaciers exhibits a pronounced trend reversal in the χ_2 component around November 2020, primarily driven by mass changes in four major glacier regions—High Mountain Asia, the Russian Arctic, the Southern Andes, and Arctic Canada South. This demonstrates that the spatially heterogeneous evolution of global MG mass can significantly influence long-term PME trends. However, discrepancies among different GIA models introduce substantial uncertainties, particularly in the χ_2 component where inter-model spread is larger, representing a primary source of error in reconstructing long-term PME trends.

For future emission scenarios (RCP2.6 and RCP8.5), simulation results indicate that by 2100 the polar drift magnitude under RCP8.5 reaches approximately 19.62 m, roughly 2.21 times that under RCP2.6 (8.86 m). The drift directions under both scenarios are generally aligned along the Greenwich meridian, leaning toward the 90°W side. Among the individual mass sources, the Greenland Ice Sheet is the dominant single driver; the Antarctic Ice Sheet ranks second, though its excitation magnitude exhibits notable fluctuations due to inter-model discrepancies; mountain glaciers exert a sustained driving effect toward the 90°E direction; and terrestrial water storage primarily governs low-frequency oscillations on interannual to decadal timescales.

Keywords: gravity field, mass redistribution, polar motion

#8

Effect of Great African Land Depressions on Gravity and Geoid

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Abstract

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

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

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

depressions on the geoid undulation is concentrated at the areas of the land depressions and spread out to a relatively large radius, reaching a value of about 1.15 m.

#9

African Unified Height System Based on Gravity Data and Geopotential Models

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Abstract

The **African Unified Height System (AUHS)** is a pioneering geodetic initiative designed to overcome the long-standing inconsistencies in vertical height referencing across the African continent. Historically, national height systems in Africa have been developed independently using different observation techniques, reference datums, and surveying standards. These inconsistencies have limited the integration of geospatial information across national boundaries and hindered regional scientific and engineering applications. The AUHS addresses these challenges by establishing a unified continental vertical reference framework based on gravity observations, geopotential models, and modern satellite geodesy.

A fundamental component of the AUHS is the integration of gravity data, which describe spatial variations in the Earth's gravitational field. These observations are obtained from terrestrial gravity surveys, airborne campaigns, and satellite gravity missions such as the **Gravity Recovery and Climate Experiment (GRACE)** and the **Gravity Field and Steady-State Ocean Circulation Explorer (GOCE)**. Gravity measurements are essential for determining the geoid, an equipotential surface that closely approximates the global mean sea level and serves as the reference surface for

orthometric heights. Since the geoid exhibits complex regional variations caused by heterogeneous mass distributions within the Earth, high-resolution geoid modeling is necessary to achieve accurate height determination.

To enhance the accuracy and spatial consistency of the reference system, the AUHS incorporates global geopotential models, including the **Earth Gravitational Model (EGM)**, together with regional terrestrial gravity observations. This integrated approach is particularly important in Africa, where many regions have sparse geodetic infrastructure and limited gravity coverage. By combining global and regional datasets, the AUHS significantly improves geoid modeling and provides a reliable foundation for continent-wide height determination.

Modern satellite geodesy plays a central role in the implementation of the AUHS. **Global Navigation Satellite Systems (GNSS)** provide precise ellipsoidal heights, which are transformed into orthometric heights using refined geoid models. Satellite altimetry further contributes valuable information over coastal regions and inland water bodies. Regional geoid models are calibrated to account for local gravity anomalies, ensuring that height measurements remain consistent across national borders. This interoperability enables seamless integration of geospatial datasets and supports large-scale infrastructure projects, transportation corridors, hydrological studies, and environmental monitoring throughout Africa.

Beyond its technical significance, the AUHS offers substantial scientific, economic, and societal benefits. A unified vertical reference system improves the accuracy of topographic mapping, engineering design, flood hazard assessment, and water resource management while reducing uncertainties in major infrastructure projects. It also strengthens scientific research in hydrology, climate change, geodynamics, and sea-level monitoring by providing a consistent continental height reference. Furthermore, the initiative promotes regional cooperation through data sharing, technical capacity building, and the harmonization of geodetic standards among African countries.

In conclusion, the African Unified Height System represents a major milestone in the modernization of geodetic infrastructure across Africa. By integrating gravity observations, geopotential models, GNSS positioning, and satellite-derived measurements into a unified reference framework, the AUHS overcomes the historical fragmentation of African height systems. The establishment of a common continental vertical datum will not only improve the accuracy and interoperability of geospatial information but also support sustainable development, scientific innovation, and resilience to environmental challenges across the continent.

#10

Higher-Degree Zonal Gravity Signatures of the Martian CO_2 Cycle.

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Abstract

The seasonal exchange of CO_2 between the Martian atmosphere and polar caps drives a planetary-scale mass redistribution, producing detectable time-variable gravity signals. While temporal variations in the lowest-degree zonal harmonics (e.g., ΔC_{20} and ΔC_{30}) have been extensively studied using spacecraft tracking, the projection of this seasonal cycle onto higher-degree zonal harmonics remains poorly constrained and computationally challenging due to orbital aliasing. In this study, we utilize a forward-modeling approach to evaluate the seasonal zonal gravity anomalies of Mars from degree2 to 7. We constructed high-resolution CO_2 mass loading fields using surface CO_2 ice and atmospheric pressure data from the Mars Climate Database (MCD v6.1), incorporating MOLA topography for precise radial corrections. Our model robustly reproduces the observed seasonal ΔC_{30} tracking signal, providing a validated baseline for extending the interpretation to higher degrees. A degree-wise amplitude spectrum reveals a distinct are systematically parity-dependent behavior: odd-degree terms stronger, annual-dominated, and highly phase-coherent, physically reflecting the pronounced hemispheric asymmetry of the CO_2 exchange. In contrast, even-degree terms exhibit more complex, semi-annual structures. Source decomposition demonstrates that the gravity response is overwhelmingly dictated by localized surface CO_2 ice—contributing 95–98% of the RMS amplitude—rather than the spatially diffuse atmospheric column. Furthermore, a globally calibrated, neutron-sensitive harmonic proxy derived from Mars Odyssey HEND data provides independent diagnostic support for the seasonal coherence of the higher odd-degree patterns (yielding correlations >0.96 for degrees 5 and 7). These findings establish that the Martian CO_2 cycle generates physically interpretable higher-degree zonal gravity harmonics. Recognizing the robustness of the odd-degree family provides a new degree-dependent framework that

can refine future spacecraft tracking inversions and improve global mass-budget estimates.

