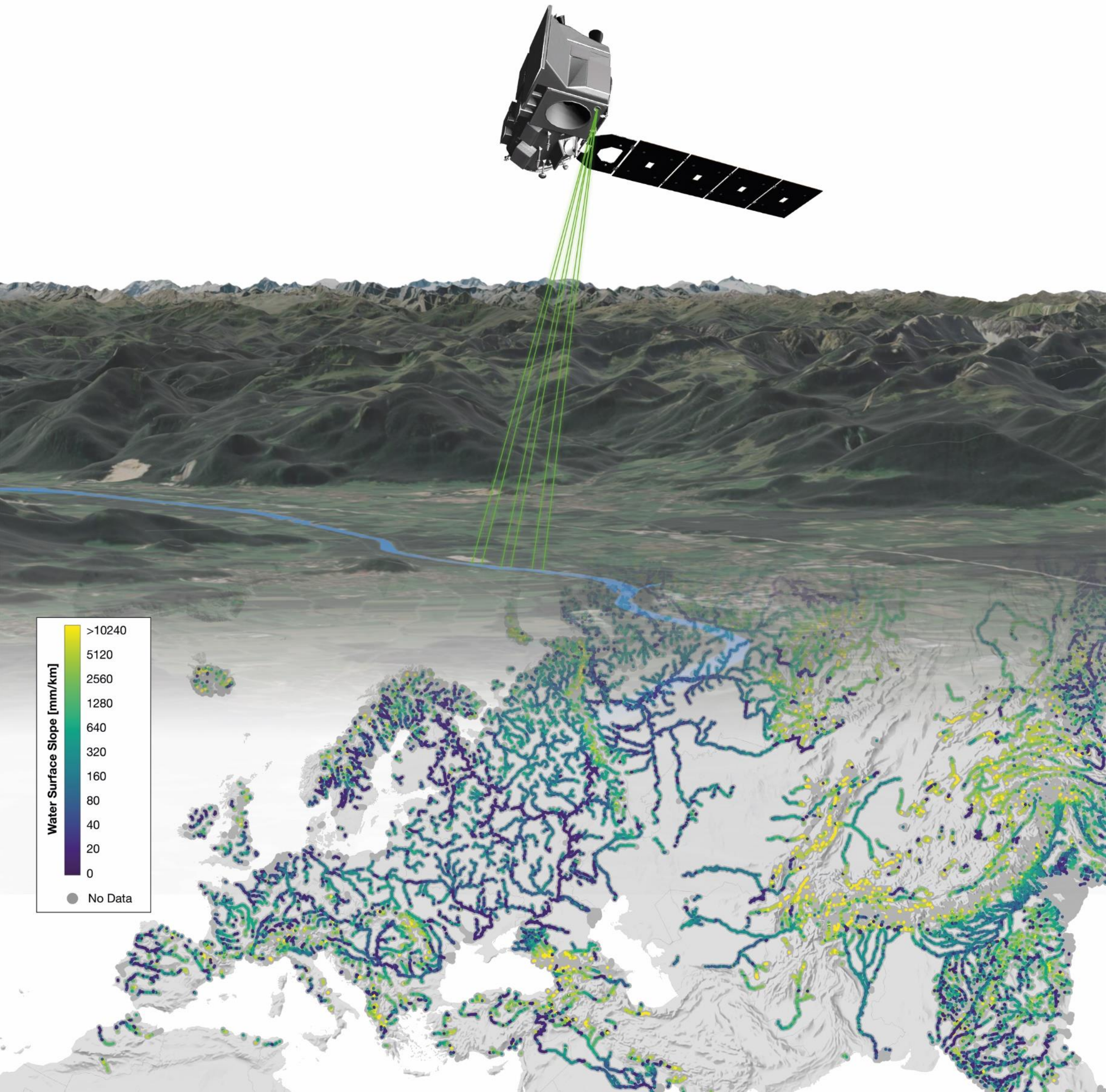
Deutsches Geodätisches Forschungsinstitut
TUM School of Engineering and Design
Department of Aerospace and Geodesy
Technische Universität München

Annual Report 2023

Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM)



Front cover: Global measurement of river surface slopes with NASA's ICESat-2 laser altimeter

In 2023, DGFI-TUM created the *ICESat-2 River Surface Slope* (IRIS) dataset. It provides global-scale average and extreme water surface slopes (WSS) calculated from ICESat-2 laser altimeter observations. Accurate WSS information are critical for determining the complex spatio-temporal dynamics of river discharge, which is one of the Essential Climate Variables (ECV) of the UN Global Climate Observing System (GCOS).

Global determination of WSS and its variability is challenging. Field measurements of WSS are not feasible on the global scale, long-range interferometric SAR measurements are relatively inaccurate, and gauge stations or virtual stations from radar altimetry lack simultaneous observations over short distances. Using ICESat-2's unique measurement geometry of six parallel lidar beams, WSS of IRIS are calculated across two beams or along individual beams, depending on the intersection angle between satellite ground track and river centerline, to ensure maximum spatial and temporal coverage. IRIS provides WSS since 2018 to date, referenced to the SWOT River Database (SWORD). This allows IRIS to be easily combined with observations from the new SWOT altimetry mission.

IRIS is described in the article *ICESat-2 river surface slope (IRIS): A global reach-scale water surface slope dataset* (Nature Scientific Data, 2023, doi: 10.1038/s41597-023-02215-x). Details on methodology and validation are provided in the article *ICESat-2 based river surface slope and its impact on water level time series from satellite altimetry* (Water Resources Research, 2022, doi: 10.1029/2022WR032842). The data are freely available from Zenodo (doi: 10.5281/zenodo.7098113), and an interactive map of IRIS is available in DGFI-TUM's Database of Hydrological Time Series of Inland Waters (DAHITI). See Section 2.3 of this report for more information on this topic.

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Preface

The Institute

The Deutsches Geodätisches Forschungsinstitut (DGFI-TUM) is a research institute of the Technical University of Munich (TUM). It is part of the Chair of Geodetic Geodynamics within the Department of Aerospace and Geodesy of the TUM School of Engineering and Design.

DGFI-TUM conducts fundamental research in Space Geodesy with the aim of precisely measuring and investigating the geometric and physical properties of the Earth system and their changes over time. In close international and interdisciplinary cooperation, DGFI-TUM analyzes and combines observation data from all relevant geodetic space observing systems and complementary data sources. A central aspect of the institute's research has always been the precise determination of the Earth's geometric shape and its changes caused by geodynamics and climate effects. For the solid Earth, this involves in particular the realization of global and regional terrestrial reference and height systems. With respect to water surfaces, DGFI-TUM focuses on the precise determination of the changing sea level, the surface dynamics of the oceans and the water levels of inland waters using satellite altimetry.

DGFI-TUM is involved in the work of the UN Global Climate Observing System (GCOS) through its participation in major international research programs, including those of ESA and the Copernicus program, and actively contributes to the determination of the Essential Climate Variables (ECVs). It also supports the work of the UN Global Geodetic Center of Excellence (UN-GGCE) within the UN Committee of Experts on Global Geospatial Information Management (UN-GGIM) towards the implementation of the UN resolution for the Global Geodetic Reference Frame (GGRF). DGFI-TUM is also a key player in the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG). The strategic orientation of DGFI-TUM is reflected in its organization into the two research areas *Reference Systems* and *Satellite Altimetry* (Fig. 1). The research areas are complemented by three overarching research topics that include the study of the state and dynamics of the atmosphere (with emphasis on ionospheric disturbances and space weather impacts), the determination of high-resolution regional gravity fields, and the enhancement of consistency in the analysis of geodetic data by establishing uniform standards and conventions in an international context.

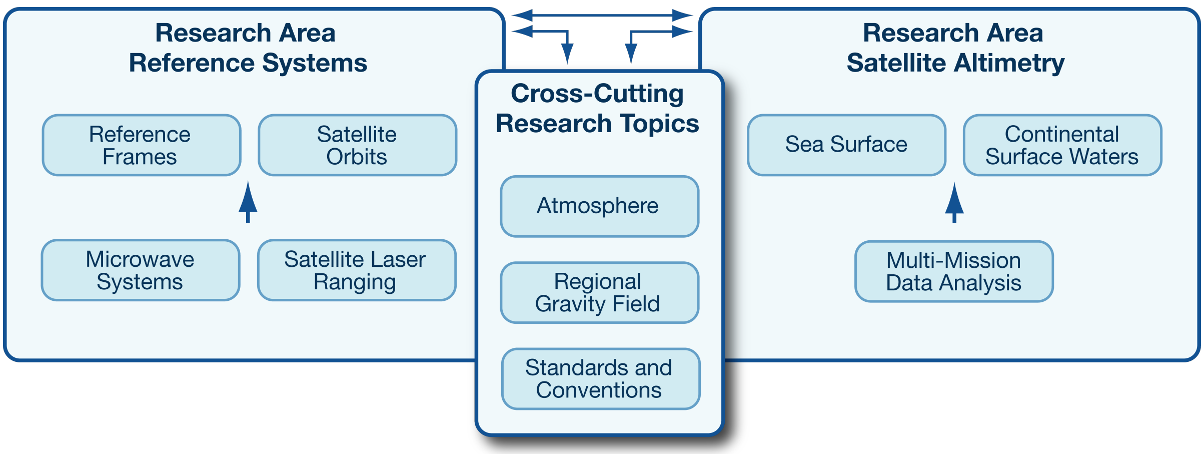


Figure 1: *Research Areas of DGFI-TUM*

As part of the *Forschungsgruppe Satellitengeodäsie* FGS (Research Group Satellite Geodesy), DGFI-TUM is involved in scientific data processing of the Geodetic Observatories Wettzell (Germany) and AGGO (Argentina). In addition, it operates GNSS stations distributed worldwide.

National and international involvement

The institute looks back on a history of more than seven decades. In 1952, it was established by the German Geodetic Commission (Deutsche Geodätische Kommission, DGK) as an independent research institution at the Bavarian Academy of Sciences and Humanities (BAdW) in Munich, and since 2015 it has been part of the TUM. Since its foundation, it has been continuously involved in significant national and international coordinated geodetic research activities and intensively networked with renowned research institutions around the world.

Many of the research projects carried out at DGFI were of great importance for the scientific progress of geodesy. In the first decades after its foundation, geodetic-astronomical observations, triangulation and height measurements were among the essential works, including the IAG project for the readjustment of the European triangulation and the adjustment of the European levelling network. Later, the focus shifted to the geodetic use of artificial Earth satellites. DGFI was involved in the first worldwide network of satellite triangulation and played a leading role in the development of dynamic methods of satellite geodesy for the precise determination of satellite orbits, the Earth's gravity field, and point positions. With the further development of modern space geodetic techniques and the expansion of the worldwide geodetic infrastructure in the 1980s and 1990s, the expansion of the Geodetic Observatory in Wettzell, and in the course of DGFI's participation in the DFG Collaborative Research Center *Satellite Geodesy* (SFB 78), the further development of theories and methods for the definition and realization of terrestrial reference systems became a focus of the institute. Since satellite altimetry became operational as a geodetic observation technique in the mid-1990s, the observation and scientific analysis of water surface dynamics has complemented the research program.

DGFI-TUM is committed in central positions in international scientific organizations, especially in the framework of the International Union of Geodesy and Geophysics (IUGG), the International Astronomical Union (IAU) and the International Association of Geodesy (IAG) (see Section 4.2). For many years, the Institute has been an important pillar of the IAG's Global Geodetic Observing System (GGOS). GGOS advocates for the implementation of geodetic infrastructures and analysis capabilities necessary for Earth system monitoring and global change research, and coordinates the generation of high quality scientific data products under predefined standards and conventions. DGFI-TUM provides the current GGOS President, chairs one of the two GGOS Bureaus (Bureau of Products and Standards), and leads two of the three GGOS Focus Areas (FA Unified Height System; FA Geodetic Space Weather Research). In addition, the institute recognizes the outstanding importance of the IAG Scientific Services that form the backbone of the national and international spatial data infrastructure. Within this framework, DGFI-TUM operates data centers, analysis centers, and research centers. It performs leading and supporting functions in IAG commissions, projects, working and study groups and thus contributes to shaping the future direction of international geodetic research.

The institute participates in research programs of the European Union (EU) and the European Space Agency (ESA) and cooperates in United Nations (UN) activities. In this regard, DGFI-TUM provides an IAG representative to the UN-GGIM Working Group for the GGRF and is a national partner of the UN Global Climate Observing System (GCOS).

Research highlights of particular scientific and public interest

During the year 2023, several scientific results gained broad attention in the scientific community and in the public. The following activities and publications can be highlighted:

- **DGFI-TUM staff member elected GGOS President:** Effective from July 2023, DGFI-TUM scientist Laura Sánchez was elected new President of GGOS, the Global Geodetic Observing System of the International Association of Geodesy (IAG). GGOS is the geodetic contribution to GEOSS and also faces important actions within UN-GGIM. For the period 2023-2027, the new GGOS Coordinating Board will promote the advancement of the global geodetic infrastructure and organize the generation of high-quality geodetic data products as a backbone for Earth system research and many other scientific and societal applications. See Section 3.3 of this report.

- **GGOS Focus Area Unified Height System (GGOS-FA-UHS) completed:** The GGOS-FA-UHS, established in 2010 and chaired by DGFI-TUM from 2015 to 2023, has been successfully completed in 2023. The main results of this work are the definition of the International Height Reference System (IHRS) and the theoretical foundations for its implementation as well as the first solution for its realization, the International Height Reference Frame (IHRF). Having achieved these goals, the focus is now on the operational infrastructure required to ensure the maintenance and availability of the IHRS/IHRF in future. This task will now be accomplished under the responsibility of the International Gravity Field Service (IGFS), while DGFI-TUM will continue supporting the IHRF developments with its research. More details are provided in Section 1.4.

