Session 1: Theoretische Geodäsie

Jendges, Lukas & Jan Martin Brockmann
IGG Uni Bonn

Iterative Signal Separation with AR Processes

Estimating deterministic trend functions from observational time series data remains a critical challenge in geophysical and climate research, particularly when confronted with data gaps, outliers, limited observation periods, short term disturbing signals and non-white noise characteristics. For instance, the established approaches ignore correlations leading to biased or non-optimal estimates. In response, this study introduces an iterative estimation approach tailored for equidistant, one-dimensional time series data, combining deterministic approximation with covariance modeling by autoregressive (AR) processes. This framework incorporates valid covariance information and also addresses outlier detection and removal using robust estimation approaches. The methodology separates the signal into long-term trends, short-term variations and a noise component, allowing for detailed analysis of both components. By leveraging AR processes for modelling the short-term variability and the noise while propagating this covariance information, statistical tests on the trend parameters become possible and ensure reliability and interpretability of results. An application to GRACE Total Water Storage data demonstrates the chances of the proposed procedure, showcasing the efficiency of this approach in mitigating biases and enhancing trend estimation in challenging datasets. Furthermore, the versatility of the proposed technique extends beyond GRACE data to any equidistant one-dimensional time series, promising a broad applicability.

Ji, Kunpu & Yunzhong Shen, Qiujie Chen, Tengfei Feng
Tongji University, College of Surveying and Geo-informatics; University of Stuttgart, Institute of Geodesy

Extended Principal Component Analysis for Spatiotemporal Filtering of Incomplete Heterogeneous GNSS Position Time Series

When ordinary principal component analysis (PCA) is employed to analyze the position time series of a regional global navigation satellite system (GNSS) station network, the GNSS time series are assumed to be homogeneous, and the missing data in the time series must be restored beforehand. To directly process incomplete and heterogeneous GNSS position time series, we develop the extended PCA (EPCA) and weighted EPCA approaches to solving for the missing values based on the best low-rank approximation in the spatiotemporal domain. The proposed approaches are used to process the real GNSS position time series of 24 stations in North China spanning 2011 to 2019 and successfully extract the common mode errors (CMEs). The proposed approaches are compared with modified PCA (MPCA) and weighted MPCA, in which an additional optimization criterion needs to be introduced in the frequency domain. The results show that EPCA can extract more CMEs than MPCA for both the unweighted and weighted cases. Consequently, EPCA outperforms MPCA in reducing noise and improving the accuracy of site velocity estimates. Repeated simulation experiments show that the CMEs extracted by EPCA are closer to the simulated true values than those extracted by MPCA. When the formal errors of the time series are considered, both weighted EPCA and weighted MPCA outperform their unweighted counterparts, and the former outperforms the latter. In addition, EPCA is computationally more efficient than MPCA since fewer unknowns need to be estimated.

Middendorf, Klara & Annette Eicker, Laura Jensen, Henryk Dobslaw
HafenCity Universität Hamburg

Utilizing Extreme Value Theory for determining the intensity of extreme events in monthly water storage time series

Under the assumption that a warming climate leads to an intensification of the global water cycle, it can be hypothesized that also the occurrence frequency and severity of extreme events such as droughts or floods will increase in the upcoming decades to centuries. To investigate this hypothesis, the occurrences of extreme events in simulations of terrestrial water storage (TWS) from global coupled climate models participating in CMIP6 will be analysed and compared against spatio-temporal changes in water mass derived from GRACE and GRACE-FO. Due to the stochastic behaviour of climate variability in unconstrained model experiments, statistical methods are utilized for the analysis. There are two different approaches commonly used in hydrological applications, which are based on Extreme Value Theory and define extremes as annual maxima (minima) or as peaks above a threshold, respectively. By using extreme distributions, a so-called return level is calculated as a measure of the frequency/intensity of extreme values. The application to monthly resolved time series of a short data record leads to challenges with both approaches. Further considerations are needed if strong serial dependencies are present. We show the difficulties as well as the potential and exemplary results for the application of the theory to the TWS time series.

Ye, Zhourun
Geodätisches Institut, Universität Stuttgart

Calculating the full tensor gravity gradient of the ocean using the SWOT satellite observations

Ocean gravity gradient data can provide high-precision and multi-component observations that are able to detect small changes in the geological structure of the seafloor. This is of great significance for geological exploration, seabed resource assessment, and seismological research. In our study, based on observations from the Surface Water and Ocean Topography (SWOT) satellite, we propose a strategy that combines deflection of the vertical (DOV) and Fast Fourier Transform (FFT) technology to calculate the full tensor ocean gravity gradient. First, taking advantage of high-resolution data from the SWOT satellite that includes along-track and cross-track observations, we solved the DOV using the least squares method. Then, the vertical gravity gradient anomaly of the sea surface was calculated from the DOV. Finally, through FFT technology, the other five tensors of the gravity gradient were computed from the vertical gravity gradient anomaly. All experimental results were compared with and verified against the published model and the solution from CryoSat-2 observations.

Session 2: Schwerefeld

Beck, Clara & Thomas Forbriger, Walter Zürn, Rudolf Widmer-Schnidrig, Nico Sneeuw
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Systematic disturbances of superconducting gravimeters – An investigation of sensor differences

We analyze the difference signal of dual sphere superconducting gravimeters (SG) to identify systematic instrumental disturbances, which would otherwise go unnoticed. Compared to classical spring gravimeters SGs excel by their superior long-term stability. However, also SG measurements suffer from systematic errors. One possibility to characterize and quantify these errors is the analysis of sensor differences either of dual sphere instruments or of two collocated instruments. For perfect instruments the sensor difference should be constant. We studied the sensor differences of all dual sphere SGs in the database of the International Geodynamics and Earth Tide Service (IGETS). As expected they show a relative drift between the sensors and steps related to operator interventions. However, we can also identify times, during which the sensor differences show more complicated behavior. The observed differences are too big to be caused by local gravity gradients. Therefore, we think, they indicate more complex systematic disturbances of SGs. These disturbances are at the level of microGal and could not be clearly identified in the gravity residuals of only one sensor. These findings from data of dual sphere SGs are cooperated by the analysis of differences between collocated single sphere SGs at the J9 observatory in Strasbourg. Knowledge of the characteristic and size of these disturbances is important if gravity changes at the microGal level are studied on long time scales, like signals from hydrology, volcanology, polar motion or long period tides. In the future we will study how these disturbances influence the determination of the gravimetric factor and phase of the Chandler wobble from long time series of SG measurements.