Keywords: Time-variable gravity, Seasonal CO_2 cycle, Zonal harmonics, MCD, Martian polar caps

#11

Status of satellite gravimetry research at HUST

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Abstract

We are witnessing an unprecedented era of satellite gravimetry. Over the past 25 years, successive satellite missions, including CHAMP, GRACE, and GOCE, together with the GRACE Follow-On mission, have continuously collected global gravity field observations. The GRACE Follow-On mission remains operational and routinely tracks temporal mass variations from orbit. Looking ahead, the future of gravity is ‘MAGIC’. MAGIC is a joint mission including NASA’s GRACE-C and ESA’s Next-Generation Gravity Mission (NGGM). Currently, GRACE-C is proceeding on schedule, and ESA-NGGM has been officially approved. Under this background, this study presents the latest progresses of the HUST-Grace2024 model in satellite gravimetry data processing, covering its core processing strategies, accuracy evaluation results, and practical performance in the COST-G international cooperation. Furthermore, the future development of China’s NGGM for Tianqin series is elaborated in detail.

Keywords: Satellite gravimetry, GRACE, GRACE Follow-On, Chinese NGGM

#12

Chandler wobble and LOD variations in recent decades

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Abstract

In 2020s the greatest minimum of the length of day (LOD) since 1930s and Chandler wobble (CW) decay have been recorded. The amplitude of the Free Core Nutation (FCN) reached minimum as well. Some researchers relate these anomalies to the processes at the core-mantle boundary, to the deceleration of the inner core, and to global warming, others – to the mutual destruction of the atmospheric and oceanic excitations. Indeed, variations of the magnetic field, some seismic evidences, and development of the eigen modes theory of Earth rotation point to the high probability of such explanations.

We point out to one more circumstance: the correspondence of the epochs of alignment of the line of lunar nodes, line of apse, and line of equinoxes, occurred in 1930s and 2020s to the episodes of greatest minima in the decadal LOD and CW amplitude. We find the asymmetry of distribution of full moon in perigee events over celestial hemispheres and orientation of the plane of lunar orbit with respect to equator able to change the amplitude of tides and produce effects in the ocean, atmosphere, and core, responsible for CW decay and some other geophysical consequences.

Keywords: LOD, Chandler wobble, tides.

#13

Inferring J_2 and Tidal Love Number Errors from Nodal Residuals of LAGEOS and LARES 2

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Abstract

The LAGEOS and LARES 2 satellites feature a butterfly orbital configuration—nearly identical semi-major axes and supplementary inclinations (70.16° and 109.85°)—designed to cancel, in their nodal drift combination, the classical J_2 precession and its associated uncertainty. After applying this cancellation and removing known non-symmetric perturbations, the residual nodal time series yields a high-precision verification of the Lense–Thirring effect.

Within these residuals, the linear and periodic components can be used to invert for mismodeling of J_2 (i.e., the even-degree zonal tides) and the degree-2 Love numbers of long-period tidal constituents. In principle, the coincidence-arc difference method isolates unmodeled perturbations. The linear component contains contributions from both the Lense–Thirring effect and the J_2 uncertainty; the latter is canceled in the butterfly combination, leaving a net linear trend proportional to the Lense–Thirring signature. Conversely, by subtracting the theoretical Lense–Thirring value from each satellite's residual before forming the combination, the remaining linear trend can be attributed to mismodeling of J_2 and other even zonal harmonics, thereby providing a direct measure of the difference between the actual J_2 and the value adopted in the orbit integration model.

The periodic components predominantly reflect mismodeling of major tidal constituents and unmodeled minor tides. Short-period tidal perturbations are largely suppressed by orbital averaging, while long-period constituents remain prominent. Two dominant signals are identified: the K_1 tide with a period of 1050 days—matching the nodal precession period of both satellites—and the K_2 tide with a period of 525 days. These signals arise from mismodeling of the degree-2 Love number k_2 for these constituents, which carries uncertainties from mantle anelasticity and core–mantle coupling. We propose that these periodic residuals can be used to invert for Love-number errors of the K_1 and K_2 tides, providing independent constraints on the frequency-dependent tidal response of the deep Earth.

The same approach can be extended to the 18.6-year tide, though alternative orbital combinations would be required, since zonal tides are canceled to first order in the butterfly configuration. In the present residuals, the observed annual, semi-annual, and 1/3-year periodicities are unlikely to originate from zonal tides; they are more plausibly attributed to atmospheric and thermal effects.

Our results demonstrate that the LARES–LAGEOS nodal residual time series offers not only a relativistic test but also a dual diagnostic tool: it simultaneously constrains J_2 uncertainties and long-period tidal Love-number errors, complementing traditional gravimetric and altimetric tidal analyses.

#14

Marine gravity field recovery and bathymetry from the SWOT mission

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Abstract

The Surface Water and Ocean Topography (SWOT) mission, launched in December 2022, employs a Ka-band radar interferometer (KaRIn) to provide two-dimensional, high-resolution sea surface height (SSH) measurements, marking a new era in satellite altimetry. This study systematically explores the multi-scale applications of SWOT in marine and coastal topographic mapping, ranging from marine gravity recovery and global bathymetric modeling to tidal flat topography reconstruction. First, by using an optimized processing strategy that integrates multi-directional geoid gradient combination, cross-track systematic bias correction, and significant wave height (SWH)-based weighted averaging, a global $1' \times 1'$ marine gravity anomaly model, SYSU_Grav, was constructed. The model achieves an accuracy of 2.80 mGal against shipborne gravity data and enables the recovery of bathymetric features with an approximately 20% improvement in accuracy in the South China Sea and Philippine Sea. Second, this study develops SYSU_Topo, a 1-arc-minute global bathymetric model, using SWOT-derived gravity anomalies and the gravity-geological method (GGM). A sliding-window strategy with boundary-constraint points is adopted to determine the optimal density contrast and reduce splicing effects caused by partition inversion. The model achieves a global RMSE of 71.03 m at single-beam checkpoints and an RMSE of 133.03 m in the South China Sea based on multi-beam evaluation, outperforming existing models such as topo_27.1 and SDUST2023BCO by 8%–26%. Furthermore, by extending the application of SWOT from open-ocean and global bathymetric mapping to complex coastal environments, this study investigates SWOT's capability for tidal flat topography reconstruction. A three-step method combining Sentinel-2 imagery with SWOT pixel cloud data is proposed to generate a 10 m resolution topographic model for large-scale tidal flats, achieving an RMSE of 0.24 m. For complex estuarine areas, an adaptive method based solely on SWOT's backscatter coefficient (Sig0) is further developed, producing a 25 m resolution model with an accuracy of 0.12 m in the Elbe Estuary. Overall, these results demonstrate the significant potential of SWOT for multi-scale marine and coastal topographic mapping and provide new methodological support for ocean geophysics, bathymetric modeling, and coastal geomorphological monitoring.