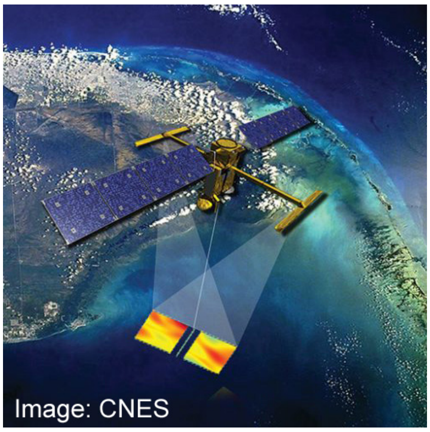
- **New DFG Research Unit 'Clock Metrology' started**: The newly established DFG Research Unit (RU) 5456 'Clock Metrology: A Novel Approach to TIME in Geodesy' aims at using novel clock technologies to combine geodetic data in order to realize highly accurate and stable geodetic reference systems. The centrepiece of the research is the development of a novel, quasi-error-free approach to combine the four geodetic observation techniques GNSS, SLR, VLBI and DORIS, which are co-located at the Geodetic Observatory Wettzell (GOW), Germany. The approach is based on the use of a common clock (CC) and a common target (CT), making time a central geodetic observable. In the first phase of

Figure 2: *Geodetic Observatory Wettzell (Image: Hessels, BKG)*

the RU, a CC/CT environment is currently being set up, tested and analyzed at the GOW. Later, time transfer between observatories via the laser-based time transfer system ACES (Atomic Clock Ensemble in Space) on board the ISS will also be utilized. The strategies developed will be of fundamental importance for the implementation of the UN resolution on the GGRF (https://www.unggrf.org/). DGFI-TUM is involved in the interdisciplinary RU with two projects (P7 and P9), see Section 1.4.

- **New IRIS data set released (title page)**: A new version of IRIS (ICESat-2 River Surface Slope) has been released in 2023. The data set provides global reach-scale water surface slope (WSS) for all important rivers and can be used to determine discharge from space. It includes about 50% more WSS observations compared to the previous version and improves the accuracy of average WSS values. Moreover, it facilitates the study of temporal changes in WSS. More information can be found in the article *ICESat-2 river surface slope (IRIS): A global reach-scale water surface slope dataset* (Nature Scientific Data, 2023, doi:10.1038/s41597-023-02215-x) and in Section 2.3.

- **First results from the SWOT mission**: The first data from the radar interferometer KaRin of the SWOT (Surface Water and Ocean Topography) mission launched in December 2022 were be analyzed at DGFI-TUM as part of the SWOT Science Team. Test data sets were integrated in DGFI-TUM's Open Altimeter Data Base (OpenADB, see 2.1) and analyzed for their usability in inland applications and in ocean tide modeling. Although the data have not yet been fully calibrated and officially released, these evaluations already showed the high potential of SWOT's new measurement technology (see Section 2.3).



- **Innovative Vertical Land Motion (VLM) reconstruction**: DGFI-TUM has developed a probabilistic global VLM reconstruction for 1995 to 2020 to determine the impact of regional and non-linear VLM on relative sea level projections up to the year 2150. The study shows that the regional differences in projected coastal sea level changes are equally influenced by VLM and climate-related processes, with VLM causing relative sea level changes of up to 50 cm by 2150. The consideration of non-linear VLM increases the uncertainty of the projections by up to 1 m on a regional scale. This emphasizes the uncertainty of future coastal impacts and the importance of including non-linear VLM in sea level projections. Details can be found in the article *Regional variations in relative sea level changes influenced by nonlinear vertical land motion* (Nature Geoscience, 2024, doi:10.1038/s41561-023-01357-2).

- **Accuracy estimation of VTEC predictions with ML techniques**: Machine learning (ML) methods are increasingly applied in space weather research due to their ability to recognize complex non-linear relationships. When estimating the Vertical Total Electron Content (VTEC) of the Earth's ionosphere, e.g. during strong space weather events, ML techniques prove to be much more suitable than conventional linear approaches. However, accuracy estimation is usually omitted. For the first time, approaches for estimating the accuracy of ML-based VTEC forecast values in the form of confidence intervals were developed and analyzed. Details of the study *Uncertainty quantification for Machine Learning-based ionosphere and space weather forecasting: Ensemble, Bayesian Neural Network, and Quantile Gradient Boosting* (Space Weather, 2023, doi:10.1029/2023SW003483) are presented in Section 3.1.

1 Research Area Reference Systems

Geodetic reference systems form the backbone for the coordinate-based determination of positions on Earth and in space. Highly accurate realizations of these systems, the so-called reference frames, enable the consistent referencing of geospatial data worldwide. They play an elementary role in modern society as they are foundational for numerous everyday applications, such as positioning and navigation or the measurement of time. Furthermore, they enable the reliable quantification of smallest changes to our planet caused by geodynamic processes or climate change.

Since decades, theoretical and methodological aspects of reference systems and their realizations have been a central topic of DGFI-TUM. Research in this field is based on the geodetic space observation techniques Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). The scientific focus is on the development of refined analysis strategies and models for these observation techniques, as well as on the advancement of combination methods. Key scientific outputs of DGFI-TUM include global and regional realizations of three-dimensional geodetic reference systems obtained from combining the different space techniques. Further research topics are the determination of precise satellite orbits, the realization of vertical reference systems as well as the consistent realization of terrestrial and celestial reference systems including Earth Orientation Parameters (EOP).

An important prerequisite for the research on reference systems is the long-standing involvement of DGFI-TUM in international science organizations, especially in the International Association of Geodesy (IAG) and the International Astronomical Union (IAU). DGFI-TUM operates, mostly on the basis of long-term commitments, Operation and Data Centers, Analysis Centers and Combination Centers (Table 1.1).

Table 1.1: *Long-term commitments of DGFI-TUM in international organizations related to the Research Area Reference Systems.*

Organization	**DGFI-TUM Commitments**
International Earth Rotation and Reference Systems Service (IERS)	International Terrestrial Reference System (ITRS) Combination Center (CC)
International VLBI Service for Geodesy and Astrometry (IVS)	Analysis Center (AC), Combination Center (jointly with BKG)
International Laser Ranging Service (ILRS)	Global Data and Operations Center (EDC), Analysis Center (AC)
International GNSS Service (IGS)	Regional Network Associate Analysis Center for SIRGAS (RNAAC-SIR)
International DORIS Service (IDS)	Associate Analysis Center (AAC)

DOGS: DGFI Orbit and Geodetic parameter estimation Software

The DGFI Orbit and Geodetic parameter estimation Software (DOGS) provides the basis for all investigations in this research area and serves as the backbone of DGFI-TUM's international contributions. DOGS comprises three branches:

- **DOGS-OC**: Orbit Computation software for the analysis of SLR and DORIS data,
- **DOGS-RI**: Radio Interferometry software for the analysis of VLBI data, and
- **DOGS-CS**: Combination and Solution library to handle, combine, and solve normal equation systems from internal and external sources.

The DOGS software has been developed by DGFI-TUM for several decades and undergoes permanent enhancement and updating for conformity with latest findings, standards and conventions. The individual branches as well as combinations of them (cf. Fig. 1.1) are used for various research projects and the institute's contributions to the IAG Scientific Services listed in Tab. 1.1.

In DOGS-OC, significant progress was made in 2023 in the development of DORIS processing in order to enable the analysis of further DORIS-equipped satellites with high accuracy. Moreover, the implementation of a novel ICGEM-format-based approach for the gravitational effect of ocean tides now allows flexible application of models and tidal admittance methods for the benefit of SLR and DORIS Precise Orbit Determination (POD). DOGS-RI has been prepared for an automatic processing of VLBI Intensive Sessions, which will be operationally applied in 2024. DOGS-CS and DGFI-TUM's auxiliary software, such as pre- and post-processing routines, also underwent developments to be compatible with most-recent standard formats for the exchange of space geodetic data, TRF (Terrestrial Reference Frame) and EOP solutions, and to enhance the integrity of the internal bookkeeping of metadata.

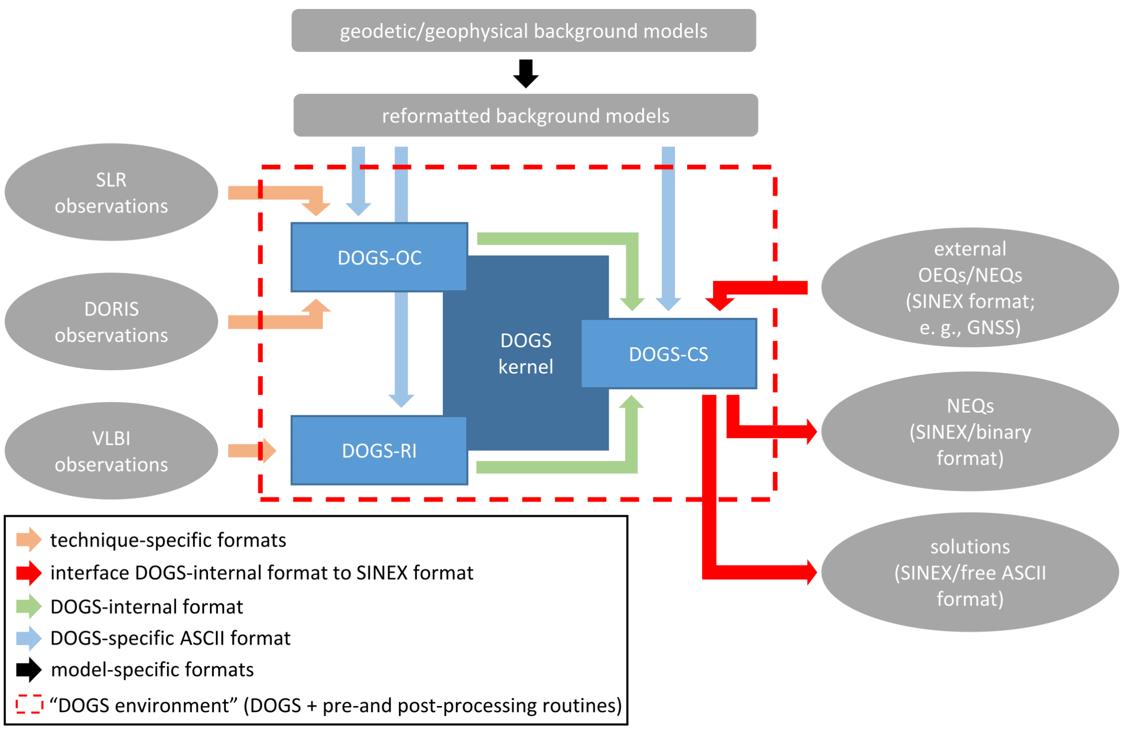


Figure 1.1: *Data flow within the branches of DOGS and its environment (OEQs: Observation equations; NEQs: Normal equations).*

DOGS-OC developments

- Development of satellite-specific attitude control functions,
- Enhancement of DORIS processing,
- Implementation of a new method to represent of the gravitational effects of ocean and atmospheric tides by separate models based on the ICGEM format,

- Implementation of elevation-dependent weighting of DORIS measurements,
- Extension of the analysis capability to further non-spherical satellites like Sentinel-6A,
- Enabling the estimation of more than two biases per observation technique,
- Implementation of most-recent non-tidal loading correction models for gravity field and station coordinates,
- Implementation of the COST-G[1] deterministic and CNES_GRGS.RL05MF_combined_GRACE_SLR_DORIS[2] Earth's time-variable gravity field models.

DOGS-RI developments

- Implementation of Baseline Clock Offsets, as fixed or estimated parameters,
- Export of pseudo-observations as separate data group within the DOGS binary format,
- Computation of baseline weights to potentially replace V004 data,
- Enhancement of the software to exclude individual stations with gravitational deformation from datum constraints.

DOGS-CS and auxiliary software developments

- Development of interfaces for the three DOGS branches to apply station coordinates and EOP from different sources for the analysis of geodetic space observations,
- Optimization of the SINEX interfaces,
- Development of the interface to import DORIS observations in Receiver Independent Exchange (RINEX) format,
- Optimization of internal parameter and metadata handling.

1.1 Analysis of Space-Based Microwave Observations

VLBI data analysis

Since 2008, DGFI-TUM acts as an operational Analysis Center (AC) of the International VLBI Service for Geodesy and Astrometry (IVS). The primary task of the IVS AC is to provide datum-free normal equations (NEQs) for the so-called rapid turnaround VLBI sessions (Glomsda et al., 2023a). These NEQs are combined at the IVS Combination Center (CC), jointly operated by DGFI-TUM and the Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie, BKG), and solved for EOP and VLBI station coordinates.

In 2023, we finalized our investigations on the reduction of non-tidal loading (NTL) in the analysis of VLBI observations, in particular with respect to VLBI-only secular terrestrial reference frames (Glomsda et al., 2023b). It was shown that the consideration of NTL signals improves the stability of positions of stations with short observation periods.