Dilixiati, Yixiati & Nico Sneeuw
Geodätisches Institut, Universität Stuttgart

Next Generation Gravity Mission Simulation for Mantle Viscosity

The GRACE and GRACE-FO missions have delivered more than two decades of data on Earth's time-variable gravity field, which have been extensively applied in various geoscientific fields. Research utilizing these data has yielded significant insights, including the mass balance of major ice sheets, sea level rise, groundwater depletion, and gravity changes associated with seismic events. However, these studies have primarily focused on the Earth's surface or near-surface regions. It is well established that mass redistribution also occurs within Earth's deeper interior, such as the mantle, which can influence the time-variable gravity field on decadal scales. Furthermore, gravity field signals generated by mantle convection can provide valuable information about mantle viscosity, a crucial parameter in understanding Earth's geodynamic processes. This study addresses the challenges associated with detecting gravity field variations caused by mantle convection. We use simulations combined with geodynamic modeling, employing a closed-loop simulation approach to generate synthetic observations using the MAGIC/NGGM constellation. Here, we present preliminary findings on the feasibility of detecting mantle signals, incorporating simple white noise in the instruments to simulate observational conditions.

Grombein, Thomas & Daniel Arnold, Adrian Jäggi
Geodätisches Institut, Karlsruher Institut für Technologie (KIT)

Gravity field recovery with nano-satellites of the Spire constellation

A growing number of Low Earth orbiting (LEO) satellites is collecting GPS tracking data that allows to recover the long wavelength part of the Earth's time-variable gravity field. Besides scientific LEO missions, commercial satellite constellations consisting of a huge number of nano-satellites are moving into focus as they have the potential to increase the spatial-temporal coverage. However, for many nano-satellites the corresponding GPS tracking data is not suitable for gravity field recovery, as they are based solely on single-frequency measurements. In this context, the Spire constellation is of special interest as it consists of more than 100 nano-satellites (called CubeSats) that are all equipped with high-quality dual-frequency GPS receivers. Furthermore, the Spire constellation provides a large variety of orbital characteristics with different (also lower) inclinations. In this study, we use GPS data from nine Spire CubeSats to derive monthly gravity field solutions covering a six-month period between May and Oct 2020. The gravity field recovery is performed with the Bernese GNSS software using the Celestial Mechanics approach. We will show that a single Spire CubeSat solution cannot compete with the ones obtained from scientific LEO missions. However, the accumulation of individual CubeSat solutions significantly increases the quality. A combined solution based on nine Spire CubeSats can reach a quality level comparable to Swarm-B, revealing even slightly improved coefficients for the very low degrees. Moreover, we will demonstrate that data from low-inclined Spire CubeSats strongly impacts the combined solution.

Gschwind, Charlotte & Thomas Grombein, Kurt Seitz, Hansjörg Kutterer
Geodätisches Institut Karlsruhe (KIT)

On the use of kinematic orbits for time-variable gravity field determination

The analysis of the Earth's time-variable gravity field provides crucial insights into the mass distribution and mass transport processes within the Earth system. Variations in the gravity field occur at different spatial and temporal scales and can only be captured globally with consistent accuracy through satellite observations. In addition to the observation data from dedicated satellite gravity missions, gravity field information can be derived from the kinematic positions of Low-Earth-Orbit (LEO) satellites. Especially during periods when observation data from dedicated gravity missions are unavailable, the kinematic positions of other LEO satellites can be used to extend the time series for observing the large-scale variations in the Earth's gravity field.

Guo, Hengyang & Xiaoyun Wan
School of Land Science and Technology, China University of Geosciences (Beijing); Institute of Geodesy, University of Stuttgart

Validation of SWOT L2 KaRIn Beta Prevalidated Data Based on Restore the Marine Gravity Field and Its Application

A part of the Ka-band radar interferometer (KaRIn) beta prevalidated data (beta data) (7 September–21 November 2023) for the surface water and ocean topography (SWOT) mission has been released. We conducted various experiments, including inverting the ocean gravity field and seafloor topography from beta data, to validate their performance. Validating the accuracy of the deflections of the vertical (DOV) by DOV products of Scripps Institution of Oceanography (SIO), the root means square of differences between the north and east components is about 1.83 urad and 2.71 urad, respectively. The precision of gravity anomaly (SWOT_GA) is about 5.07 mGal compared with shipborne gravity. The results derived from 1-cycle data are comparable with those obtained from nadir altimeters. The accuracy of seafloor topography inverted from SWOT_GA is about 68 m validated by shipborne depth, which is almost the same as the topography obtained from SIO_GA and SDUST2021GRA. The results have demonstrated that beta data can be used to compute high-precision ocean gravity fields and seafloor topography products. This proves the success of the first operational run of KaRIn and the capability of SWOT to support studies related to ocean science. The prevalidated data will be more accurate after further calibration, which will lead to higher accuracy of the inverted gravitational field products in the future.