Keywords: SWOT, marine gravity, bathymetric model, tidal flat topography

#15

Revealing buried tectonic structures in the Gulf of Mexico using SWOT-derived marine gravity

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Abstract

Satellite altimetry has long provided the only global coverage of the marine gravity field, yet conventional nadir altimetry is limited in spatial resolution and performs poorly in sediment-covered and coastal regions. The Surface Water and Ocean Topography (SWOT) mission, launched in December 2022, offers a new opportunity to overcome these limitations through wide-swath, high-precision measurements of sea surface height. Here we show that 1.5 years of SWOT data recover marine gravity fields with ~10-km resolution and improve gravity accuracy by ~8% relative to the best multi-mission altimetry models, with the largest gains in near-coastal zones. Applied to the Gulf of Mexico, SWOT-derived vertical gravity gradients sharpen the expression of known tectonic elements—including extinct spreading ridge segments, fracture zones, outer marginal troughs, and salt-basin architecture—and reveal previously unresolved tectonic fabrics that are invisible in bathymetry and blurred in conventional gravity fields. These include linear structures near the Chicxulub impact crater and gravitationally detached foldbelts buried beneath thick sediments. Interpreted within established tectonic models of Gulf opening, these observations provide new, independent constraints on passive-margin evolution and plate kinematics. More broadly, this study demonstrates that SWOT-derived marine gravity extends satellite altimetry beyond its traditional oceanographic applications, providing a powerful remote sensing tool for imaging buried tectonic structures in sediment-covered basins worldwide.

Keywords: SWOT wide-swath altimetry, Gulf of Mexico, marine gravity field, vertical gravity gradients, passive-margin tectonics

#16

Multi-Scale Band-Limited SRBF Modelling for Regional Gravity Field Recovery in Mountainous Regions

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Abstract

Accurate recovery of regional gravity fields in mountainous regions remains a major challenge due to complex terrain, heterogeneous gravity observations, and the widespectral range of gravity signals. Conventional regional gravity field modelling approaches often face difficulties in integrating heterogeneous gravity observations characterized by different spatial resolutions, spectral contents, and error structures. Thiscontribution presents recent developments in band-limited spherical radial basis function (SRBF) modelling for high-resolution gravity field recovery in mountainous areas. A multi-scale modelling framework is introduced in which gravity signals are decomposed into low-, medium-, high-, and ultra-high-frequency components and recovered using dedicated SRBF representations. The approach allows satellite gravity models, airborne gravity observations, terrestrial gravity data, and topography-related gravity information to be integrated within a unified spectral framework. The methodology has been evaluated in several challenging mountainous regions in western North America. Results demonstrate that the combination of satellite and airborne gravity observations significantly improves medium-frequency gravity field recovery compared with airborne-only modelling, yielding improvements of up to several centimetres in geoid accuracy. Furthermore, the proposed multi-scale SRBF strategy enables a more effective reconstruction of high-frequency gravity signals and substantially improves geoid determination accuracy. Independent GPS/levelling validations indicate that the resulting

geoid models achieve cm-level accuracy and consistently outperform conventional single-scale SRBF solutions, demonstrating the effectiveness of multi-scale spectral decomposition for regional gravity field recovery in mountainous environments.

Keywords: spherical radial basis functions, gravity field recovery, geoid determination, airborne gravity, multi-scale modelling, mountainous regions

#17

Full Signal Variance Covariance Regularization for Satellite-Only Static Gravity Field Modeling

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Abstract

Recent advances in satellite gravimetry have enabled the integration of multi-mission observations for high-resolution static gravity field modeling. However, conventional regularization approaches often neglect correlations among spherical harmonic coefficients, which limits their ability to stabilize medium- and high-degree solutions. To address this limitation, this study proposes a Full Signal Variance-Covariance (FSVC) regularization method, in which a full regularization matrix is constructed from a priori gravity anomaly signal amplitudes. The method is applied to combined normal equations derived from GOCE satellite gravity gradiometry data, GRACE observations, and Swarm kinematic orbit data. Three satellite-only static gravity field solutions are generated for comparison: a Kaula-constrained solution, a diagonal signal variance-covariance solution, and an FSVC-constrained solution. This comparison is designed to evaluate whether incorporating full covariance information can improve the stability and accuracy of gravity field recovery. Spectral evaluations show that the FSVC-constrained solution more effectively suppresses medium- to high-degree noise than diagonal regularization schemes. Spatial comparisons further indicate that the FSVC solution produces smaller gravity anomaly discrepancies, particularly in regions with
complex land-sea distributions. Independent validation using GNSS/Leveling data also

confirms the improved accuracy of the FSVC-regularized solution. These results demonstrate that accounting for correlations among spherical harmonic coefficients 2enhances the reliability of satellite-only static gravity field models. The proposed FSVC regularization approach provides a promising strategy for future multi-satellite gravity mission integration. The resulting Tongji-GMMG2025S model will be publicly released through the International Centre for Global Earth Models (ICGEM) in an upcoming update.