Furthermore, the IVS AC reprocessed all VLBI observations using ITRF2020 for the a priori antenna positions, as well as additional gravitational deformation models for particular antennas. Glomsda et al. (2023c) analyzed the corresponding new set of NEQs (dgf2023a), and investigated their impact on the estimated geodetic parameters. To validate the new ITRS realizations, also the scale parameter that describes the change in size between two station networks in a similarity transformation was analyzed. This resulted in the detection of a significant difference

[1] Peter H., et al. (2022): *COST-G gravity field models for precise orbit determination of Low Earth Orbiting Satellites*. Advances in Space Research, doi:10.1016/j.asr.2022.04.005.

[2] Lemoine J.-M., et al. (2023): *New mean gravity field model CNES_GRGS.RL05MF_combined_GRACE_SLR_DORIS*. IDS AWG Meeting

between the VLBI scale parameters obtained in transformations with respect to the three existing ITRS 2020 realizations (i.e., ITRF2020, JTRF2020, and DTRF2020, see Fig. 1.2). The moving medians (red lines) show that the VLBI scale is drifting upwards from 2013 in relation to ITRF2020 and JTRF2020, but not in relation to DTRF2020, the ITRS realisation of DGFI-TUM (see Section 1.4). The IVS AC of DGFI-TUM is participating in a corresponding IVS working group, which has the task of investigating this further.

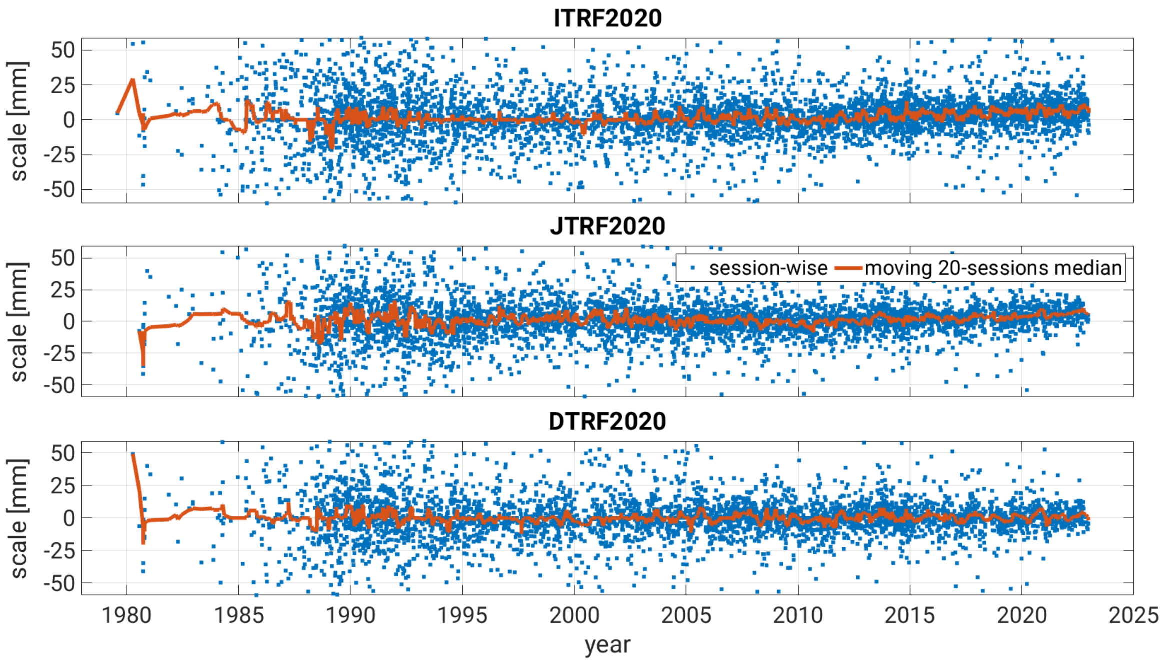


Figure 1.2: *Scale parameters (blue dots) and moving medians (red lines) of similarity transformations between VLBI single session solutions and ITRF2020 (top), JTRF2020 (middle), and DTRF2020 (bottom).*

The ITRS 2020 realisations will be extended to include observation data between 2021 and 2023. In terms of VLBI, this means that more session types than the rapid turnarounds will be analyzed, and therefore the IVS AC at DGFI-TUM will process all remaining sessions that were not yet included in dgf2023a.

Finally, an automated analysis of the so-called intensive sessions, which last 1 hour and are scheduled for daily DUT1 determination, has been implemented. The quality assessment of the corresponding results is an important task for 2024. Another important research question is still the comparison and combination of legacy and the new-generation VGOS (VLBI Global Observing System) observations.

VLBI combination

DGFI-TUM and BKG jointly operate the IVS CC, which is responsible for the operational combination of all VLBI sessions provided by the IVS ACs. In addition to station coordinates and EOP, also radio source coordinates are now considered in the combination. Further current efforts relate to the consistent estimation of celestial and terrestrial reference frames. Our contributions primarily comprised theoretical developments on the combination strategy and the implementation of software adaptations in DOGS-CS.

DORIS data analysis

DGFI-TUM has been an Associate Analysis Center (AAC) of the International DORIS Service (IDS) since 2019. A major component in DGFI-TUM's contribution to the IDS is the precise orbit determination (POD) of Earth observation satellites (Rudenko et al., 2023a).

In 2023, several modifications in DGFI-TUM's POD processing were implemented to further improve the quality of DORIS orbits. In particular, it is now possible to estimate more than two bias types per station during data processing. Next to the range and time biases also used in SLR processing (see below), analysing DORIS observations on specific satellites requires additional bias types to compensate for frequency drifts and offsets at each ground beacon. The beacon network maintained by the IDS currently consists of about 60 sites. They track nine satellites with DORIS receivers onboard.

The DORIS microwave signal is influenced on its path through the atmosphere. To take this effect into account as effectively as possible in the orbit modelling, an elevation-dependent weighting of the observations was implemented. In addition to the observations provided by the IDS in IDS2.2 format, observations of some contemporary satellites are given in the so-called RINEX/DORIS format. This format was implemented for processing DORIS data in DOGS-OC, so that the POD of several satellites, e.g. Jason-3, is now possible up to the present day.

The innovations mentioned above lead to improved orbit quality. Figure 1.3 shows the arc-wise RMS of the DORIS residuals for Jason-3 before and after the modifications made in 2023. The average RMS decreases from 0.67 to 0.46 mm/s, indicating a better agreement of the observations with the newly modelled orbit. A previously conspicuous seasonal signal is resolved and the scatter of the values is reduced.

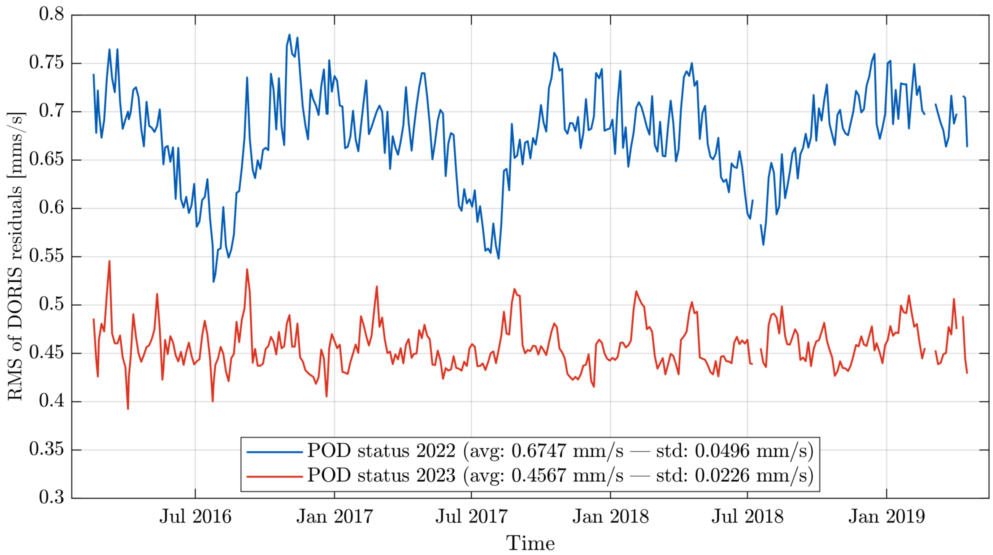


Figure 1.3: *Arc-wise RMS of DORIS observation residuals for Jason-3 before and after the implementations made in 2023.*

GNSS data analysis

DGFI-TUM's research in GNSS data analysis focuses on improving strategies for datum realization and observation combination in regional GNSS networks, modeling surface kinematics to assess deformation or seismic effects on station positions, and determining accurate time series to measure non-linear station motions.

Most developments are based on the analysis of the GNSS SIRGAS (Sistema de Referencia Geodésico para las Américas) network in Latin America (Sánchez, 2023). This is one of the most active seismic regions in the world and also exhibits strong seasonal signals related to non-tidal loading in the Amazon region. In this context, DGFI-TUM not only evaluates weekly network solutions and calculates cumulative solutions and deformation models for the whole continent, but also supports the Latin American analysis centers by transferring knowledge on appropriate GNSS data analysis (Costa et al., 2023). DGFI-TUM results are further applied as input data for various research tasks. As an example, Fig. 1.4 shows a time series of deformation models for the Andean region between 1995 and 2022. The analysis strategies, research results and data products generated by DGFI-TUM on this topic are available at www.sirgas.org and ftp.sirgas.org.

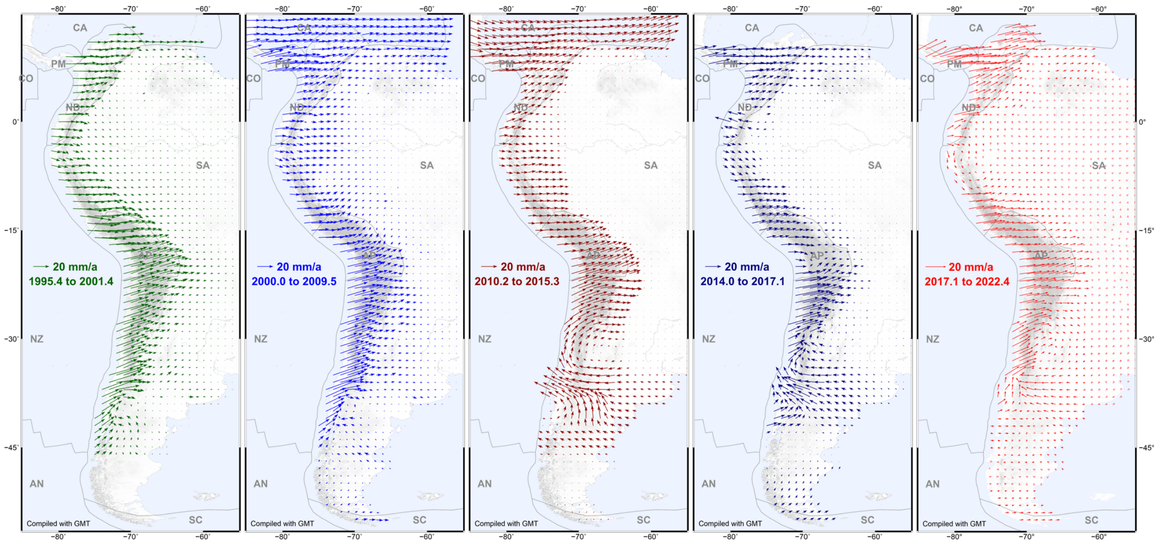


Figure 1.4: *Time series of deformation models for South America between 1995 and 2022.*

1.2 Analysis of Satellite Laser Ranging Observations

SLR data analysis

Within the International Laser Ranging Service (ILRS), DGFI-TUM has been involved as an ILRS Analysis Center (AC) for many years. Several official ILRS data products were calculated operationally on a daily or weekly basis in 2023 (Tab. 1.2). Following the release of model updates like a new realization of the SLR-specific reference frame SLRF2020[3], the new SLRF2020 Data Handling File (DHF)[4], an updated target signature model[5] and a new version of the reference EOP (20 C04)[6], the ILRS Analysis Standing Committee (ASC) decided to switch to new operational data products at the end of 2023. Therefore, the DGFI-TUM ILRS AC calculated all operational data products based on the updated models in parallel to the official ones. DGFI-TUM also participated in the v85 ILRS reprocessing campaign, which involved calculating v80-like loose-constrained solutions (see Tab. 1.2) from 1993 to the end of 2023. The last three years are included in the ILRS combined solution as the contribution to the update of the ITRS 2020 realisations scheduled for 2024.

[3] SLRF2020 product, Greenbelt, USA: NASA CDDIS, doi:10.5067/SLR/slrf2020_001

[4] Data Handling File for SLRF2020, Greenbelt, USA: NASA CDDIS, doi:10.5067/SLR/slrf_2020_DHF_001

[5] Rodríguez J., et al. (2019): *Upgraded modelling for the determination of centre of mass corrections of geodetic SLR satellites: impact on the terrestrial reference frame.* J. Geod., doi:10.1007/s00190-019-01315-0

[6] https://hpiers.obspm.fr/iers/eop/eopc04/

Table 1.2: *Routine and project-specific solutions computed by the ILRS AC of DGFI-TUM during 2023.*

ILRS code	description	file format
v170/v180	daily LA-1/-2, ET-1/-2 TRF and EOP solutions	SINEX
v70/v80	weekly LA-1/-2, ET-1/-2 TRF and EOP solutions	SINEX
v70-sp3c/v80-sp3c	weekly LA-1/-2, ET-1/-2 (reduced dynamic) orbit solutions	SP3C
—	daily orbit predictions for LA-1/-2, ET-1/-2	CPF(v2)
v230/v280	weekly LA-1/-2, ET-1/-2 TRF and EOP solutions (incl. biases)	SINEX
v320	weekly LA-1/-2, ET-1/-2, LR-2 TRF and EOP solutions (incl. biases)	SINEX
v85	reprocessing of v80 solutions from 1993 onwards	SINEX

A special focus was put on the computation of the new v320 solutions including observations to LARES-2 (LR-2), in addition to Lageos 1 and 2 (LA-1/2) and Etalon 1 and 2 (ET-1/-2). The number of observations and the relative weights λ of the satellite-specific normal equations (NEQs) of LR-2 are comparable to LA-1/-2 within the DGFI-TUM combination (cf. Fig. 1.5). The v320 solutions will serve as input for a refined version of the ILRS DHF including long-term mean range biases for LR-2. In a second step, this refined DHF shall be used to include LR-2 as the 5th satellite into the operational ILRS ASC data products.