Kupriyanov, Alexey & Arthur Reis, Manuel Schilling, Vitali Müller, Jürgen Müller
Leibniz Universität Hannover (Institut für Erdmessung)

Benefits of Optical Accelerometery and Satellite Formations for Future Gravimetry Missions

From the beginning of 21st century satellite gravimetry missions have provided unique data about mass change phenomena in the Earth’s system. These valuable observations are planned to be continued within the next years by successor missions: GRACE-Continuity (GRACE-C) and Next Generation Gravimetry Mission (NGGM). They shall form a double-pair Mass change And Geosciences International Constellation (MAGIC). In this study, we focus on the performance evaluation of novel optical accelerometers (ACC), where a test mass displacement is measured by laser interferometry instead of capacitive sensing as it is done in electrostatic inertial sensors. Also, different satellite formations are analyzed that may be applied in subsequent missions. So far, only electrostatic accelerometers (EA) were utilized in satellite gravimetry missions at Low Earth Orbit. This kind of instruments are one of the limiting factors in current space gravimetry due to the well-known drift in the low frequency domain. This drift originates from the polarization wire that connects the Test Mass (TM) with the electrode housing and thermal stability of the system. To overcome this issue, the LISA-Pathfinder mission demonstrated promising results by utilizing a Gravitational Reference Sensor (GRS) – an optical accelerometer. Moreover, for the first time a wireless ultraviolet TM discharge system was implemented there instead of a polarization wire. In our research, we modeled a wireless simplified-GRS – both electrostatic and optical ACCs with parameters based on inertial instruments from the LISA-Pathfinder. Closed-loop simulations, including the satellite dynamics and using gravity field recovery software tools, were carried out in order to quantify the performance of the novel sensors and compare it with current EA and other concepts, e.g. Cold Atom Interferometry (CAI) ACCs and hybridized (EA+CAI) ACCs. In this presentation, we compare the performance of different accelerometers and gradiometers, and apply them in novel triple satellite formations with inter-satellite range measurements in cross-track direction. An impact on retrieved gravity field models from the GRACE-like satellites with extended solar arrays, in order to meet the power requirements of additional novel sensors and drag compensation system, has also been assessed.

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Institut für Erdmessung, Leibniz University Hannover.

Validation of Mass Changes Based on Recent GRACE and GRACE-FO Monthly Gravity Field Solutions

This study aims to validate mass change measurements using the latest data releases from the GRACE (Gravity Recovery and Climate Experiment) and GRACE-FO (Follow-On) missions. These missions have been operational since 2002 and provided essential data for monitoring mass redistributions through Earth's gravity field variations. Hydrological changes, glacial isostatic adjustment, and atmospheric and oceanic dynamics influence mass redistribution. We conducted thorough research by analyzing the monthly gravity field solutions (Level 2) from GRACE/GRACE-FO data. We employed signal recovery techniques such as C20/C30 and Degree-1 replacements, static field removal, and filtering methods like Gaussian smoothing, DDK, and VADER filters. We also carried out investigations on LRI monthly solutions. To enhance data accuracy, we used leakage correction techniques, including scaling factor and extended boundary approaches, along with Singular Spectrum Analysis (SSA) for gap-filling. GRACE solutions were validated using the WaterGAP model for Germany and satellite altimetry data for Sea Surface Height (SSH) for the Caspian Sea. The evaluation metrics included R^2 (coefficient of determination) to measure the linear relationship strength between GRACE-derived and WaterGAP-simulated Total Water Storage Anomalies (TWSA) and the amplitude ratio to compare variability and trends. We approximated the time series of TWSA using linear and sinusoidal components and calculated the annual amplitude and ratio to assess consistency between the datasets.

Vincent, Asha & Jürgen Müller
Leibniz University Hannover Institute of Geodesy

Clock-based Networks for Monitoring Global Sea Level

Physical height changes are related to vertical land displacement and geoid height variations. The core of physical heights is geopotential numbers. Atomic clock observations can provide direct measurement of local gravity potential variations. Tide gauges give the Relative Sea Level changes (RSL) connected to the nearby GNSS benchmarks (BM) or local tidal datums i.e., referenced to the ellipsoid. When land motion is reduced from RSL one obtains Absolute Sea Level change (ASL). In order to derive a globally consistent measure of ASL, the corresponding measurements of RSL and land motion need to be referenced to the geoid. Here, clocks can be used with superior spatial and temporal resolution compared to existing geodetic techniques. A combination of a space-based clock and a ground-based clock serve as references to derive time-variable potential changes at the site of interest. The gravity potential difference with respect to the reference clock can be assumed to be purely gravitational as the temporal centrifugal variations are negligible. The time-variable gravitational potentials are categorized into tidal effects and non-tidal effects. We have reduced tidal effects such as solid-earth tides, ocean-load tides, pole tides, and LOD (Length of Day) tides. Non-tidal effects include mass redistributions in the geosphere, hydrosphere, and atmosphere. For a realistic scenario, clock observations are simulated by considering link uncertainties and tidal model errors together with the clock noise. We demonstrate the procedure of utilizing atomic clock networks to derive globally consistent ASL, potentially replacing the GNSS BMs in the future.

Wöhnke, Viviana & Annette Eicker, Matthias Weigelt, Marvin Reich, Andreas Güntner, Torsten Mayer-Gürr
HafenCity University Hamburg

Regional modelling of water storage variations from combined GRACE/-FO and GNSS data in a Kalman filter framework