Keywords: GOCE, GRACE, Regularization, Full Signal Variance-Covariance

#18

Physics-Informed Dual-Stream Learning for Daily GRACE/GRACE-FO Downscaling

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Abstract

We introduce a daily, 25-km downscaled GRACE/GRACE-FO Terrestrial Water Storage Anomaly(TWSA) dataset for the contiguous United States spanning 2002–2024. To address the spatiotemporal resolution mismatch between coarse monthly satellite observations and daily hydrological dynamics, we develop a physics informed Dual-Stream deep learning architecture that decomposes the downscaling task into two synchronously trained components. The first component, a physics constrained estimator Φphys, operates in the monthly domain and integrates a multi modal fusion operator with a differentiable constraint layer. This layer solves a localized inverse problem using Landweber iterations, followed by a global mass budget projection that enforces the mass conservation constraint. The second component, a probabilistic estimator, Φunc, learns a conditional predictive distribution from daily hydrometeorological inputs while being jointly supervised by the monthly GRACE observations. To accommodate the heavy tailed distribution of GRACE residuals, the estimator models the conditional predictive distribution using a Student-t likelihood, thereby reducing the influence of extreme residuals during optimization relative to conventional Gaussian assumptions. The network is trained using a composite objective that combines observational fidelity, adaptive Pearson correlation soft constraints, and a tail adaptive Student-t negative log-likelihood. This coupled optimization encourages the probabilistic branch to inherit the mass conserving behavior learned by the physics branch while preserving predictive flexibility. We evaluate the proposed framework considering the daily hydrologic extreme events. The resulting reconstruction is consistent with the imposed conservation constraints while providing spatially resolved estimates of aleatoric uncertainty, yielding a physically interpretable daily TWSA product suitable for hydrological and climate applications.

Keywords: GRACE, GRACE-FO, Dual Stream learning, Deep Learning, Spatio-temporal Downscaling

#19

An AI-Driven Hydrogeodetic Framework for Monitoring and Predicting Land Subsidence Using GNSS, InSAR, and Multi-Layer Compaction Observations

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Abstract

Land subsidence induced by excessive groundwater extraction is a major geohazard threatening coastal alluvial plains worldwide. While individual geodetic techniques provide valuable deformation information, they are often limited in spatial coverage, temporal continuity, or subsurface characterization. This study presents an AI-driven hydrogeodetic framework that integrates continuous GNSS observations, MT-InSAR, precise leveling, and multi-layer compaction monitoring wells to quantify, interpret, and predict land subsidence in central Taiwan.

Fifty continuous GNSS stations, more than 1,000 km of leveling surveys, multi-temporal Sentinel-1 InSAR observations, and multi-layer compaction monitoring wells were integrated to characterize deformation from the surface to deep aquifer systems. Cross-validation demonstrates excellent agreement among GNSS, leveling, and InSAR measurements, confirming the capability of satellite observations for regional deformation monitoring. InSAR time-series further reveal detailed spatiotemporal deformation patterns that are closely associated with groundwater-level variations and aquifer-system compaction.

To extend geodetic observations from monitoring to forecasting, long-term InSAR deformation time series were combined with groundwater observations to develop an AI-based prediction model capable of capturing nonlinear subsidence evolution. The model provides reliable forecasts of future deformation and enables early identification of potential subsidence hotspots under different groundwater-use scenarios. Results indicate localized subsidence of 1–3 cm yr^{-1} in Changhua and more extensive deformation of up to 3–5 cm yr^{-1} in Yunlin, with cumulative subsidence exceeding 2 m at several locations since the early 1990s.

The proposed framework establishes an integrated workflow from monitoring, mechanism analysis, to AI-assisted prediction, providing an effective solution for groundwater management, land subsidence early warning, and climate-resilient geohazard mitigation.

Keywords: AI, Land subsidence, InSAR

#20

A continuous piecewise polynomial fitting algorithm for detecting trend changing points

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Abstract

Geophysical time series often contain trend changing points, simply called breakpoints. The commonly used overall linear fitting cannot fit such data well. This paper proposed a continuous piecewise polynomial fitting algorithm for detecting the breakpoints, considering its highly nonlinear characteristics and periodic signals. Additionally, a Monte Carlo-based confidence interval estimation method is presented. The reliability of the confidence interval estimation method and the stability of the proposed algorithm are validated. Comparing to the continuous piecewise linear fitting and other commonly used methods, the proposed algorithm not only obtains better fitting results and more accurate breakpoints, but also could simultaneously estimate signal periods. The algorithm is applied to several typical sea level datasets, yielding more precise estimates of breakpoints and corresponding piecewise trends. It is found that the global mean sea level caused by glacier mass loss transitioned from a linear rise to an accelerated rise trend around the year 1962 ± 1, with two approximately 52- year and 27-year periodic signals.

Keywords: trend changing, time series analysis, piecewise fitting

#21

A Novel Non-Singular and Numerically Stable Algorithm for Efficient Tesseroid Gravity Forward Modeling

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Abstract

Gravity forward modeling, based on Newton's law of gravitation, describes the relationship between subsurface mass density distribution and observed gravity data. It has broad applications in global geodynamics, resource exploration, and planetary sciences. The tesseroid (spherical prism) is widely used to represent mass density elements on a spherical Earth, but its application is hindered by singularities, numerical instabilities near computation points, and the trade-off between accuracy and efficiency in large-scale modeling. To address these theoretical deficiencies, we propose a novel tesseroid gravity forward modeling algorithm formulated in the spherical harmonic domain. The spherical harmonic coefficients are separated into three parts: (1) an analytical, non-singular expression in the radial direction; (2) an analytical, non-singular expression in the longitudinal direction; and (3) a latitudinal integral, efficiently evaluated without singularities using the Gauss–Legendre quadrature (GLQ). Fast Fourier transform (FFT) technique is combined with spherical harmonic synthesis to further enhance computational efficiency. Validation with spherical shell tests shows that accuracy depends jointly on the spherical harmonic expansion degree and the GLQ order, meaning that higher expansion degrees require more GLQ nodes, while greater computation heights reduce the required order. For a single tesseroid, the proposed method matches the adaptive discretization method in both spatial distribution and magnitude of gravity disturbances, with mean differences below 1 mGal, while reducing computation time by 35%. Application to the Tibet topographic model confirms differences below 2 mGal, with runtime reduced to 45% of the adaptive discretization method. At the global scale, differences remain below 1 mGal, and computation time is reduced to only 0.05% of the adaptive discretization method. These results demonstrate that the proposed algorithm is accurate, robust, and highly efficient, making it well-suited for large-scale gravity forward modeling on a spherical Earth.