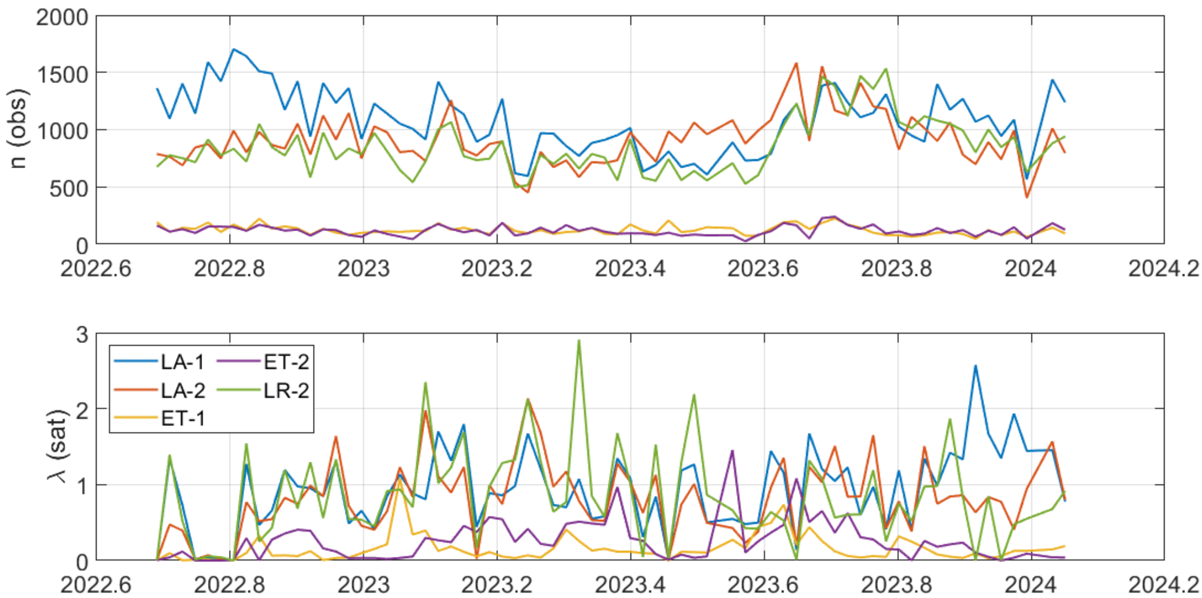


Figure 1.5: *Upper panel: number of observations to LA-1/-2 and ET-1/-2 used within the operational ILRS data products and the number of observations to LR-2. Lower panel: relative NEQ weights applied within the operational processing.*

DGFI-TUM has also operationally computed ten-satellite solutions used for various geodetic applications such as the estimation of the spherical harmonics of the Earth's gravity field model from degree zero (equivalent to the geocentric gravitational constant GM), degree one (related to the Earth system center of mass) and degree two (mainly related to the Earth's flattening).

SLR data management

DGFI-TUM has operated the EUROLAS Data Center (EDC) since the founding of the ILRS in 1998. The EDC is one of two ILRS Data Centers worldwide (the other is the Crustal Dynamics Data Information System, CDDIS[7], operated by NASA). The EDC, as an ILRS Operation Center (OC) and as an ILRS Data Center (DC), has the task to ensure the quality of the submitted SLR data. There is a daily and hourly data exchange with the NASA OC and CDDIS. All data and science products are publicly available to the ILRS community via FTP (ftp://edc.dgfi.tum.de) and the dedicated website https://edc.dgfi.tum.de; see Section 4.6.

The EDC maintains several mailing lists for the exchange of information, data and results. In 2023, 74,841 Consolidated Prediction Format (CPFv2) files from 129 satellites were made available to SLR stations. In addition, the EDC distributed SLR-Mails (47 messages), SLR-Reports (768), and SLR-Urgent-Service-Mails (91). 202,174 pass segments of normal points (NPTv2) were submitted in 2023 by 39 SLR stations observing 113 different satellites. There were 23 new satellite missions tracked by SLR stations, namely 19 BeiDou satellites, Compass-G8, Glonass-144, Glonass-147, and IRNSS-1J.

1.3 Determination of Satellite Orbits

Precise orbit determination (POD) for altimetry satellites

Precise orbits of altimetry satellites are a prerequisite for investigating sea level changes with mm-accuracy from the distance measurement between altimeter and sea surface. Orbits are usually determined from SLR, DORIS and GNSS observations. The process of the POD requires precise models of the forces acting on the satellites, reliable information on their orientation, highly accurate reference frames and correction models for station positions and observation data.

In 2023, DGFI-TUM worked on further improvements of POD for altimetry satellites and calculated for the first time precise orbits of the four altimetry satellites TOPEX/Poseidon and Jason-1/-2/-3 based on SLR observations over 1992-2021 (Rudenko et al., 2023c). As part of the **DFG project MEPODAS** (Mitigation of the current errors in precise orbit determination of altimetry satellites), Rudenko et al. (2023b) reviewed the most important aspects in the models used for the POD of altimetry satellites over the last 30 years and provided estimates of about 1 cm orbital accuracy in the radial direction of the orbits. Moreover, Zeitlhöfler et al. (2023) developed station-specific SLR measurement corrections for TOPEX/Poseidon accounting for significant variations in the optical phase center of the satellite retroreflector array. Additionally, Alkahal (2023) investigated the impact of new models of the thermospheric density (NRLMSIS 2.0)[8] and of the Earth's gravity field[9] on the POD of altimetry satellites.

Furthermore, the ITRS 2020 realisations were implemented to derive a priori positions and velocities of tracking stations. A correct use of these realisations requires the application of the long-term mean range biases (RBs) of the SLR stations according to the recommendations of the ILRS DHF for SLRF2020. This reduced the mean RMS value of the SLR observation residuals from 2.39 to 1.96 cm (Fig. 1.6)[10].

[7] https://cddis.nasa.gov/

[8] Emmert J., et al. (2021): *NRLMSIS 2.0: A Whole-Atmosphere Empirical Model of Temperature and Neutral Species Densities*. Earth and Space Sci., doi:10.1029/2020EA001321

[9] https://grace.obs-mip.fr/variable-models-grace-lageos/mean-fields/release-05/

[10] Rudenko S., Bloßfeld M., Kehm K., Dettmering D., Zeitlhöfler J.: *Impact of SLR long-term mean range biases on ITRF2020-based orbits of altimetry satellites*, submitted

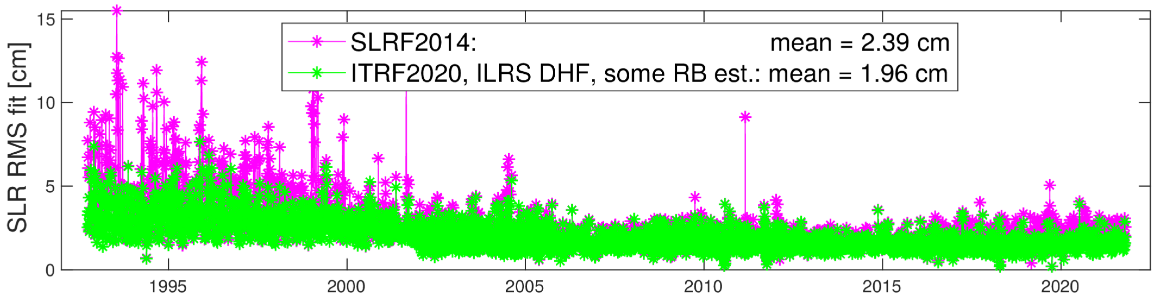


Figure 1.6: *RMS of SLR observation residuals of TOPEX/Poseidon and Jason-1/-2/-3. Solutions were obtained by employing SLRF2014 (magenta) and ITRF2020 together with the ILRS DHF recommended RBs (green).*

Attitude modeling

A major challenge in the POD of non-spherical satellites is determining the correct orientation of the spacecraft (and the solar panels). While for spherical satellites the reflection plane is assumed to be almost constant with respect to the center of mass, the measurements for non-spherical satellites and consequently also the derived orbit positions are influenced by the attitude of the satellite (Fig 1.7). The orientation of the spacecraft also affects the influence of non-conservative forces, e.g. atmospheric drag, the Earth's albedo and infrared and solar radiation, as these forces act on the satellite surface and depend on the cross-sectional area with which they interact.

DGFI-TUM's POD software DOGS-OC is able to model the attitude of the spacecraft on the basis of two methods. On the one hand, the orientation can be realized by applying a nominal attitude model. The model describes the theoretical behaviour of the spacecraft body and the solar panels and is based on the orbit angle and the position of the satellite in relation to the Sun. Depending on these parameters, the Jason satellites are in what is known as fixed or sinusoidal mode. In fixed mode, the satellite flies forwards or backwards and rotates sinusoidally around the yaw axis (which is orientated perpendicular to the surface of the reference ellipsoid, i.e. geodetic pointing). On the other hand, attitude quaternions can be used. These orientation observations are derived from star tracker cameras and represent the attitude of the satellite body and the solar panels more precisely.

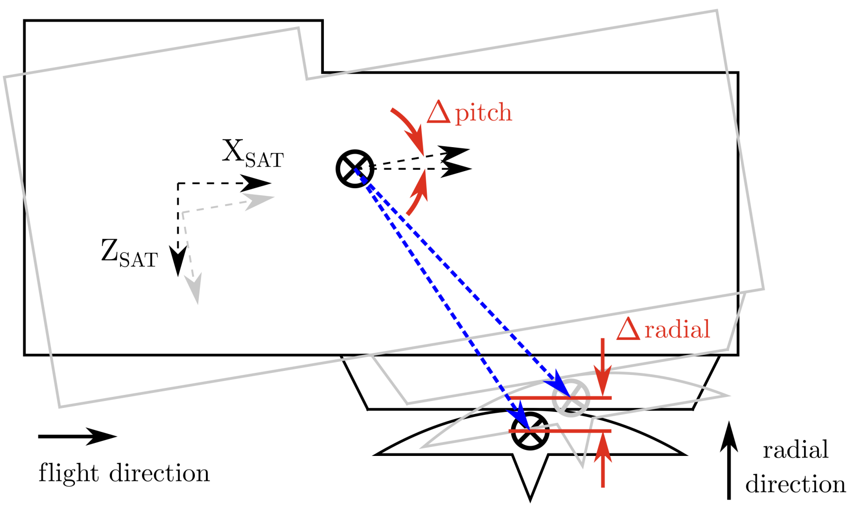


Figure 1.7: *A change in the pitch angle of an altimeter satellite results in a change of the altimeter phase center in radial direction and can cause an erroneous estimate of the sea surface height.*

In 2023, the quality of the nominal attitude model for the TOPEX/Poseidon altimetry mission, operative between 1992 and 2005, was investigated by comparing the realized attitude with an attitude based on quaternions. Nowadays, attitude quaternions are continuously available for altimetry missions. For TOPEX/Poseidon, however, the orientation data were not provided regularly, but only in short intervals. The analysis of these intervals generally shows a good agreement between the nominal model and the quaternion data using SLR-only (applying the SLR measurement correction function; Zeitlhöfler et al., 2023) and DORIS-only orbits, but also reveals some smaller systematic differences between both methods. The extent of these differences and possible impacts on derived geodetic parameters were analyzed in a dedicated study[11].

1.4 Determination of Reference Frames

ITRS Combination Center at DGFI-TUM: Calculation of DTRF2020

In 2023, the ITRS Combination Center (CC) at DGFI-TUM focused on the finalization of the ITRS 2020 realization DTRF2020 (Seitz et al., 2023). After the input data of VLBI, SLR, GNSS and DORIS were finally combined, the release of DTRF2020 was provided in early 2023 to the IERS Directing Board and the related IAG Scientific Services.

The main innovations of DTRF2020 compared to our previous version DTRF2014[12] are:

- Six additional years of observation data,
- Several new stations and satellites, technical improvements at various stations,
- Technique-specific input data series calculated according to the latest general and technique-specific models,
- GNSS provides for the first time an independent scale realization, made possible by the disclosure of the Galileo satellite calibrations,
- DTRF2020 scale is realized for the first time from VLBI and GNSS observations,
- DTRF2020 considers for the first time all three components of non-tidal loading (NTL): atmospheric, hydrological and oceanic NTL, consistently derived from the IERS Global Geophysical Fluid Center (GGFC; http://loading.u-strasbg.fr/GGFC/). NTL data cover the full observation time span of the geodetic space techniques (1979.0 - 2021.0),
- Post-seismic deformation of stations affected by earthquakes are modeled and considered in DTRF for the first time.