Water mass changes at and below the surface of the Earth cause changes in the Earth's gravity field which can be observed by at least three geodetic observation techniques: ground-based point measurements using terrestrial gravimeters, space-borne gravimetric satellite missions (GRACE and GRACE-FO) and geometrical deformations of the Earth's crust observed by GNSS. Combining these techniques promises the opportunity to compute the most accurate (regional) water mass change time series with the highest possible spatial and temporal resolution, which is the goal of a joint project with the interdisciplinary DFG Collaborative Research Centre (SFB 1464) "TerraQ – Relativistic and Quantum-based Geodesy". A method well suited for data combination of time-variable quantities is the Kalman filter algorithm, which sequentially updates water storage changes by combining a prediction step with observations from the next time step. As opposed to the standard way of describing gravity field variations by global spherical harmonics, we introduce space-localizing radial basis functions as a more suitable parameterisation of high-resolution regional water storage change. An estimation environment has been set up for the combination of GRACE/-FO satellite gravimetry with GNSS station displacements. The feasibility and stability of the approach is first demonstrated in a closed-loop simulation to test the setup and tune the algorithm. Subsequently, it is applied to real GRACE and GNSS observations to sequentially update the parameters of a regional gravity field model for Central Europe. The implementation was designed to flexibly include further observation techniques (e.g. terrestrial gravimetry) at a later stage. This presentation will outline the Kalman filter framework and regional parameterisation approach, and address challenges such as the relative weighting between the GRACE and GNSS data, and the appropriate choice of the Kalman filter process model and radial basis function parameterisation.

Session 3: Geodätische Referenzsysteme und Erdrotation

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A possible imprint of ENSO on polar motion excitation

The El Niño–Southern Oscillation (ENSO) is the leading mode of natural variability in the atmosphere-ocean system, involving circulation anomalies in the tropical Pacific and teleconnections to other parts of the globe. Whereas the strong control of ENSO on zonal atmospheric angular momentum – and thus changes in the length-of-day – has been known for decades, detection of a similar effect in polar motion has remained elusive. Here we test the hypothesis that ENSO excites polar motion by oceanic, and not atmospheric angular momentum changes. To this end, we calculate monthly ocean bottom pressure (OBP) anomalies and depth-integrated horizontal transports from the ocean component of four CMIP6 (Coupled Model Intercomparison Project 6) climate models and subject these fields to a lagged regression on each model's ENSO index over 165 model years. The regression reveals statistically significant ENSO-driven OBP changes across all the climate models considered, characterized by decreases in pressure (about −3 hPa per unit change of the ENSO index) over Australasian shelf regions and widespread positive anomalies (2 hPa) in the Bellingshausen Basin from late austral winter to early autumn around an El Niño event. These

mass changes primarily perturb the oceanic angular momentum vector along the 90°E meridian and translate to polar motion excitation anomalies of –4 mas (milliarcseconds) for a peak value of 2.0 in the ENSO index. Such negative anomalies, amounting to ~40% of typical interannual amplitudes in the overall oceanic excitation, are indeed seen in the observed polar motion excitation during recently observed El Niño events (e.g., 1997/98, 2006/07, 2009/10), after correcting for the effects of other geophysical fluids. The study therefore suggests a prominent role for ENSO in driving polar motion variability on interannual time scales.

Reinhold, Anton & S. Glaser, A. Kehm, M. Seitz
Rheinische Friedrich-Wilhelms-Universität Bonn

On simulations studies for novel combination strategies of space geodetic techniques

The project "Novel clock technologies for combination on ground and in space" as part of the DFG research unit "Clock Metrology" addresses innovative combination strategies of all four space geodetic techniques – DORIS, GNSS, SLR, VLBI – to significantly improve the global Terrestrial Reference Frames (TRF) in view of the GGOS (Global Geodetic Observing System) goals of 1 mm accuracy and 1 mm/decade long-term stability. To achieve this goal, a completely new approach to combining the space geodetic techniques is being developed. On the one hand, a common target (CT), i.e. a common reference point, will be introduced to combine all space techniques at the Geodetic Observatory Wettzell (GOW). On the other hand, a common clock (CC) will be implemented at GOW to reference the observations of all techniques to a single time frame. All four space geodetic techniques are simulated employing the CT and CC to assess their impact on the TRF combination. In this study, we exhibit the first results of the SLR simulations. As the basis for these simulations, we performed Precise Orbit Determination (POD) for Etalon-1/2 and Lageos-1/2 with current state-of-the-art models and standards based on real observation data to determine realistic accuracy measures for today's SLR observations. The newest SLRF2020 realization, the SLR-specific version of the International Terrestrial Reference Frame (ITRF) 2020, was used as a priori station network. For the quality validation of the POD, we evaluated the orbital fit, internally as well as externally w.r.t the combined International Laser Ranging Service (ILRS) solution. The RMS of the orbital fit reaches approximately 5 mm and was added as observation uncertainty in form of a white noise in the following SLR simulation. Subsequently, weekly normal equation systems from the simulated data were accumulated to a combined global TRF solution over the time span of 7 years to evaluate the impact on derived station coordinates and Earth Rotation Parameters (ERPs). The estimated corrections to the station positions do not exceed a level of a few millimeters indicating a high accuracy solution.

Wang, Jungang & Jungang Wang, Susanne Glaser, Eri Hawkins Stern, Robert Heinkelmann, Kyriakos Balidakis, Georg Beyerle, Maorong Ge, Harald Schuh
TU Berlin

Investigating the VLBI Scale w.r.t. ITRS Realizations 2020

Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) are the two main techniques for determining the scale of the current International Terrestrial Reference Frame (ITRF). In the three realizations of the International Terrestrial Reference System (ITRS) 2020, the VLBI scale exhibits a drift relative to ITRF2020 (post 2013.75) and JTRF2020 (post 2012.00), but not to DTRF2020. This study examines the scale behavior of the International

VLBI Service (IVS) combined solution w.r.t. the three ITRS2020 realizations. Our findings reveal that the scale rate can be significantly influenced by the exclusion of individual stations, demonstrating a network effect largely attributable to the uneven distribution of the network and the inhomogeneous observing frequency of different stations. For instance, excluding NYALES20 reduces the VLBI scale rate, whereas excluding KOKEE increases it. We also identified non-linear displacements at specific stations, such as NYALES20, which likely contribute to the scale drift due to improper velocity modeling in ITRF2020. Correcting these non-linear displacements using GNSS co-location stations can mitigate the scale drift, although not entirely eliminate it. Additionally, applying GRACE MASCON (Mass Concentration blocks) displacements to model velocity changes before and after 2013.75 further reduces the VLBI scale rate relative to ITRF2020. Notably, DTRF2020 exhibits significant positive biases compared to ITRF2020 at stations observed only after 2010, reaching up to 10 mm. Excluding post-2010 stations results in a larger scale rate of IVS combined solution relative to both ITRF2020 and DTRF2020.