Keywords: Tesseroid; Non-Singular and Efficient; Spherical harmonic; Gravity forward modeling.

#22

Wide-area PPP-RTK-based multi-link synchronous time and frequency transfer

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Abstract

Precise time and frequency transfer based on the Global Navigation Satellite System(GNSS) has become an important technique for remote time comparison and timereference dissemination. With the development of wide-area Precise Point PositioningReal-Time Kinematic (PPP-RTK), GNSS time transfer is expected to provide improvedstability, continuity, and autonomy. However, its practical performance is still limited by several factors, including unmodeled code errors, day boundary discontinuities in precise satellite clock products, and dependence on global orbit products. These limitations may degrade the stability of receiver clock estimates, interrupt multi-day time transfer, and restrict autonomous operation when external product support is limited. This study aims to enhance wide-area PPP-RTK time and frequency transfer from three aspects. First, a code-error-refined PPP/PPP-RTK model is developed. By reducing the influence of time-varying code biases and emphasizing phase-only observations, the proposed strategy weakens the impact of unmodeled code errors on clock estimation and improves time transfer stability. Second, a PPP-RTK model with synchronous estimation of receiver and satellite clocks is proposed. Instead of directly relying on external precise satellite clock products, satellite clocks are estimated together with receiver clocks within a network,

thereby avoiding the introduction of day boundary jumps and enhancing the continuity of multi-day time transfer. Third, a PPP-RTK model based on parameterized broadcast ephemeris orbit errors is investigated. By characterizing the time-varying components of broadcast orbit errors and reducing dependence on precise orbit products, this model provides a feasible solution for autonomous wide-area time and frequency transfer. The proposed methods are evaluated using multi-station GNSS observations under wide-area time transfer scenarios. The results indicate that code error refinement improves time transfer stability, synchronous satellite clock estimation effectively mitigates discontinuities caused by precise clock products, and parameterized broadcast ephemeris orbit correction supports autonomous PPP-RTK time transfer with reduced product dependence. Overall, this study establishes a systematic PPP-RTK-based framework for improving the stability, continuity, and autonomy of GNSS time and frequency transfer over wide-area networks.Keywords: GNSS, PPP-RTK, wide-area, time and frequency transfer, unmodeled code errors refinement, synchronous satellite clock estimation, parameterized broadcast ephemeris orbits

#23

Interpretable data-driven storm surge forecasting for ungauged coastal areas

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Abstract

Storm surges (SSs) cause massive losses in coastal areas. Accurate, timely, and high-spatial-resolution forecasts are crucial for mitigating SS impacts. However, such information can only be obtained from high-fidelity numerical models, which require accurate bathymetric data and high computational resources. Here, we demonstrate that data-driven forecasting can serve as an independent and skillful approach to produce SS forecasts for ungauged areas. We show that the proposed data-driven model achieves precision in predicting SSs at up to 15-hour lead time in ungauged areas that is similar to or better than the precision of nowcasts (0-hour lead time) from the state-of-the-art numerical Global Tide and Surge Model. In addition, the developed model works well under extreme SSs (close to or exceeding 2-2.5 meters) and shows stronger stability in ungauged areas than the Global Surge and Tide Operational Forecast System. Further analysis demonstrates that SS forecasting is more of a forcing problem. Treating it as an initial-value problem in data-driven models is NOT suitable, resulting in rapid accuracy loss (up to 50%) and pronounced forecast delays. Interpretability analysis reveals that when lead time exceeds 9–12 hours, the most influential factor shifts from historical SS to future meteorological fields. This indicates that intensified atmospheric forcing during hurricanes induces more drastic sea-level fluctuations, diminishing the temporal autocorrelation of the surge sequence. This work highlights the potential of the data-driven model as a valuable support for SS disaster early warning; its interpretability provides in-depth insights into SS forecasting and enhances confidence in its practical application.

Keywords: coastal extreme sea level; storm surge disaster; data-driven model; ungauged forecast; interpretability analysis

#24

Modelling Intraplate Deformation and Stress in the Indian Plate: Implications for Seismic Hazard and Continental Dynamics in Central Asia

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Abstract

The Qinghai–Xizang Plateau, Xinjiang, Siberia, and their surrounding regions form one of the most active zones of continental deformation and mountain building on Earth. This area contains the world's highest plateau, major active fault systems, and extensive glaciers. It serves as the source of major river systems and hydrological basins (lakes) that define a distinctive climatic regime and a province of frequent, large-magnitude earthquakes. The Xizang Plateau is the product of the active India–Eurasia continent-continent collision, which began ~50–55 million years ago when the Indian Plate subducted beneath Eurasia. The plateau rose through three stages subduction collision, convergent compression, and isostatic uplift forming the world's highest and largest plateau. Xinjiang reflects Palaeozoic accretionary processes overprinted by the distant collision, while Siberia is dominated by a stable craton flanked by peripheral orogenic belts. In this study, we present 3D finite element modelling of intraplate deformation and stress distribution within the Indian Tectonic Plate and examine its effects on the surrounding regions. This analysis can enhance the interpretability of seismic and geological studies. Furthermore, the model can aid seismic hazard assessment, help identify seismically active zones, and provide insights into active intraplate deformation within seismically active regions of the Indian Plate through interpretation of strain rate and stress distribution data. These processes have a major impact on surrounding regions and are scientifically important not only for Asia, but also for understanding global change and Earth-system interactions.