The DTRF2020 release comprises technique-specific SINEX files, containing station coordinates at the reference epoch 2010.0 and corresponding velocities, an EOP file, NTL correction time series and offsets/trends of the NTL models (referred to the Earth's center of mass and center of figure), station residual as well as SLR translation time series. DTRF2020 is available via Zenodo (Seitz et al., 2023). The new DTRF website https://dtrf.dgfi.tum.de/en/dtrf2020/ provides detailed information about the DTRF2020 combination strategy, released files and DTRF2020 application, and it provides important links and references.

[11] Zeitlhöfler J., Bloßfeld M., Lemoine F., Seitz F. (2024): *Quality assessment of the nominal attitude model of TOPEX/Poseidon using quaternion data*. Advances in Space Research, doi:10.1016/j.asr.2024.03.031

[12] Seitz M., Bloßfeld M., Angermann D., Seitz F. (2022): *DTRF2014: DGFI-TUM's ITRS realization 2014*. Advances in Space Research, doi:10.1016/j.asr.2021.12.037

An important innovation is the use of consistent NTL models for all three loading components atmosphere, hydrosphere and ocean. Figure 1.8 shows the improvement of the RMS of GNSS station height residuals when NTL is reduced from the observations. A general improvement and clear regional patterns correlating with the NTL signal can be observed. Figure 1.9 shows the impact of NTL corrections on the amplitudes of annual and semi-annual signals in GNSS height series. Most stations show a clear reduction of the annual signal. The same holds for the annual signal in the datum parameters (translation and scale).

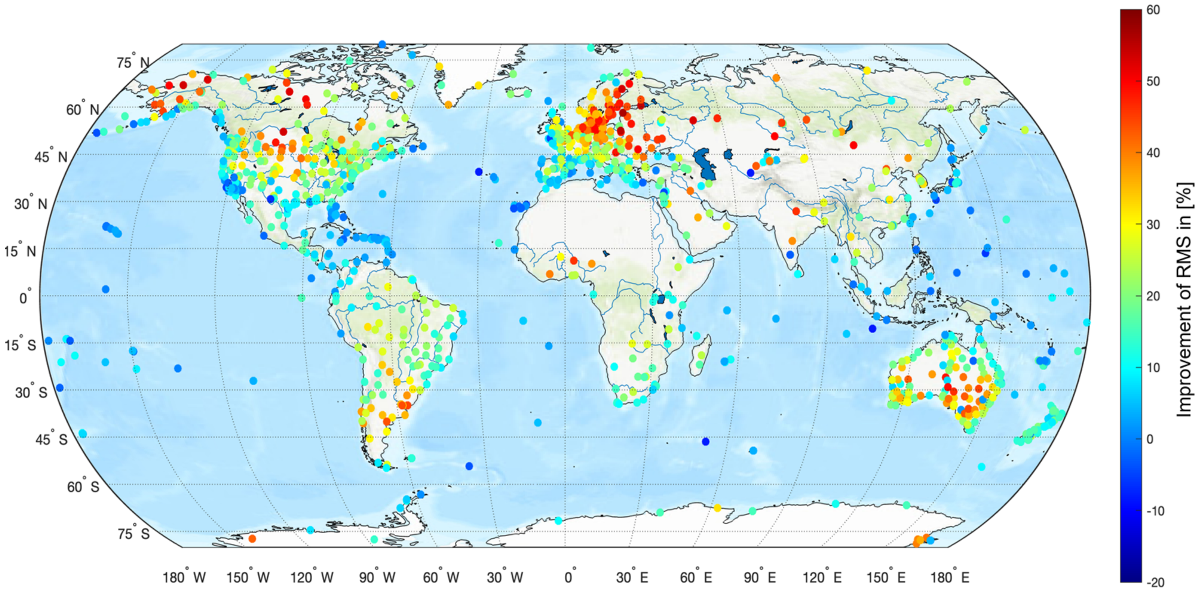


Figure 1.8: *Improvement of RMS of GNSS station height residual time series when NTL is reduced from observations at NEQ level.*

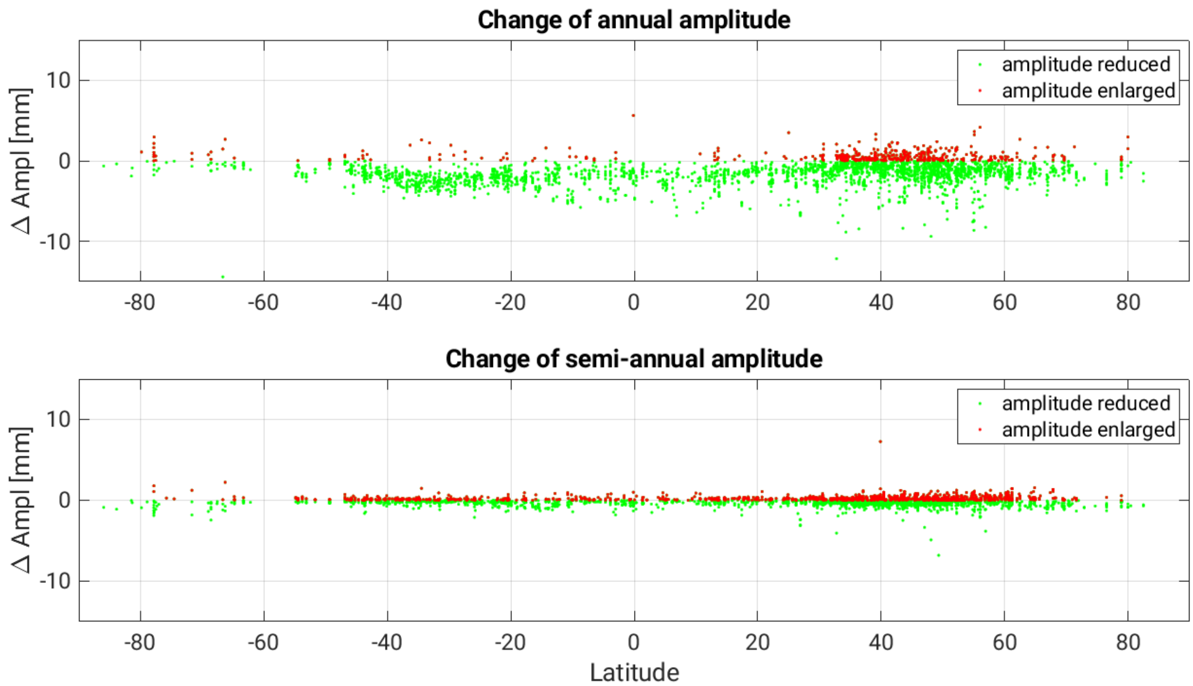


Figure 1.9: *Change in amplitude of annual and semi-annual signals of GNSS station height residual time series when NTL is reduced from observations at NEQ level. Amplitude changes are plotted against the station latitude. The mean amplitude changes are -1.33 mm for the annual and -0.14 mm for the semi-annual signal.*

International Height Reference Frame (IHRF)

Since the introduction of the International Height Reference System (IHRS) by IAG in 2015, its realization has been a main objective in Geodesy. The IHRS is a geopotential-based reference system co-rotating with the Earth. Its realization is the International Height Reference Frame (IHRF): a global reference network with precise geopotential numbers referring to the IHRS. The primary coordinates are geopotential numbers $C = W_0 - W$ referring to the potential value $W_0 = 62{,}636{,}853.4$ m^2/s^2. The spatial location of the stations at which the geopotential numbers are calculated is defined by the coordinates (X, Y, Z) in the ITRF. In a geopotential-based height system, the vertical datum is realized by a geoid or quasi-geoid model. Thus, the accuracy of the geopotential numbers undergoes the same limitations of the precise geoid modeling. In regions with advanced geodetic infrastructure, it has been demonstrated that physical heights derived from GNSS and an accurate geoid or quasi-geoid model can achieve accuracies of 2 to 10 cm. In regions with less developed geodetic infrastructure, uncertainties can reach up to 40 cm, with extreme cases of about 1 m in areas with strong topographic gradients. The main accuracy restriction in these regions is the low availability or quality of surface, i.e., terrestrial, airborne, or shipborne gravity data. Given the economic constraints in some regions and the impossibility of systematically carrying out gravimetry to improve the coverage and distribution of gravity data, one of the current challenges is to recover as many existing gravity surveys as possible using modern mathematical methods that allow the evaluation and refinement of gravity data acquired long ago or lacking standard procedures and metadata.

Efforts have been made at DGFI-TUM within the **DFG project Geo-H** (Enhanced geopotential field modeling as basis for the establishment of precise height systems) to evaluate the feasibility of a precise realization of the IHRS in data-challenging regions. In a case study of Colombia, we develop novel approaches to validate and improve the quality of old gravity datasets and to generate a quasi-geoid model with the highest possible accuracy. As the only South American country with coastlines on both oceans, the Pacific and the Atlantic Ocean, Colombia features strong topographic gradients with elevations reaching more than 5,000 m above mean sea level, and a large area of about 40% covered by the Amazon rainforest. The available terrestrial gravity observations were collected between 1941 to 2000 from 101 gravity surveys; the airborne data consist of 17 flight campaigns, which have already been post-processed separately with the corresponding metadata missing. As the earliest terrestrial surveys date back to the time before GNSS, positions of these observations were frequently read from maps. Thus, systematic errors and mistakes are probably included in the records. To identify and remove these errors, we developed a novel approach based on spherical radial basis functions (SRBFs). More details are provided in Section 3.2.

After data cleaning, we computed a quasi-geoid model applying the SRBFs. The terrestrial and airborne data are combined with a global gravity model (GGM) and topography effects are removed following the remove-compute-restore (RCR) procedure. In the offshore area, satellite altimetry-derived gravity data are additionally incorporated, which are obtained from the latest release of the DTU (Technical University of Denmark) gravity anomaly grid, DTU21GRA. The resulting high-resolution quasi-geoid model, denoted as QGeoidCOL2023, is evaluated using the GNSS/leveling data both in the absolute and relative manner. As a reference, the latest South American quasi-geoid model QGEOID2021 as well as five recent high-resolution GGMs are also validated using the same GNSS/leveling data. Each GGM is truncated at degree 2159, and the topography model ERTM2160 is added to count for the very high frequency parts. Table 1.3 lists the statistics of the comparison between these quasi-geoid models and the GNSS/leveling data. Note that a correction surface has been applied to account for the systematic effects between the gravimetric and GNSS/leveling-based height anomaly, which are caused by datum inconsistencies, systematic distortions, and geodynamic effects. QGeoidCOL2023 is the best performing quasi-geoid model, showing the smallest standard deviations (STD) relative to the GNSS/leveling data, which is 27% smaller compared to the mean STD given by the five high-resolution GGMs and 36% smaller than the one delivered by QGEOID2021. The relative validation results (Liu et al., 2024[13]) is visualized in Fig. 1.10. Our model QGeoidCOL2023 shows lower RMS errors than the GGMs and QGEOID2021 in all the baseline length groups. These results indicate the validity and benefits of the developed methods and data processing procedures, which can be used for other data-challenging areas to facilitate the realization of the IHRS or any geopotential-based height system.

Table 1.3: *Comparison between different quasi-geoid models and the GNSS/leveling data in Colombia ([cm]).*

	Min	Max	Mean	STD
QGeoidCOL2023	-76.06	65.21	0.00	15.76
QGEOID2021	-85.37	72.93	0.00	24.51
EGM2008	-80.73	83.85	0.00	28.09
EIGEN6C4	-93.29	66.80	0.00	21.10
GECO	-110.82	60.37	0.00	20.39
SGG-UGM-1	-71.03	68.28	0.00	20.93
XGM2019	-75.93	80.06	0.00	17.86

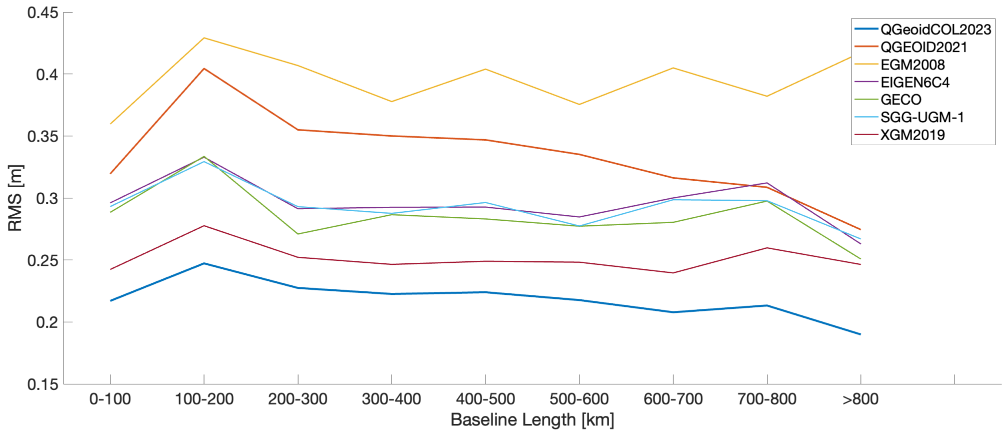


Figure 1.10: *Relative validation in terms of RMS error between the quasi-geoid models and the GNSS/leveling data depending on the baseline length.*

GGOS Focus Area 'Unified Height System' and Coordination Center for the IHRF

DGFI-TUM took over the leadership of the GGOS Focus Area 'Unified Height System' (GGOS-FA-UHS) in July 2015. The GGOS-FA-UHS was established in 2010 to lead and coordinate the efforts needed to establish a global standard for the precise determination of physical heights. During the IAG term 2011-2015, DGFI-TUM participated in various discussions focused on the best possible definition of a global unified vertical reference system. This resulted in the IAG Resolution for the Definition and Realization of an IHRS, approved at the IUGG2015 General Assembly in Prague, Czech Republic. DGFI-TUM estimated the potential value W_0 adopted as

[13] Liu Q., Schmidt M., Sánchez L., et al. (2024): *High-resolution regional gravity field modeling in data-challenging regions for the realization of geopotential-based height systems.* Earth, Planets and Space, doi: 10.1186/s40623-024-01981-1

the reference level for the IHRS[14], and co-authored the publication providing the scientific support for the IAG2015 Resolution on the IHRS[15]. During 2015-2019, activities were undertaken to investigate the best strategy for the implementation of the IHRS, i.e. the establishment of the IHRF. DGFI-TUM proposed a preliminary selection of stations for the IHRF reference network and promoted the evaluation of different calculation methods for the determination of potential values as IHRF coordinates[16]. The results, including a DGFI-TUM computation method[17], are compiled in the special issue *Reference Systems in Physical Geodesy* of the Journal of Geodesy (Sánchez et al., 2023).