Yeskali, Yertay & Ming Hui Xu, Jens Wickert
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Imaging of ICRF3 sources with European VLBI Network for phase-referencing

An accurate and stable celestial reference frame (CRF) is the fundamental basis for both astronomy and geodesy. In order to investigate and improve the consistency of the CRFs between optical and radio wavelengths, we have conducted 4 epochs of Very Long Baseline Interferometry (VLBI) observations for about 20 radio sources with European VLBI Network (EVN). In this study we will derive and investigate imaging results of ICRF3 sources, which are the calibrators for the radio stars in order to eliminate the common error sources, such as atmospheric and instrumental effects. Here, imaging these calibrator sources to derive the map of their brightness distribution on the sky is the key and first step of the successful determination of astrometric parameters (i.e., position, proper motion, and parallax) of the radio stars. The visibility data are calibrated based on the standard procedure of astronomical VLBI observations and further imaged by using model fitting. We will report about the data processing and imaging results of our EVN observations.

Session 4: Ingenieurgeodäsie und GNSS

Wang, Lingke & Duo Wang, Hansjoerg Kutterer
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A New Tropospheric Delay Model for High-Resolution Regional Integrated Water Vapor Retrievals Using Gaussian Mixture Long Short-Term Memory Network

The quality of Zenith Wet Delay (ZWD) in tropospheric delay significantly impacts the accuracy of Integrated Water Vapor (IWV) estimation. While the Global Navigation Satellite System (GNSS) provides reliable station-specific ZWD products, their spatial resolution is inherently limited by the GNSS station distribution. On the other hand, empirical models combined with numerical weather models (NWMs), such as the fifth generation of European Reanalysis (ERA5) and Vienna Mapping Functions 3 (VMF3), can produce global gridded ZWD estimates. However, these models exhibit centimeter-level discrepancies when compared to GNSS-derived ZWD. This paper proposes a deep learning method based on the Gaussian Mixture

Long Short-Term Memory (GM-LSTM) network, which learns the probability density mapping between empirically derived ZWD and GNSS-derived ZWD. Once this mapping is established, it can be used to infer the ZWD probability distribution and its uncertainty at any location within the study area. To validate the performance of the tropospheric delay model, we combine the Zenith Hydrostatic Delay (ZHD) from VMF3 with the corresponding ZWD to obtain the Zenith Total Delay (ZTD), since the Generic Atmospheric Correction Online Service (GACOS) only provides ZTD products. Upon evaluation across eight different latitude regions in Europe, the ZTD inferred by the proposed GM-LSTM model achieved state-of-the-art performance with an average Root Mean Square Error (RMSE) of 4.6 mm. Compared to ZTD estimates from ERA5 ray tracing, VMF3, and GACOS, the GM-LSTM model demonstrated average performance improvements of 67.68%, 48.74%, and 49.63%, respectively, thus enhancing the accuracy of IWV estimation. Furthermore, the GM-LSTM model's effectiveness was verified using meteorological records, showing it can accurately reflect uncertainties caused by spatially heterogeneous rainfall events. With homogeneous training data, the model performs well even during heavy rainfall, a capability not matched by other tropospheric delay estimation methods.

Session 5: Umweltmonitoring und Fernerkundung

Blank, Daniel & Annette Eicker, Andreas Güntner
HafenCity University Hamburg

Revisiting drought cascades with daily satellite observations of soil moisture and terrestrial water storage

Changes in soil water storage can be studied on a global scale using a variety of satellite observations. With active or passive microwave remote sensing, we can study the upper few centimeters of the soil, while satellite gravimetry allows us to detect changes in the entire column of terrestrial water storage (TWS). The combination of both types of data can provide valuable insight into hydrological dynamics in different soil depths towards a better understanding of changes in subsurface water storage. We use daily Gravity Recovery and Climate Experiment (GRACE) data and satellite soil moisture data to identify extreme hydroclimatic events, focusing on prolonged droughts. To enhance our comprehension of the subsurface, we utilize not just surface soil moisture data but also integrate information on root zone soil moisture. Original level-3 surface soil moisture data sets of SMAP and SMOS are compared to post-processed level-4 data products (both surface and root zone soil moisture) and a multi-satellite product provided by the ESA CCI. The main goal of this study is to use remote sensing for the investigation how drought affects water storage in the soil across different layers, from the top layer to the root zone and finally the whole water column of TWS. To identify different dynamics, we compute the rate of change of anomalies to assess how quickly the system accumulates storage deficits during drought conditions and recovers from them for different soil depths. Our investigation focuses on the temporal dynamics of near-surface soil moisture and TWS, highlighting the cascading effects that propagate from the surface into the subsurface. The results we obtained indicate characteristic patterns of the temporal dynamics of drought recovery in varying soil depths. Specifically, our analysis shows that surface soil moisture recovers faster than TWS, and that this recovery process slows down as soil integration depth increases.