Keywords: 3D finite element modelling, Seismic hazard assessment, Earth-system interactions

#25

The link between co- and postseismic slip in the 2024 Wushi Mw7.0 earthquake sequence constrained by geodetic data

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Abstract

The interplay between mainshock, afterslip and aftershocks has always been one of the focal issues in seismological research. Decoding the associated surface deformation and underlying fault kinematics are of great significance for understanding earthquake physics and assessing seismic hazards. Advances in satellite geodesy and modeling techniques allow for measuring crustal deformation over the earthquake cycle and modeling the corresponding slip evolution. Herein, based on InSAR and GNSS observations, we reproduce the crustal deformation and its evolution during the 2024 Wushi earthquake sequence, which involves the Mw7.0 mainshock, at least two Mw>5.5 aftershocks and obviously aseismic slip among them. The underlying seismic and aseismic slip evolution are subsequently investigated. Our results show that the north-dipping Mw7.0 mainshock ruptured the eastern segment of Maidan fault in southeastern Tianshan. Its coseismic slip is mainly distributed at depths of 5-25 km, with no reliable surface rupture. An unexpected Mw5.6 aftershock occurred on a south-dipping branch fault ~7 days later, causing ~2-km-long surface rupture. The shallow rupture of the aftershock located in the stress shadow caused by the deeper mainshock. Interestingly, the very early afterslip (0-7 days) occurred dominantly updip of the mainshock, causing a significant stress loading on the shallow branch fault, which probably triggered the occurrence of the following rupture. The afterslip extended westward in the following ~1.5-year period and finally possibly triggered another Mw6.0 aftershock to the west of the mainshock. This study detailed describes the link between co- and postseismic slip in a long-lasting earthquake sequence, which contributes valuable understandings focus on the fault behaviors and slip evolution during the earthquake cycle.

Keywords. The 2024 Wushi earthquake; Geodetic data; Coseismic slip; Afterslip; Slip evolution

#26

Distributed weak upper mantle beneath the northern Shan Plateau revealed by far-field postseismic response of the 2025 Mw7.8 Mandelay earthquake

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Abstract

The Shan Plateau contains one of the most complex conjugate strike-slip fault systems in East Asia. The region is characterized by intense tectonic deformation and frequent seismic activity. However, the related deep-seated geodynamic mechanism remains debated. The regional lithosphere structure and material properties are therefore important for understanding the geodynamic processes beneath the Shan Plateau. Widespread coseismic and postseismic deformation was caused by the 2025 Mw 7.8 Mandalay earthquake. This event provides an important opportunity to constrain the lithospheric rheology and its influence on regional crustal deformation beneath the Shan Plateau. Data from 21 continuous GNSS stations were collected to evaluate the far-field coseismic and 1-year postseismic displacements in the northern Shan Plateau. A refined coseismic slip model of the 2025 Mandalay earthquake was constrained by near-field SAR/optical images and our new far-field GNSS observations. A layered viscoelastic lithospheric model was subsequently developed to simulate and explain the far-field postseismic observations, in order to constrain the regional lithospheric rheological properties, especially the upper-mantle rheology. The steady-state viscosity of the upper mantle beneath the Shan Plateau was estimated to be ~2·1019 Pa·s. This value is significantly lower than the geodetic-derived upper-mantle viscosities estimated across the Tibetan Plateau, which indicated a weakening of the lithospheric mantle beneath the northern Shan Plateau. Combined with multidisciplinary evidence, the regional weak lithospheric mantle is interpreted to be related to the asthenospheric upwelling caused by lateral tearing of the Indian slab beneath the Shan Plateau. This mechanism probably produced a large-scale lithospheric weakening and decoupling beneath the Shan Plateau. The development of the complex fault system and the upper-crustal distributed deformation could also be explained by the geodynamic process.

Keywords: The 2025 Mandelay earthquake, Postseismic deformation, GNSS, Viscoelastic relaxation, Upper mantle

#27

Coseismic slip distribution of the Mw 6.0 Asadabad, Afghanistan, Earthquake and its Mw 5.6 aftershock

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Abstract

The 31 August 2025 Mw 6.0 Asadabad earthquake and its 4 September 2025 Mw 5.6 aftershock caused significant crustal deformation in northeastern Afghanistan along the Konar fault. Herein, we exploit Sentinel-1 ascending and descending interferometric synthetic aperture radar (InSAR) observations to constrain the coseismic slip models for both events. The mainshock deformation field reveals peak LOS displacements of approximately 20 cm, with inversion results indicating a northeast-striking (44°), southeast-dipping (56°) fault plane. The slip is confined to an asperity between approximately 6 and 10 km depth, with a peak slip of ~1.8 m and a geodetic moment of 1.14×10^{18} N·m (Mw 6.02). The absence of surface rupture confirms a fully buried fault scenario. The Mw 5.6 aftershock is modeled on a separate, shallower fault plane (strike 57°, dip 36°) with slip concentrated between 1.5 and 5 km depth and a peak slip of ~0.65 m. Coulomb failure stress change (ΔCFS) analysis shows that the central and deeper portions of the aftershock fault plane experienced a well-defined positive ΔCFS lobe reaching approximately 8 to 12 bar, providing strong evidence that the mainshock promoted failure on the aftershock fault through static Coulomb stress transfer.

Keywords: Coseismic slip distribution; InSAR; Sentinel-1; Asadabad earthquake sequence; Coulomb stress transfer; Hindu Kush tectonics.

#28

A Unified Framework for Full Spatiotemporal Simulation of Earthquake-Induced Viscoelastic Deformation

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Abstract

Earthquake-induced deformation, including crustal motion and gravity changes, provides fundamental constraints on earthquake-cycle processes and lithosphere-mantle rheology. Following coseismic faulting, stress redistribution within the lithosphere and mantle drives time-dependent viscoelastic relaxation. GNSS, InSAR, gravity measurements, and other geophysical observations have substantially improved our understanding of postseismic deformation. However, accurately modeling its full spatiotemporal evolution remains challenging because of Earth's spherical geometry, radial heterogeneity, self-gravitation, complex rheological behavior, and relaxation timescales ranging from the coseismic stage to thousands of years.

Here, we summarize a unified theoretical and numerical framework developed by our group for simulating earthquake-induced viscoelastic deformation over the full quasi-static time range in a spherical Earth. The framework combines the dislocation theory, vector spherical harmonics, and the viscoelastic correspondence principle. It provides solutions for both point and finite-fault sources, from the Earth's surface to its interior. The framework also supports a wide range of linear rheological models, including Maxwell, Kelvin-Voigt, standard linear solid, Burgers, generalized Maxwell, and extended Burgers rheologies. This flexibility enables systematic investigation of how lithospheric and mantle rheological structures control deformation through time.

For homogeneous and layered Earth models, the framework combines analytical solutions with numerical schemes to improve the accuracy and efficiency of coseismic and postseismic deformation calculations. By solving the governing equations in the Laplace domain and applying stable inverse transformation techniques, it enables continuous modeling from the immediate post-earthquake response to the long-term fully relaxed state, without explicitly resolving individual relaxation modes. The resulting solutions include three-dimensional displacement, and gravitational potential perturbations, and other derived physical quantities. We will also introduce a modular Fortran implementation of the framework, with MATLAB and Python versions planned to support broader community use. This framework provides a comprehensive tool for interpreting geodetic observations, investigating earthquake-cycle dynamics, and constraining the rheological structure and evolution of the Earth's interior.