For the term 2019-2023, the objectives of the GGOS-FA-UHS focused on (i) compiling detailed standards, conventions and guidelines to support a consistent determination of the IHRF at global, regional and national levels; (ii) coordinating with regional/national experts in gravity field modeling the computation of a first IHRF solution; and (iii) designing an operational infrastructure that will ensure the long-term sustainability and reliability of the IHRF. Outcomes are outlined in a detailed roadmap for the determination and maintenance of the IHRF[18]. With these objectives achieved, the GGOS-FA-UHS completed its goals and was closed during the IUGG2023 General Assembly in Berlin, Germany.

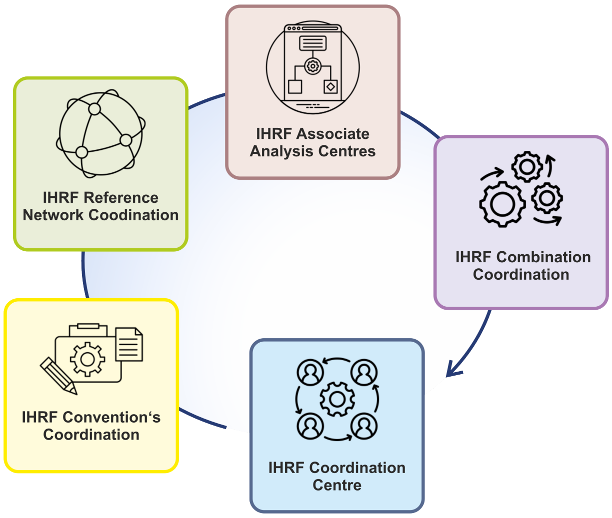


Figure 1.11: *Data flow between the IHRF Coordination Center and its components.*

The focus is now on the operational infrastructure required to ensure the maintenance and availability of the IHRS/IHRF in the future. In line with IAG practice, the development of theory and methods for the continuous improvement of the IHRS/IHRF will be continued by the IAG Commissions and the Inter-Commission Committee on Theory, while the operational performance will be ensured by the IAG Scientific Services, in this particular case the International Gravity Field Service (IGFS). With this in mind, and based on the recommendations of DGFI-TUM, the Central Bureau of the IGFS developed a proposal for the establishment of a central coordinating body for the IHRF, composed of individual modules taking care of the main components of the IHRF. The central management body is the IHRF Coordination Center (IHRF-CC) and its

[14]Sánchez L., et al. (2016): *A conventional value for the geoid reference potential W_0*. J. Geodesy, doi:10.1007/s00190-016-0913-x

[15]Ihde J., Sánchez L., et al. (2017): *Definition and proposed realization of the International Height Reference System (IHRS)*. Surveys in Geophysics, doi:10.1007/s10712-017-9409-3

[16]Wang Y.M., Sánchez L.,..., Schmidt M., et al. (2021): *Colorado geoid computation experiment: overview and summary*. J. Geodesy, doi:10.1007/s00190-021-01567-9,

[17]Liu Q., Schmidt M., Sánchez L., Willberg M. (2020): *Regional gravity field refinement for (quasi-) geoid determination based on spherical radial basis functions in Colorado*. J. Geodesy, doi:10.1007/s00190-020-01431-2

[18]Sánchez L.,..., Liu Q. (2021): *Strategy for the realisation of the International Height Reference System (IHRS)*. J. Geodesy, doi:10.1007/s00190-021-01481-0

modules are the IHRF Reference Network Coordination, the IHRF Conventions' Coordination, the IHRF Associate Analysis Centers and the IHRF Combination Coordination (Fig. 1.11). The IAG Executive Committee unanimously approved the IHRF-CC at its meeting on December 10, 2023. Thus, a new component of the IGFS dedicated to the IHRF has been created and will ensure the long-term availability and reliability of the IHRF. DGFI-TUM will continue supporting the development of the IHRF with research activities dedicated to the improved high-resolution modeling of the Earth's gravity field.

Combination and prediction of Earth Orientation Parameters

Earth orientation parameters (EOP) describe the instantaneous orientation of the Earth with respect to inertial space. The precise determination and prediction of these parameters are a fundamental prerequisite for various applications that rely on the transformation between Earth-fixed and space-fixed reference frames. These applications include navigation on Earth and in space, positioning and surveying, the measurement of time, spacecraft orbit determination, and the analysis of all geodetic space observations.

State-of-the-art EOP predictions suffer from various deficiencies related to heterogeneous processing standards and parametrization of the technique-specific input data. Kehm et al. (2023) describe a processing strategy developed within the framework of the completed **ESA project ESA-EOP** (Independent Generation of Earth Orientation Parameters) led by DGFI-TUM. Jointly with BKG, GFZ and TU Wien, current deficiencies of EOP determination and prediction were identified, and a strategy for consistent final, rapid and predicted EOP was developed. Since 2023, ESA operates a routine EOP prediction service based on these developments[19].

DGFI-TUM was also involved in an initiative led by ETH Zürich with special focus on the potential of machine-learning-based EOP prediction (Kiani Shahvandi et al., 2023). Thereby, various input time series were used for prediction with different tuning of the machine learning algorithm. This study was performed and presented within the framework of the Second EOP Prediction Comparison Campaign (EOP PCC) organized by the IERS.

The new **DFG project PROGRESS** (Pro- and Retrospective highly accurate and consistent Earth Orientation parameters for Geodetic Research within the Earth System Sciences), a joint project of DGFI-TUM, FSG-TUM and GFZ, aims to demonstrate the benefits from fully harmonized processing standards, i.e., parametrization and background models, and a fully consistent combination. Current work focuses on elaborating the processing setup for the space geodetic input data. In a later stage of the project, combination and prediction will be realized in a common model- and filter-based approach. Intercomparison with AI-based results will be performed in co-operation with ETH Zürich.

Clock Metrology: A Novel Approach to TIME in Geodesy

The newly established **DFG Research Unit 5456 Clock Metrology** (A Novel Approach to TIME in Geodesy, https://clockmetrology.de) aims to realize highly accurate long-term stable geodetic reference systems by linking geometric systems to time and to demonstrate a path towards a consistent realization of space-time. Investigations within the RU are linked to the Geodetic Observatory Wettzell (GOW), Germany. GOW represents an ideal test environment for the investigations within the RU as it co-locates all four geodetic space techniques and will be equipped with a common target (CT) and a common clock (CC) in near future. DGFI-TUM is involved in the RU with two projects (P7 and P9) which both started in 2023.

[19] http://navigation-office.esa.int/Earth_Rotation_Parameter_Products.html

Project P7: The application of time in closure as a novel strategy towards error-free space geodetic observations

This project aims to quantify and understand time-related errors of the four geodetic space techniques VLBI, SLR, GNSS and DORIS. The separation and analysis of these errors allows the determination of the error sources and, eventually, their compensation to obtain error-free observations. For this purpose, a multi-technique station fiducial (common target) is installed at GOW. It is connected to the space techniques via delay-compensated cables and enables the calibration and validation of the measurements.

In 2023, the work within this project started with the analysis of SLR range biases (RBs) occurring at GOW's two SLR telescopes, namely the Wettzell Laser Ranging System (WLRS) and Satellite Observing System Wettzell (SOS-W). Figure 1.12 shows the long-term mean RBs of measurements from SOS-W to eleven spherical satellites. The values are compared to biases listed in the ILRS Data Handling File (e.g., top blue line), and their offsets are related to hardware and software changes at the instruments.

The analysis of the VLBI observations began with a comparison of the clock parameters determined with DOGS-RI. For this purpose, sessions with observations from two of the three telescopes at the GOW, namely the 20-m Wettzell radio telescope (WTZ) and the northern twin telescope (WTN), are used and the parameter time series are examined for systematic behaviour or instantaneous changes (Fig. 1.13). As in the case of SLR, site logs with hardware and software changes are used to explain possible discontinuities in the data.

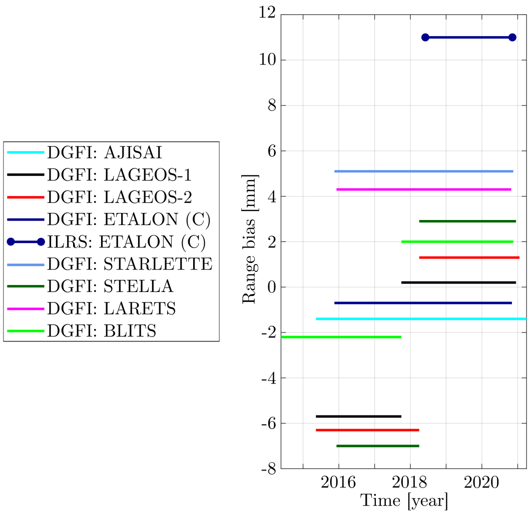


Figure 1.12: Long-term mean SLR range biases of SOS-W for eleven satellites derived with DOGS-OC.

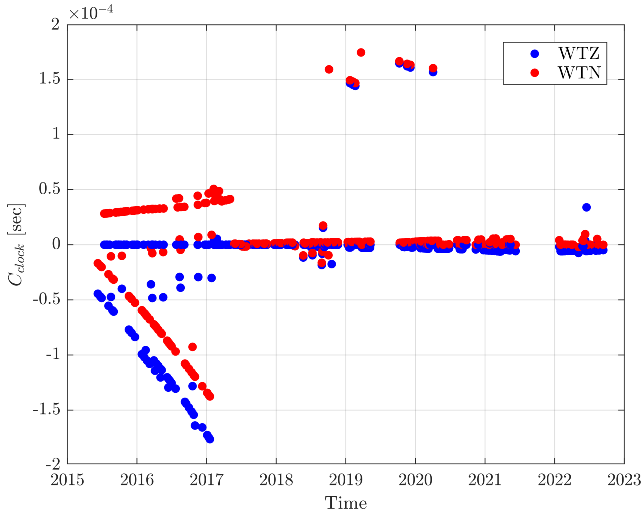


Figure 1.13: VLBI clock correction parameters from VLBI sessions with the telescopes WTZ and WTN derived with DOGS-RI.

Project P9: Novel clock technologies for combination on ground and in space: real data and simulation

This project aims at a highly accurate, long-term stable realization of the ITRS. The goal of the project, which is being carried out jointly by DGFI-TUM and the University of Bonn, is to achieve a quasi-error-free combination of geodetic space observations using CC and CT at co-location sites on the basis of real and simulated data. In this way, the combination via classical local tie measurements with their inherent discrepancies is replaced by a spatio-temporal, quasi-error-free combination of the techniques, which has not been possible until now.

The infrastructure for the realisation of a CC and a CT for all instruments of the observatory is currently being set up at the GOW, so that it will be the first site where the observations of all techniques refer to the CT as a common reference point by means of delay-compensated time links. The work in project P9 began with the identification of discrepancy patterns between the position time series realized for the individual instruments at the GOW. Figure 1.14 clearly shows a systematic discrepancy between the difference time series and the local tie in the north component as well as periodic variations in the height. Both need to be investigated in more detail. The patterns found shall be explained by known events, e.g. reported in the site logs of the individual instruments, or other external influences such as meteorological conditions. The work relies on an iterative exchange with other projects of the RU, whereby this first phase of the project requires particularly close cooperation with the second DGFI-TUM project P7. In close dialogue with GOW, external and internal (instrument/infrastructure-related) sources of the discrepancies shall be identified.