Sneeuw, Nico & Omid Elmi, Mohammad J.Tourian, Peyman Saemian
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Remote Sensing-Based Extension of GRDC Discharge Time Series - A Monthly Product with Uncertainty Estimates

Quantifying river discharge is crucial for addressing a wide range of scientific questions related to hydrology, hydraulics, biogeochemistry, and water resource management. However, the Global Runoff Data Center (GRDC) data set has experienced a significant decline in active gauges since the 1980s, with only 14% remaining active as of 2020. To extend the discharge estimates for inactive GRDC stations, we developed the Remote Sensing-based Extension for the GRDC (RSEG) data set, which integrates legacy gauge discharge data with remote sensing observations. We employ a stochastic nonparametric mapping algorithm to extend the monthly discharge time series for inactive GRDC stations, benefting from satellite imagery- and altimetryderived river width and water height observations. After a rigorous quality assessment of our estimated discharge, involving statistical validation, tests and visual inspection, results in the extension of discharge records for 3377 out of 6015 GRDC stations with an average discharge exceeding 10 m³/s. The quality of discharge estimates for rivers with large or medium mean discharge is quite satisfactory. However, for river reaches with a low mean discharge, the performance is less accurate. The RSEG data set retains monitoring capability for 83% of the total river discharge measured by GRDC stations, equivalent to 7895 km³/month.

Elmi, Omid
Geodätisches Institut, Universität Stuttgart

Long-term Analysis of Global Surface Water Volume Change Using Remote Sensing Data

The availability and variations of continental water storage are of great importance for society, as they influence agricultural, industrial, and domestic water use. Among the components of water storage, terrestrial surface water—specifically lakes and reservoirs—is essential for both wildlife and human habitats. They store freshwater in the most accessible way, control seasonal floods, and generate hydropower. Despite their importance, the estimation of surface water storage variation on a global scale is often derived from simplified models due to the absence of necessary gauge and remote sensing measurements. In this study, we produce monthly water volume anomaly time series for 182260 global lakes and reservoirs larger than 1 km² for the period from 1985 to 2018. To achieve this, we obtained water area time series of lakes and reservoirs from the Joint Research Center Global Surface Water data set. We gathered all publicly available in situ water level time series and generated additional water level time series using satellite altimetry data from various missions and data sets. For the remaining lakes and reservoirs, water height information was extracted from the TerraSAR-X digital elevation model. After collecting the required data, we developed an empirical water area-level model for each water body and then estimated the water volume variation time series. With this data set, we can investigate the temporal and spatial variations of surface water stored in lakes and reservoirs from 1985 to 2018 on a global scale. This study aims to answer these fundamental questions: 1) What are the temporal behaviors of surface water volume variations in different river basins? 2) Does the water volume variation trend align with other hydrological parameters' temporal variations? and 3) What are the major natural and anthropogenic factors that explain the long-term water volume variation?

Emam, Ahmed & Mohamed Ibrahim
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Foundation model reliabilty for satellite imagery

Protected natural areas are essential for preserving biodiversity, maintaining ecosystem services, and providing refuges for many species. These areas, characterized by minimal modern human impact, are crucial for environmental conservation and scientific research. However, assessing their naturalness and ecological integrity remains a complex task due to their vastness and poor accessibility. Despite extensive research highlighting the advantages of foundation models for various downstream tasks, there is a notable gap in ensuring the reliability and explainability of these models when applied to environmental monitoring. To address this gap, we propose the T-REX framework, a significant contribution to the field that introduces the REX score. The REX score is a comprehensive metric that assesses each pixel's contribution to naturalness and the associated uncertainty. A REX score close to 1 indicates a high contribution to naturalness with high certainty, while a score near 0 signifies negligible contribution and low certainty. This dual assessment ensures a more reliable and explainable analysis of natural environments. Utilizing multimodal foundation models offers new avenues for understanding and mapping the naturalness of these protected areas through satellite imagery analysis. We applied the T-REX framework to a study site in Fennoscandia using two open-source satellite datasets. Our findings demonstrate that moors and heathlands have high REX scores, reflecting their significant and certain contributions to naturalness. Conversely, water bodies exhibit lower REX scores, indicating minimal and uncertain contributions. By providing an objective and quantifiable assessment of naturalness, the T-REX framework advances our ability to protect and understand these vital ecosystems. Our contribution, through the development of the T-REX framework and the introduction of the REX score, addresses the research gap in reliability and explainability, representing a significant step forward in the application of foundation models to environmental conservation.

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A Method for Estimating Daily Discharge Using Space-based Discharge Estimates

An accurate estimate of river discharge is vital to quantifying the global hydrological cycle and managing water resources. Given the steadily deteriorating data provision from gauge networks, hydrological monitoring through spaceborne sensors becomes a necessity. The SWOT mission is the first satellite to conduct a global survey of the Earth’s surface waters, measuring water surface elevation, river width, and surface slope for estimating discharge. Since SWOT can only sample mid-latitude locations approximately twice per its 21-day cycle, we develop a linear dynamic system for daily discharge estimation over continuous reaches in a single-branch river network. The linear dynamic system includes a process model based on a physically-based spatiotemporal correlation and observation equations utilizing SWOT discharge products. We solve this dynamic system through a Kalman filter, which is simultaneously executed in the time and space domain to obtain daily discharge. Since SWOT discharge products are currently inaccessible, we use a perturbed version of synthetic SWOT datasets obtained by Monte Carlo simulation to test the feasibility of our approach. The validation of the estimated discharge against true discharge in the synthetic datasets over all rivers leads to a median correlation as high as 0.95, a median NSE for residuals as high as 0.82, and a median relative bias as high as 5.22%, respectively. Our method delivers promising results and the hope of obtaining daily discharge once the required SWOT data is available.

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Fault tolerant approach to regenerate Level 1B SAR altimetry waveforms for enhancing Level 2 retrackers performance

In studying narrow rivers and small inland water bodies, noisy waveforms on certain cycles can result in gap or false measurements within water level time series data. This study deals with identifying and regenerating anomalous waveforms generated in the Level 1B processing chain of satellite altimetry. Efficient identification and recovery of anomalous waveforms are essential for obtaining precise water level measurements.