Keywords: Co-seismic deformation, Post-seismic relaxation, Spherical Earth model, Linear rheology, Inverse Laplace transform

#29

Interseismic, coseismic, and early postseismic slip associated with the 2025 Mw 8.8 Kamchatka Earthquake

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Abstract

The 29 July 2025 Mw 8.8 Kamchatka earthquake reactivated much of the rupture zone of the 1952 Mw 8.8-9.0 event and was followed by vigorous aftershocks and volcanic unrest. To understand how strain accumulates and is released throughout the seismic cycle, we integrate geodetic and seismological observations to quantify interseismic coupling, coseismic rupture, and early postseismic afterslip along the Kuril-Kamchatka subduction zone.

Interseismic coupling is derived from 22 GNSS velocity vectors using a back-slip inversion on the Slab2 fault geometry in a layered elastic half-space. The model resolves three strongly coupled asperities, with the highest slip deficit rates near the 2025 epicenter. Coseismic slip is jointly inverted from GNSS and ascending/descending Sentinel-1 interferograms, together with back-projection imaging of high-frequency seismic radiation from global arrays. The rupture propagated unilaterally toward the southwest at 1.9-2.3 km/s and produced two main slip asperities with a peak slip of 7.6 m. High-frequency energy is complementary to the large-slip patches, suggesting variable rupture velocity and frictional properties along strike. The average coseismic slip exceeds the interseismic slip deficit accumulated since 1952, indicating dynamic overshoot. Early postseismic afterslip, constrained by one-month GNSS and InSAR displacements, partially overlaps the coseismic rupture and extends downdip and southwest, releasing approximately 9.9% of the coseismic moment.

Coulomb stress transfer analysis reveals cascading triggering from the Mw 7.4 foreshock to the mainshock and subsequently to the Mw 7.4 and Mw 7.8 aftershocks.

Furthermore, three-dimensional finite-element modeling shows that coseismic and postseismic slip induced extensional dilatation in the upper crust beneath Klyuchevskoy, Krasheninnikov, Bezymianny and Sheveluch volcanoes, which may promote magma ascent. These results improve our understanding of the interplay among interseismic, coseismic and postseismic slip and have implications for seismic and volcanic hazard assessment in Kamchatka.
Keywords: Kamchatka earthquake;coseismic rupture; afterslip; stress triggering;
volcano-strain interaction;

#30

Satellite Geodetic Detection of Coseismic Gravity Changes Associated with the 2025 Mw8.8 Kamchatka Earthquake

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Abstract

The moment magnitude 8.8 megathrust earthquake that struck Russia's Kamchatka Peninsula on 29–30 July 2025 was the world's largest earthquake since the 2011 Tohoku event. We examine whether geodetic observations can resolve gravity changes produced by coseismic mass redistribution near the source fault. The analysis combines time-variable gravity measurements from the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission with geoid estimates derived from Surface Water and Ocean Topography (SWOT) radar altimetry. Empirical orthogonal function (EOF) analysis is applied to observations covering the epicentral region throughout 2025. Using monthly GRACE-FO gravity-field solutions produced by the Center for Space Research (CSR), we identify positive and negative coseismic gravity anomalies reaching approximately 4 μGal in magnitude. Their peak-to-peak extent and spatial pattern are consistent with predictions from a fault-dislocation model. For the SWOT analysis, the static sea surface is treated as an approximation of the geoid after dynamic sea-level variations are removed while the earthquake contribution is retained. The leading EOF components display opposing spatial anomalies around the epicentre and step-like temporal changes across the earthquake. The co-seismic geoid-height changes predicted by dislocation models range from approximately −6 to +6 mm, which are marginally detectable in the SWOT observations. Generally, the GRACE and SWOT results illustrate the potential of complementary satellite gravimetry and altimetry for detecting earthquake-related mass redistribution, despite their differing sensitivities to coseismic signals.

Keywords: Kamchatka earthquake, coseismic gravity change, GRACE-FO, SWOT, empirical orthogonal function, satellite geodesy

#31

Calculation of Seafloor-Geometry Gravity Effects and Its Relevance to Bathymetric Modeling in the Mediterranean Sea

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Abstract

Gravity-Geological Methods (GGM) estimate seafloor depth from gravity anomalies that are correlated with available bathymetric data. The representation of the gravitational effect of the seafloor topography is a major element of GGM. The standard implementation is often based on a Bouguer plate approximation to represent the bathymetric mass effect. In this paper we compare sea floor topography gravity effects using the Bouguer plate approximation with the effects of detailed seafloor topography. The plate approximation considers the bathymetric mass effect as a horizontal slab of uniform lateral extent set by the local water depth, and therefore ignores the lateral variation in seafloor relief. The effect of seafloor topography, on the other hand, is calculated by accounting for the gravitational contributions of detailed bathymetric irregularities. The Mediterranean Sea was selected as the study area because it includes deep basins exceeding 4.5 km in depth, steep continental margins, submarine ridges and island systems. Calculations were performed at 1 arc-minute resolution, using GEBCO_2024 bathymetry. The first analysis was restricted to the marine areas at least 20 km away from the coastline to minimize the coastline effects. The difference between the Bouguer plate representation and detailed effect of the seafloor-topography in this offshore area is of the order of -45 to +29 mGal for a density contrast of 1 g cm^{-3}. Secondly, the magnitude of the difference is about 130 mGal including nearshore areas. In the augmented seafloor topography effect, the density contrast between water and seafloor is considered in the marine cells only. In contrast, the Bouguer plate representation extends the marine density-contrast volume into land cells, thus larger nearshore differences are assessed.

The outcomes offer a first indication that the bathymetric gravity component employed in GGM could be affected by the way the seafloor geometry. Preliminary spatial patterns indicate that the differences are not uniformly distributed across the study area and are more pronounced in regions characterized by steep bathymetric gradients and complex submarine areas. In GGM applications, such differences may affect the bathymetric gravity component removed from gravity anomalies before density iterations, thus the proposed framework can help bathymetry modeling.