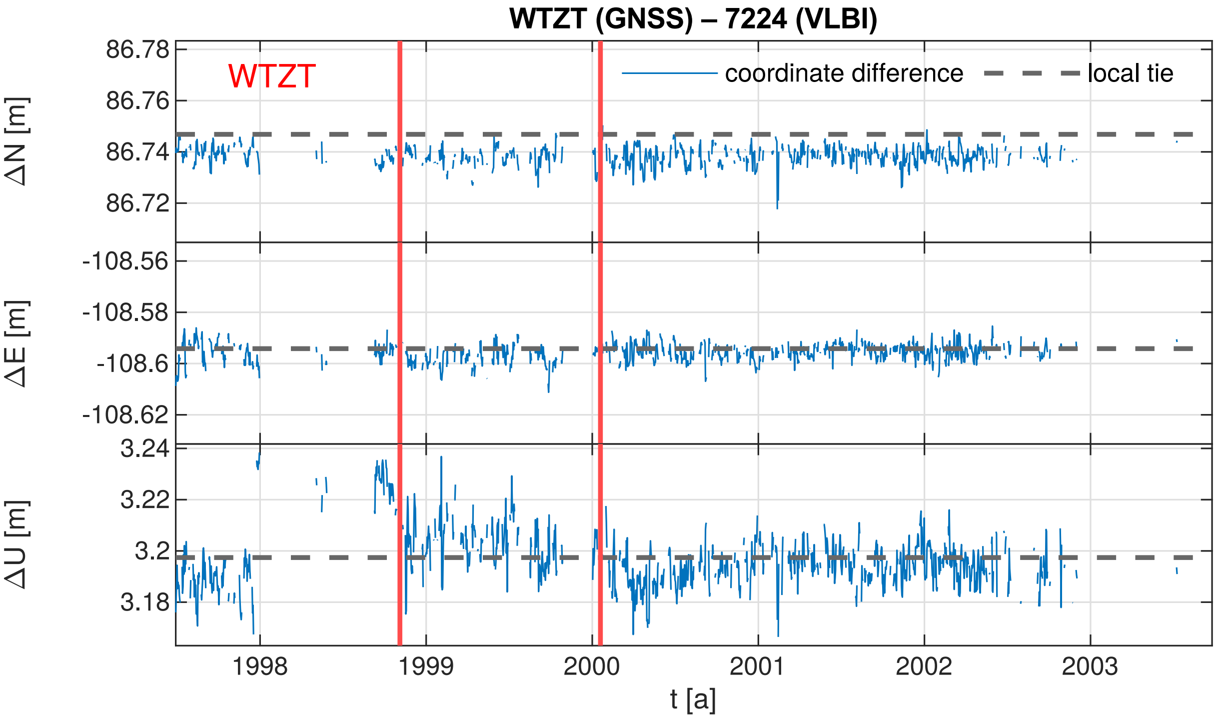


Figure 1.14: *Difference of the position time series of GOW's GNSS station (WTZT) and VLBI station (WTZ) plotted relative to the local tie, i.e. the coordinate difference between both stations from local survey. Red vertical lines mark GNSS antenna changes. They are reflected by artificial jumps in the time series.*

Once the identified discrepancies are explained and resolved, CC/CT-based combination strategies will be developed using both simulated and real observation data. They will focus on the combination of all common parameters such as troposphere, orbit parameters and EOP. The combination results will serve as a demonstrator of the benefits of CC/CT-based solutions for the achievable accuracy of ITRS realizations.

Related publications

Alkahal R.: *Impact of refined geophysical models on orbits of altimetry satellites* (Master Thesis), DGFI-TUM, mediatum.ub.tum.de/doc/1713132/1713132.pdf, 2023

Angermann D., Pail R., Seitz F., Hugentobler U.: *The importance of geodetic reference frames - A uniform basis to tackle current and future challenges*. GIM International, 37, 43-45, 2023

Costa S.M., Sánchez L., Piñón D., Tarrio-Mosquera J., Guimarães G., Gómez D., Drewes H., Mackern-Oberti M., Antokoletz E., de Matos A., Blitzkow D., da Silva A., Inzunza J., España D., Rodríguez O., Rozas-Bornes S., Guagni H., González G., Paucar-Llaja O., Pampillón J.M., Alvarez-Calderón A.: *Status of the SIRGAS Reference Frame: Recent Developments and New Challenges*. International Association of Geodesy Symposia, doi:10.1007/1345_2023_227, 2023

Glomsda M., Seitz M., Angermann D.: *Comparison of Simultaneous VGOS and Legacy VLBI Sessions*. In: Armstrong K., et al. (Eds.), IVS 2022 General Meeting Proceedings, 2023a

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2 Research Area Satellite Altimetry

Satellite altimetry is the space-based technique for the precise measurement of water surfaces in both the ocean and inland waters. For more than 30 years, a variety of altimetry missions has continuously monitored the temporal changes in water levels, wave structures, surface currents, continental discharge and storage changes and many other oceanic and hydrological parameters. With its measurement data, satellite altimetry enables the long-term analysis of climate impacts and thus makes a substantial contribution to understanding the Essential Climate Variables (ECV) defined by the UN Global Climate Observing System (GCOS). The classic altimetry missions to date work with nadir-orientated altimeters to determine water heights directly below the satellite. This severely limits the spatial resolution of the measurements. With the launch of SWOT in late 2022, carrying the first wide-swath altimeter on a satellite, a significantly improved spatial resolution of ocean measurements and complete coverage of continental surface waters is now possible. Since 2023, SWOT has been delivering the first (test) data sets, and DGFI-TUM has built up its capacity to process SWOT data and analyze and validate the first data sets. DGFI-TUM pursues the strategy of combining the measurement data from all available altimetry missions in a multi-mission approach and utilizing them jointly for a variety of marine and inland applications. This requires careful harmonization and calibration of the data (Section 2.1), which the institute makes available together with derived scientific products to the public via its own altimeter database OpenADB (Section 4.6). The combined multi-mission data is used for ocean research including coastal, shelf and polar regions (Section 2.2) and for studies on continental hydrology (Section 2.3).

2.1 Multi-Mission Analysis

Open Altimeter Database (OpenADB)

The combination of observation data from different altimetry missions into a multi-mission data approach requires careful harmonisation and calibration of all available measurement data. DGFI-TUM has been operating an Open Altimeter Database (OpenADB) for many years, which enables consistent data management and combination (Schwatke et al., 2023). It consists of the internal Multi-Version Altimetry (MVA) data repository and the OpenADB web portal (openadb.dgfi.tum.de). OpenADB provides user-friendly access to derived along-track science data products such as sea surface heights and tides. It also provides general information about the data provided in the database, satellite altimetry missions, their observation systems and configurations (see also Section 4.6).

In 2023, the MVA database was supplemented by a large number of new reduction models, including the ERA-5 troposphere corrections, orbit solutions and reprocessed and new altimeter data, e.g. from Sentinel-6 F08 and SWOT nadir. In addition, the integration of SWOT wide-swath data was initiated in order to be able to consistently combine this new type of mission data with conventional altimeter observations in the future.

Impact of altimeter corrections on sea level results

In order to derive highly accurate water levels from altimeter observations, the measured distances between satellite and water surface must be corrected for various physical influencing factors. The uncertainties of the corresponding correction models have a direct effect on the accuracy of the computed water levels. Systematic errors such as drifts in radiometer measurements are fully reflected in derived parameters such as global sea level rise or certain components of ocean tides and are thus particularly critical.

For example, a lack of scaling of the orbital heights of GNSS-based ionospheric corrections to the altitude of the altimeter satellites can cause a trend error in global mean sea level of up to 1 mm/year[20]. This can be reduced by an order of magnitude by using plasmasphere models or machine learning techniques (Dettmering and Schwatke, 2023). The trend differences between various wet tropospheric corrections, namely the radiometer correction and the GPD+ correction, were also compared. Differences of up to 0.2 mm/year were found, which are likely caused by drifts in the radiometer measurements[21].

Tidal frequencies were evaluated within several correction models, and strategies were developed and implemented to treat these frequencies prior to the creation of empirical tidal models[22]. Of particular importance is the Dynamic Atmosphere Correction (DAC), which in principle was processed at the time of its creation to remove tidal frequencies, particularly solar tides. However, during the tidal analysis using this correction, several tidal constituents were identified that potentially affect the tidal modeling (Figure 2.1). Work is currently ongoing to adequately deal with these tidal frequencies in several corrections to further improve tidal estimates.

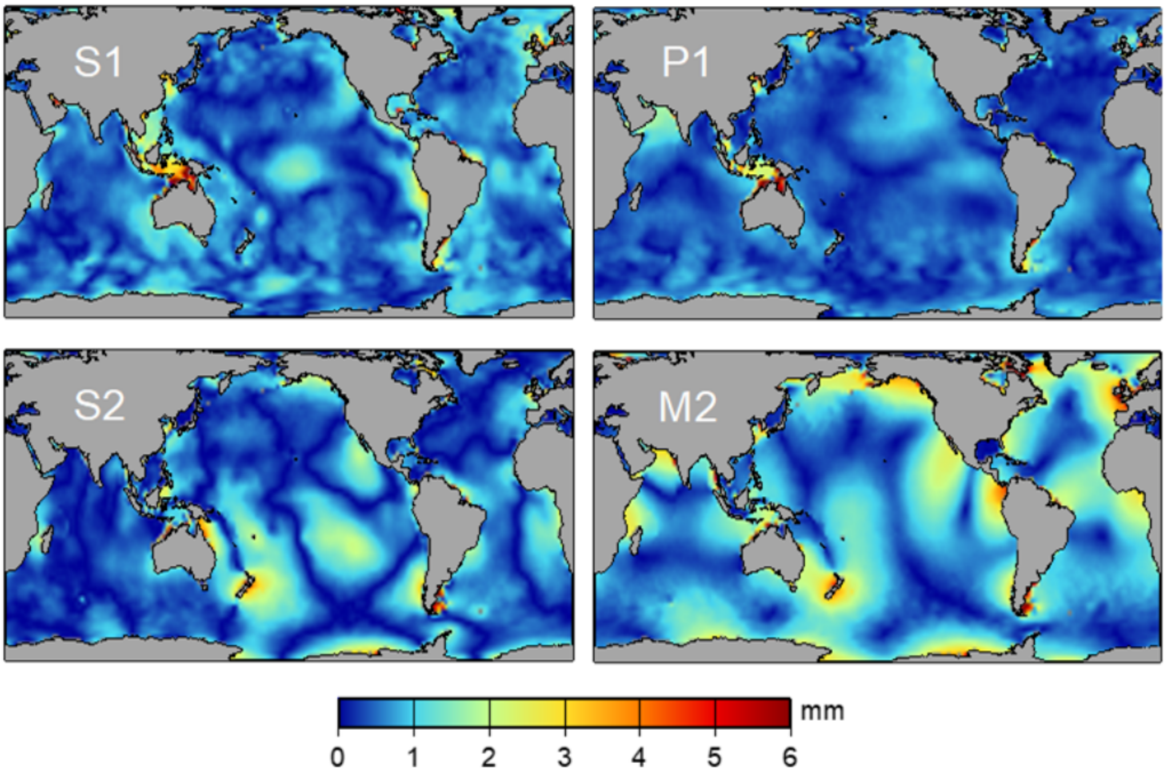

Figure 2.1: *Results of harmonic analysis on gridded DAC for four of the major tidal constituents.*

[20] Dettmering D., Schwatke C. (2022): *Ionospheric corrections for satellite altimetry - impact on global mean sea level trends.* Earth and Space Science, doi:10.1029/2021EA002098

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[22] Hart-Davis M.G., Ray R., Bordas Diaz L., Schwatke C., Dettmering D., Seitz F. (2023): *Towards the optimisation of altimetry corrections for improved ocean tide modelling.* EGU General Assembly 2023, Vienna, Austria

Using satellite altimeter crossover differences for orbit validation

Differences in sea surface height at crossing points of satellite missions can be used to compare the quality of different satellite orbits. Based on a multi-mission crossover approach[23], the orbit quality of different satellites was evaluated. This analysis is part of the **DFG project MEPODAS** (Mitigation of the current errors in precise orbit determination of altimetry satellites) (Rudenko et al., 2023) as well as of the **ESA project CPOD** (Copernicus Sentinels Precise Orbit Determination Service). 15 different orbit variants were analyzed for the Sentinel-3A, Sentinel-3B and Sentinel-6A satellites. All solutions are of good and comparable quality with a few outliers in some solutions. The largest discrepancies were found in the geographically correlated errors (GCE), which show large-scale differences in the mm range. These orbit errors are directly transferred to the uncertainties of the mean sea level height. Figure 2.2 shows an example of the GCE differences of four selected solutions compared to the CPOD Combined Solution.

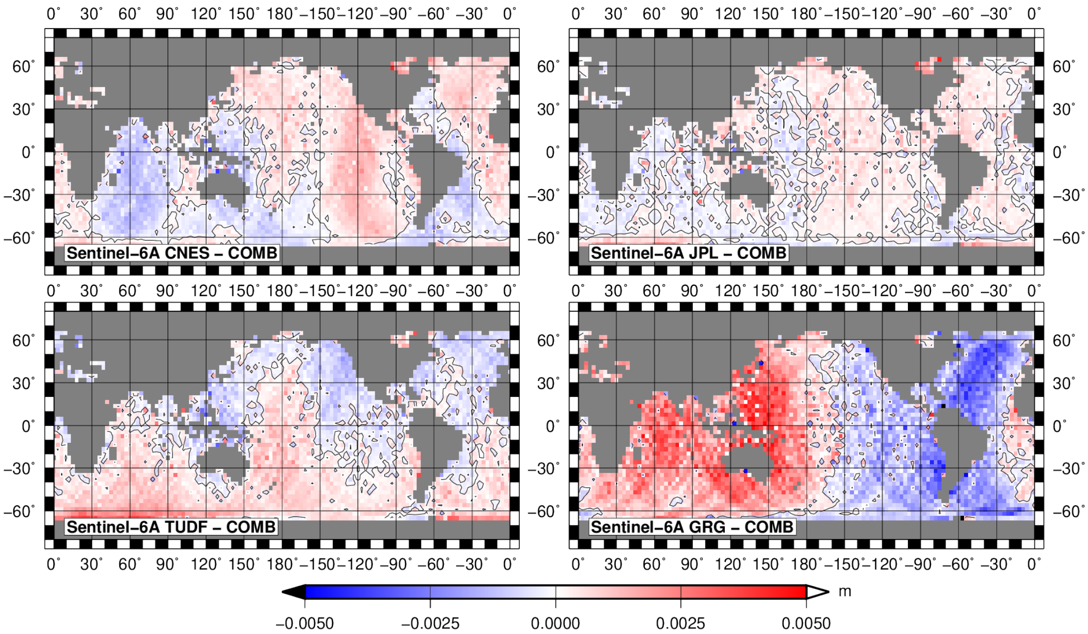

Figure 2.2: *Geographically correlated orbit errors of Sentinel-6A for the year 2023: differences of four orbit solutions (CNES, JPL, TUDF, GRG) with respect to the CPOD Combined Solution (COMB).*

2.2 Sea Surface

Analysis and exploitation of the tandem phase between Sentinel-6 and Jason-3

In the framework of the **ESA project S6-JTEX**, the quality and the quantity of sea level measurements in the coastal zone was assessed using both standard data and dedicated reprocessing for SAR and low rate (LR) waveforms during the tandem mission of Sentinel-6 (S6) and Jason-3 (J3) (Passaro et al., 2023). For the first time, latest developments in coastal altimetry could be compared on different altimeters spanning the same tracks almost simultaneously.