To find abnormal waveforms, our framework utilizes an unsupervised machine learning technique. We categorise different parameters of the satellite's altimeter like AGC parameter, tracker range, and features related to the shape of waveforms for instance waveform's skewness, number and location of peaks. Then we identify abnormal waveforms using a two-step density distribution probability analysis. The main purpose of this study is to propose a robust strategy to regenerate and improve abnormal waveforms in the level 1B SAR processing chain. In contrast to previous studies focusing solely on investigating L1B waveforms to determine precise retracking gates for multipeak and noisy waveforms, we propose an additional step in the L1B processing chain, specifically tailored to coastal and inland waters, enabling the recovery of abnormal waveforms. In both fully focused and unfocused SAR processing, the final waveform is formed through the combination of various beam looks from the altimeter during fixed illumination time to the desired point on the surface, certain looks in the stack may exhibit undesirable patterns due to variations in environmental characterization, antenna footprint, and sidelobe gain. The proposed methods will mitigate the presence of undesirable waveforms in the stack before generating the final waveforms. We applied the proposed methodology for Sentinel 3-A/ 3-B data products over different inland waters and validated our results against in-situ data. The results demonstrate that the water level time series, obtained by regenerated waveforms have significantly improved. The results show the potential of our proposed framework for detecting and recovering anomalous waveforms leading to robust water level estimates from satellite altimetry data.

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Sea Level Rise in Indonesia: Insights from GNSS-IR and Tide Gauges

Continuous and accurate sea level monitoring is fundamental to understand and mitigate climate change and its impact on Indonesia, a vast archipelago susceptible to sea level rise and vertical land motion. However, the limited number of publicly available tide gauges data on Indonesian coasts and consequently a lack of comprehensive studies on sea level trends around Indonesia hinders better understanding for better development of effective environmental monitoring and adaptation planning. This study is one of the first to investigate the potential of the GNSS Interferometry Reflectometry (GNSS-IR) method as a tool for high-resolution sea level observations in Indonesia. We found that in a challenging coastal environment, GNSS-IR can provide time series with 40-minutes frequency and 6 cm standard deviation compared to the collocated tide gauge station. Additionally, 35 tidal constituents can be resolved with the time series estimated by the GNSS-IR. These findings highlight the potential of GNSS-IR to improve and densify the sea level observation network throughout the globe. A complementary analysis on vertical land motion (VLM), satellite altimetry (SLR) and

relative sea level rise (RSLR) over 20 collocated Indonesian locations reveals discrepancies between different sources of tide gauge data, emphasizing the need for a robust and accurate national tide gauge network. Notably, 85% of stations show positive RSLR value while Jakarta, Northern Java and Southern Sumatra exhibit rates 2.5x faster than the global mean. These findings underline the need for comprehensive research to improve sea level monitoring methodologies and accuracy, specifically in challenging locations with sparse dataset to inform more effective coastal management and adaptation approach.

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Status of GFZ Global Ionospheric Disturbances Monitoring System and Initial Results

Analysis of ionospheric disturbances plays an important role in improving the accuracy of space geodetic applications. Recently, it has also been used extensively in early warning systems and in assessing the severity of natural disasters such as solar storms, earthquakes, tsunamis, etc. To monitor ionospheric disturbances in different regions, the GFZ German Research Centre for Geosciences is establishing a global network of high-rate GNSS stations, operating at a frequency of 50 Hz. This report introduces this monitoring system and initial results at stations in areas near the magnetic equator. It will include a 3-D model of Total Electron Content (TEC) variations and scintillations over an entire year to provide a comprehensive understanding of the temporal and spatial variations of these phenomena. In addition, the report will present the application of machine learning techniques to the analysis and prediction of meteorological parameters collected at the station, such as temperature, humidity, pressure, and Precipitable Water Vapor (PWV).

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Satellite Altimetry-based Extension of global-scale in situ river discharge Measurements, SAEM

Freshwater is vital for life, necessitating accurate monitoring to address global water challenges. Measuring river discharge, an important metric of river water volume has become increasingly challenging due to the decreasing number of operational gauges worldwide. This reduction, especially in key areas, underscores the need for innovative methods. Remote sensing offers a promising solution. We present a new dataset, the Satellite Altimetry-based Extension of global-scale in situ river discharge Measurements (SAEM), combining satellite altimetry with a wide network of river gauges to comprehensively understand global river dynamics. In SAEM, we have tracked more than 45,000 gauges and estimated height-based discharge for about 9,000 gauges. Beyond the river discharge time series, the SAEM dataset includes three additional products, each offering a distinct contribution to understanding river discharge dynamics: (1) The core of the SAEM dataset is a catalogue of Virtual Stations (VSs), defined by specific criteria. This catalogue provides each station's coordinates, information on satellite altimetry missions, distance to the discharge gauge, and relevant quality flags. (2) The dataset also features the altimetric water level time series for those VSs where we successfully obtained high-quality discharge data. These series come from pre-existing level-3 water level time series and new ones generated in this study. For the former, SAEM includes

the corresponding IDs that are provided from the level-3 databases. The level-3 data are sourced from established databases, including Hydroweb, the Database of Hydrological Time Series of Inland Waters (DAHITI), the Global River Radar Altimeter Time Series (GRRATS), and HydroSat. (3) The third product of SAEM consists of rating curves for the accepted VSs, where the conversion of water level time series into discharge data is modelled using rating curves derived from a Nonparametric Stochastic Quantile Mapping Function approach. SAEM dataset is crucial for effective water resource management, sustainable development, and tackling the challenges posed by climate change. It addresses the limitations of current river discharge datasets by using satellite altimetry and river gauges, providing a global solution.