Keywords: bathymetric gravity effect, seafloor topography, Mediterranean Sea, gravity-geological method, bathymetric modeling

#32

Improving Mediterranean Sea Level Predictions using the hybrid VMD-DMD Decomposition Algorithm

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Abstract

Accurately forecasting sea-level changes in the Mediterranean isn't just an academic exercise; it's a practical necessity for safeguarding coastal infrastructure and communities. But the challenge lies in the inherently unstable, non-stationary nature of sea-level records, which makes conventional forecasting approaches prone to error. To address this, we developed a hybrid forecasting framework that combines a hybrid decomposition technique, Variational Mode Decomposition (VMD) and Dynamic Mode Decomposition (DMD), with a powerful predictive model: Long Short-Term Memory (LSTM) networks. Our analysis draws on three decades of monthly sea-level anomaly data from 16 tide-gauge stations spread across the Mediterranean, covering 1993 to 2022. The real workhorse here is the VMD-DMD decomposition step. By breaking the raw sea-level signal into physically meaningful components, we were able to reconstruct the original signal far more accurately than with VMD alone, cutting the average reconstruction error from over 24.22 mm down to just 7.38 mm. That's a substantial improvement right out of the gate. When it came to prediction, we put our model through a rigorous gauntlet of baselines: a naive persistence forecast (zero-order hold), a simple three-layer MLP, and a standalone LSTM without any decomposition. Unsurprisingly, those baselines struggled. But once we added decomposition into the model, even the modest MLP saw its explanatory power jump from an R^2 of 0.35 to 0.88. Our complete VMD-DMD-LSTM model delivered the best results across the board, with an R^2 of 0.92, an RMSE of about 20.4 mm, and a mean absolute error of 15.3 mm. That represents a 68% reduction in error relative to the naive forecast, and it still outperformed the decomposed MLP by 18%. To further validate our approach, we ran a direct comparison against a well-known model, the VMD-EEMD-LSTM model, using the exact same dataset. Our framework came out ahead, achieving roughly 12% lower errors. Overall, what we've built is more than just another forecasting tool. It's a systematic way to untangle the complex, multi-scale dynamics that drive sea-level variability, while effectively filtering out residual noise. The result is a set of forecasts that are not only more accurate but also more dependable for the kind of high-stakes decisions involved in coastal risk management.

Keywords: Hybrid VMD-DMD-LSTM model; Nonlinear vertical land motion; The Mediterranean region

#33

Seamless Daily 250-m Flood Mapping Under Cloudy Conditions Using MODIS Terra-Aqua Fusion

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Abstract

Continuous flood mapping is essential for disaster response and hydrological analysis, but optical satellite observations are often interrupted by persistent clouds during the rainfall events that generate floods. We developed a daily 250-m flood-mapping framework that uses the full observational capacity of the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra and Aqua sensors. Same-day Terra and Aqua acquisitions are fused at the pixel level to increase clear-sky coverage, residual cloud gaps are filled through automated spatiotemporal interpolation, and water extent is reconstructed using hydro-geomorphic constraints from historical water occurrence and Height Above Nearest Drainage (HAND). The framework was evaluated using 225 same-day Landsat and Sentinel-2 reference scenes over Poyang, Dongting, and Taihu Lakes in China. Binary water mapping achieved a mean F1 score of 0.91 and an Overall Accuracy (OA) of 97.4%, while sub-pixel water fraction assessment reached a mean F1 score of 0.78 and an OA of 92.6%. Simulated cloud-occlusion experiments further showed stable performance under heavy data loss, with OA values from 81.5% to 99.3%. Applications to flood events in India, the United States, and southern China produced seamless daily inundation sequences that captured flood onset, expansion, peak, and recession under cloudy and rainy conditions. These results show that reliable daily flood observation from optical satellite data is achievable at regional to large scales, supporting rapid flood monitoring, disaster management, and long-term hydrological change analysis.

Keywords: Flood monitoring; MODIS; Terra-Aqua fusion; Cloud removal; Hydro-geomorphic reconstruction

#34

Machine Learning-Based Quantitative Assessment of Hydraulic-Fracturing-Induced Seismic Hazard Using Multi-Source Data: A Case Study of the Weiyuan Shale Gas Field, Sichuan, China

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Abstract

Seismic hazard assessment is one of the principal objectives of earthquake research. With the rapid expansion of shale gas development, hydraulic-fracturing-induced earthquakes, characterized by anthropogenic forcing, shallow focal depths, and potentially severe localized damage, have become an important issue requiring urgent attention in seismic hazard assessment. In this study, a machine-learning-based framework was developed to assess the hazard of hydraulic-fracturing-induced seismicity in the Weiyuan shale gas development area. Six categories of inducing factors were integrated, including the relative fluid injection volumes of horizontal wells and hydraulic fracturing pads, the long-term mean InSAR deformation velocity field, cumulative InSAR deformation during the sampling period, reservoirs, faults, and b-values. The framework further incorporated imbalanced-sample processing, Gaussian kernel density estimation smoothing, feature standardization, Bayesian optimization, and SHAP-based interpretability analysis to perform an overall classification of induced-earthquake risk. The results indicate that relative fluid injection volume is the dominant factor controlling the spatial differentiation of induced-earthquake risk, followed by the long-term mean deformation velocity field and the b-value. The long-term mean deformation velocity field is more important than the cumulative deformation during the sampling period, suggesting that a persistent long-term deformation trend is more sensitive to induced-earthquake risk than the total deformation accumulated over a specific period. This finding also indicates that hydraulic-fracturing-induced seismicity may involve a certain time-lag effect, which may be associated with the delayed response of pore-pressure diffusion and the gradual evolution of faults toward a critically unstable state. Compared with conventional empirical weighting methods, the proposed model avoids subjective weighting and provides probabilistic outputs for different risk levels. The results also demonstrate the potential value of long-term geodetic deformation observations in assessing induced-earthquake risk in hydraulic fracturing regions. This study provides a useful reference for local-scale identification of induced-earthquake risk and refined dynamic risk management in shale gas development areas.

Keywords: Induced seismic hazard assessment, Hydraulic fracturing, Machine learning, InSAR, Geodetic information, Shale gas development area