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Ship-based GNSS contribution to tsunami warning in the North Eastern Atlantic and Mediterranean region

Tracking changes in sea-surface height with ship-based GNSS can be used to detect tsunamis in the open ocean. We propose that a network of ships, based on voluntary participation of cargo and tanker vessels could contribute to tsunami warning, augmenting the existing systems in the North Eastern Atlantic and Mediterranean region (NEAM). Several case studies based on tsunamis generated at the locations of historical events are examined based on the distribution of ships that would be expected from such a network. We find that ships are likely to be in position to be the first sensors reached by these tsunamis regardless of their source (seismic, volcanic, landslide). The ships have an excellent coverage of the most active tsunamigenic zones in the NEAM region and would add a great contribution to augment data from the existing tide gauges. However, the relatively high noise characteristics previously found in ship-based GNSS data requires four or more ships before an unambiguous detection can be made based only on the ship data which may increase the effective detection time for such a network. In all cases, ships would still make a consequent and precise contribution to the characterization of a tsunami event as they would provide observations from otherwise unsampled locations. The global nature of GNSS and ship routes make this a promising, low-cost approach, to augment tsunami detection.

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AI4GNSS-R: Implementing and Interpreting AI for GNSS-R Applications in Ocean and Atmosphere

The capability of Deep Learning (DL) for operational wind speed retrieval from the measured Delay-Doppler Maps (DDMs) has been recently investigated. Furthermore, it is shown that applying deep learning to process the GNSS-R measurements can help significantly improve the quality of existing ocean wind speed products from GNSS-R satellite missions. Therefore, the research project Artificial Intelligence for GNSS Reflectometry (AI4GNSSR) was proposed to implement Artificial Intelligence for processing GNSS-R measurements to characterize geophysical parameters, enhance the physical understanding of GNSS-R technique, and investigate new applications and approaches. From this effort, a global ocean wind speed dataset is created by processing the observables of NASA's Cyclone GNSS (CyGNSS) mission. The initial implementations of AI algorithms have shown great potential in improving the

quality of the existing wind speed products. The deep learning-based data fusion model, which considers external precipitation information, is able to correct the rain effects, especially for wind speeds larger than 16 m/s. Our data fusion model outperforms the operational MVE algorithm by 40%. To validate our model's performance under extreme weather, we present a case study of Hurricane Laura in August 2020, demonstrating its practical effectiveness. To interpret our model, we implement the Explainable AI (XAI) to evaluate the impact of both Delay-Doppler Map (DDM) pixels and ancillary parameters on model predictions. The AI4GNSS-R project underscores the capability of AI to advance GNSS-R applications in oceanic and atmospheric research while demonstrating the great potential of AI to enhance physical understanding and expand the applications of GNSS-R technology.

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Retrieving the root-zone soil moisture from GRACE/-FO-based global assimilation model GLWS2.0 and validating its dynamics using in-situ data over West Africa region

Soil moisture is a key state variable in some hydrological processes such as soil water retention, infiltration, evapo-transpiration, and groundwater recharge, which controls the exchange of water and heat energy between the land surface and the atmosphere. Quantifying its dynamics is crucial for understanding the global water cycle and surface energy balance. However, if some physically-based hydrological models can simulate the soil moisture patterns at different depth, this remains a challenge for conceptual hydrological models. This study aims to retrieve the root-zone soil moisture from a conceptual model, WaterGAP, as well as the GRACE/-FO-based global assimilation model GLWS2.0 which is based on WaterGAP, and validate its dynamics using satellite and in-situ data over West Africa region. An approach based on the analytical solution of Richards' equation is used to translate water content in the single soil moisture reservoir from the models to different depth. The results based on this approach are found to be in a reasonable agreement with in-situ data and numerical solutions from a physically-based model CLM. These results also highly correlate with the remote sensing data from ESA CCI satellite mission. This approach provides a potential solution not only to expand the shallow vertical support of the microwave satellites with good spatial resolution but to better isolate the groundwater storage dynamics from the GRACE/-FO-based assimilated signal.

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Improving inland water altimetry based on analyzing dual-frequency altimeter waveform data

Satellite altimetry has revolutionized our understanding of inland water due to its frequent sampling and global coverage. However, its application in inland water is limited by interference from land and calm water within the altimeter and radiometer footprint. Various dedicated retracking solutions have been proposed and tested in recent years to mitigate the influence of altimeter footprint contamination. Nevertheless, effectively separating the water body components of the waveform remains challenging. In this study, we conduct a

systematic analysis comparing Ku-band and C-band waveforms from Jason-1, Jason-2, and Jason-3 radar altimeters in inland water. Due to the differing backscatter coefficients of water bodies and land for different radar frequencies within altimeter footprints, dual-frequency waveforms exhibit high correlation in inland water bodies. As the distance from the shore decreases, contamination of waveforms by land increases, resulting in significant disparities in the correlation between waveforms of Ku- and C-band. Based on this analysis, we propose establishing a model to fit the relationship between dual-frequency waveforms. By analyzing the relationship between dual-frequency waveforms of water bodies, we are able to distinguish segments containing water and non-water components. The classical open ocean Brown model is then modeled using the least squares method to characterize it. Different weights are allocated to the water and non-water components to reduce contamination from non-water body land in waveform retracking. We evaluate our method on a limited number of lakes and reservoirs and validate the results against in situ water level data. Our results demonstrate that our method has the potential to reduce the influence of footprint contamination and improve the accuracy of water level estimation.

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Detecting water bodies using SWOT and ICESat-2 measurements

Water resources are vital to humans, but areas and volumes of water bodies (lakes, rivers, and seas) on Earth’s surface are constantly changing. Therefore, effective and timely detection of water bodies is crucial. The SWOT (Surface Water and Ocean Topography) mission provides large-area three-dimensional coordinates of water bodies using InSAR techniques, while ICESat-2 (Ice, Cloud, and Land Elevation Satellite-2) offers cross-section information of water bodies using satellite laser penetration depth. This presentation will demonstrate the water detection capabilities, the possible improvements and potential combination of these two Satellites’ datasets in future.