[23]Bosch W., Dettmering D., Schwatke C. (2014): *Multi-mission cross-calibration of satellite altimeters: constructing a long-term data record for global and regional sea level change studies*. Remote Sensing, doi: 10.3390/rs6032255

The performance was analyzed using metrics inherited from previous literature to guarantee the objectiveness of the analysis. We focused on the quantity of retrievals (outliers analysis), their precision (along-track noise analysis), potential systematic differences (bias analysis), and their accuracy (comparison against in-situ data). An example of these latter is given below.

In order to evaluate the coastal accuracy of the products, Fig. 2.3(a) shows the mean correlation with the tide gauge series grouped by distance to coast. Panels (b) and (c) display the number of tide gauges and the number of available tracks for each altimetry dataset. This indicates the different amount of valid data for each dataset when approaching the coast, given the different amount of missing or unrealistic sea level estimations. Panels (d) and (e) show the location of the tide gauges and the correlations with the reference product of S6 (EUM PDAP HR) for two different binned coastal distances.

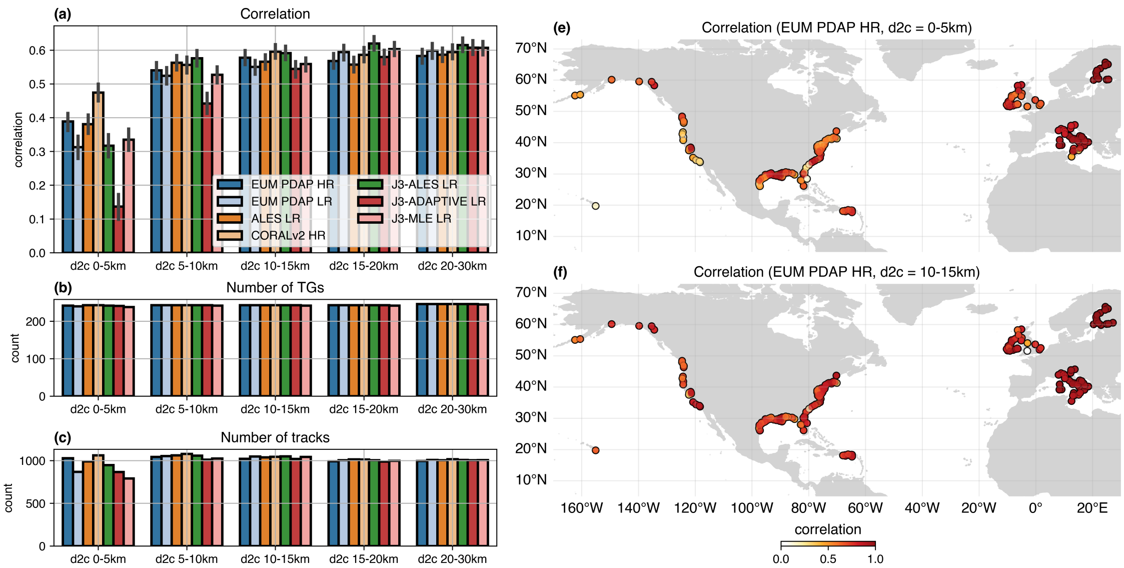

Figure 2.3: *(a): Mean correlations (with 90% confidence intervals) per dataset and distance to coast. (b) and (c): number of tide gauges and total number of available tracks for which correlations are computed. (d) and (e): best correlation per tide gauge for different distances to the coast and for the EUM PDAP HR dataset.*

The two main findings were: Firstly, the official SAR altimetry products are advantageous in the coastal zone with respect to the ones based on the LR mode. For example, the official S6 SLA product from SAR altimetry shows an 8% improvement in our correlation analysis. An exception is the SWH from SAR, which is still biased relative to the LR record, as already noticed by previous studies (e.g. Schlembach et al., 2023). Secondly, it was demonstrated that dedicated coastal retracking can significantly improve the performance of SAR altimetry. In particular, the main message was that the official SAR altimetry product EUM PDAP HR achieves the coastal performance of the same level of enhanced coastal altimetry reprocessing of LR data (ALES LR, J3-ALES LR) and that its performance can be further improved using a dedicated subwaveform approach applied to the same SAMOSA physical model (CORALv2 HR).

In the same project, a collaboration with the University of Porto aimed at identifying signatures of internal solitary waves in sea level, wave height, and backscatter coefficient measured by S6 and J3 (Magalhaes et al., 2023). For this purpose, our ALES LR retracker was successfully employed, opening up a new application for this technique.

DGFI-TUM has also been working on getting Sentinel-6 data even closer to the coast by processing it as fully-focused SAR altimetry (Ehlers et al., 2023; Schlembach et al., 2023). This technique exploits the fully coherent processing of the received radar pulse echoes during the whole target illumination time, by which a theoretical along-track resolution of less than a meter can be achieved for coherent targets.

Coherent modes of coastal sea level change

Sea level dynamics in the coastal zone can differ significantly from that in the open ocean. The presence of the continental slope, shallow waters and the coastlines give rise to a variety of processes that mediate the response of coastal sea level to local and remote forcing and can produce coherent spatiotemporal sea level variations in alongshore direction. Yet where and how coastal sea levels exhibit variations that emerge as persistent and recurrent patterns along the world's coastlines, remains poorly understood. We aimed to identify large-scale patterns of coherent modes of monthly coastal sea level variations from coastal altimetry and tide gauge data. This work was conducted within the International Space Science Institute **ISSI project** 'Understanding the Connection Between Coastal Sea Level and Open Ocean Variability Through Space Observations' led by Calafat F. & Jevrejeva S. (see also Laignel et al., 2023).

We developed a Bayesian Mixture Model to probabilistically infer the cluster-membership of globally distributed monthly tide gauge and altimetry observations. The geographical distribution of the detected clusters (based on monthly data) are shown in Fig. 2.4A and 2.4B. Both, the tide gauge clusters and the altimetry-based clusters form regionally confined groups. This underlines the inherent regional coherence of coastal sea level, as such a regional confinement is not enforced within the model itself (distances between stations are unknown to the model).

Overall, there is a high correlation between the estimated tide gauge cluster time series and most of the tide gauge time series within the respective clusters (Fig. 2.4C and Fig. 2.4D). Nine tide gauge clusters show an average correlation of 0.76 (i.e., the average of the averaged correlations between the cluster time series and the associated tide gauge time series), indicating an overall explained variance of 57% (square root of the correlation times 100%). This is a striking result, as it supports the hypothesis that much of the variability observed in these regions can be attributed to common driving factors. Therefore, this disentangling of the regional clustering of variability is critical for future analyses focused on understanding the causes of these common variations.

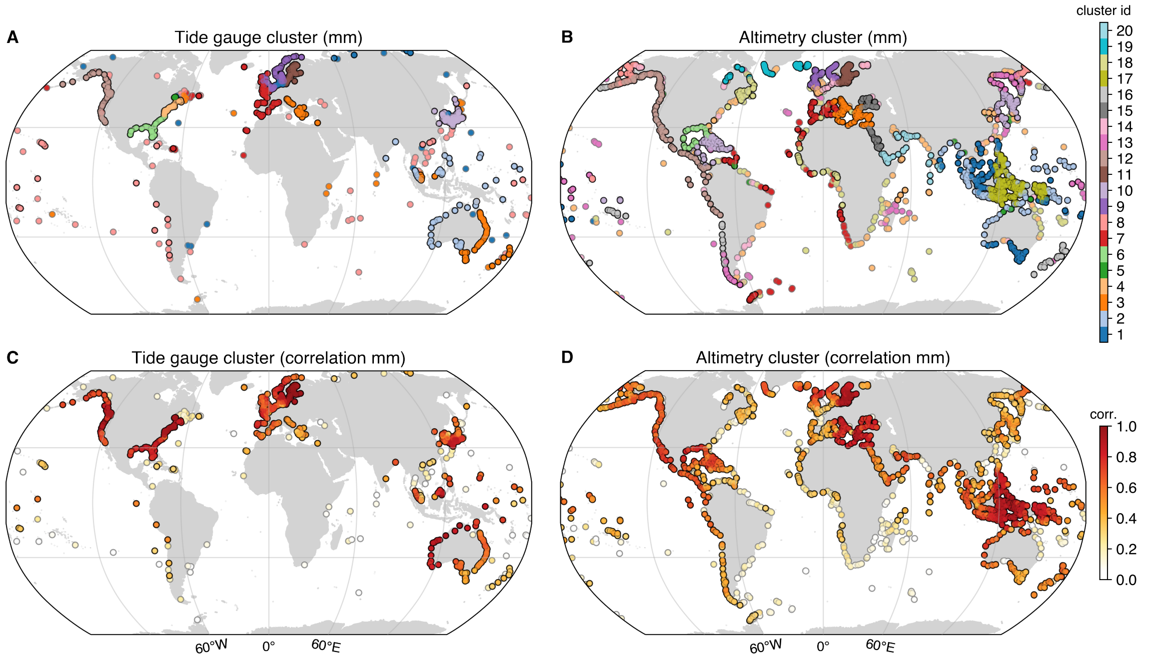

Figure 2.4: *Clusters based on monthly mean (mm) tide gauge (A) and coastal altimetry (B) observations, as derived by the Bayesian Mixture Model approach. (C) and (D) show correlations of cluster time series with the associated monthly individual (virtual) station time series. Gray circles indicate points with correlations <0.3.*

The introduction of coastal altimetry in our investigations reveals many more regions of coherent coastal sea level variations than can be observed by the tide gauge network. Many of these additionally detected station clusters, particularly in the Indian Ocean or around the South Atlantic basin, have so far been poorly described. Using the altimetry data, we also obtain a much better understanding of where the monthly sea level variations are highly coherent and where they are not. While we find generally high correlations with the cluster time series at the eastern boundaries, marginal and semi-enclosed seas, some stations along the western boundaries appear to be poorly captured by the cluster analysis. The causes of these characteristics need to be better understood, particularly for the eastern South American, African, and Australian coasts.

Mapping sea level anomalies with Random Forest Regression

Altimetry observations are spatially and temporally distributed measurements along the orbit. Interpolation algorithms are routinely used to generate regular (grid) data of the sea surface. The European Union's Earth observation program, Copernicus, publishes daily maps of sea level over the entire ocean surface of the Earth via the Copernicus Marine Service (CMEMS). These daily CMEMS maps are produced using a method based on optimal interpolation that requires several steps and assumptions.

Recently, it has been argued that data-driven interpolation performs better than conventional optimal interpolation methods, where the choice of covariance priors results in over-smoothing the sea level variability. We therefore investigated a Random Forest (RF) Regression-based method for gridding sparse along-track measurements based on neighboring observations (Passaro and Juhl, 2023). The study was performed on a regional scale for one year of data in the North Sea, and we validated it against tide gauge data and the optimally interpolated maps from CMEMS. While the CMEMS daily grids were validated using only monthly averages of tide gauges as ground truth, in this work we used the daily averages from the Global Extreme Sea Level Analysis (GESLA, version 3).

The concept is to train the RF regressor for the estimation of the unknown sea level anomalies (SLA, our target parameter) at a set of grid points by using along-track SLA as truth. As predictors, we use means, weighted means and standard deviations of the SLA in different neighborhoods in space and time. To better describe the evolution of the target variable in space and time, the ratios between these predictors from the different neighbors are also used as predictors. Figure 2.5 shows the time series of daily averaged data from tide gauges (in green) whose locations are indicated at the top of each sub-figure. The result of our study (ML, in blue) and the CMEMS product (in orange) corresponding to the closest location of each tide gauge are shown for from January to December. The CMEMS time series appears much smoother over time, while the ML result maintains time scales that better match those of the gauges, although of course it does not capture the full extent of high-frequency variability. Although CMEMS is smoother than the ML result, the root mean square error (RMSE) calculated based on the gauge data as truth is systematically lower for ML. This gives us confidence that the ML time series is not simply noisier than CMEMS, but that it is indeed more accurate.

We extended the analysis to the entire North Sea and generated one year of daily sea level maps that are on average 10% better correlated with tide gauge observations compared to CMEMS data. The main result of this study is that along-track SLA data can be used to train ML algorithms aimed at generating gridded maps. The method allows a more realistic representation of sea level variability. The validation was performed using high frequency tide gauges, which we consider to be much more realistic than using monthly averages when assessing the ability of the altimetry to monitor sea level on short time scales.

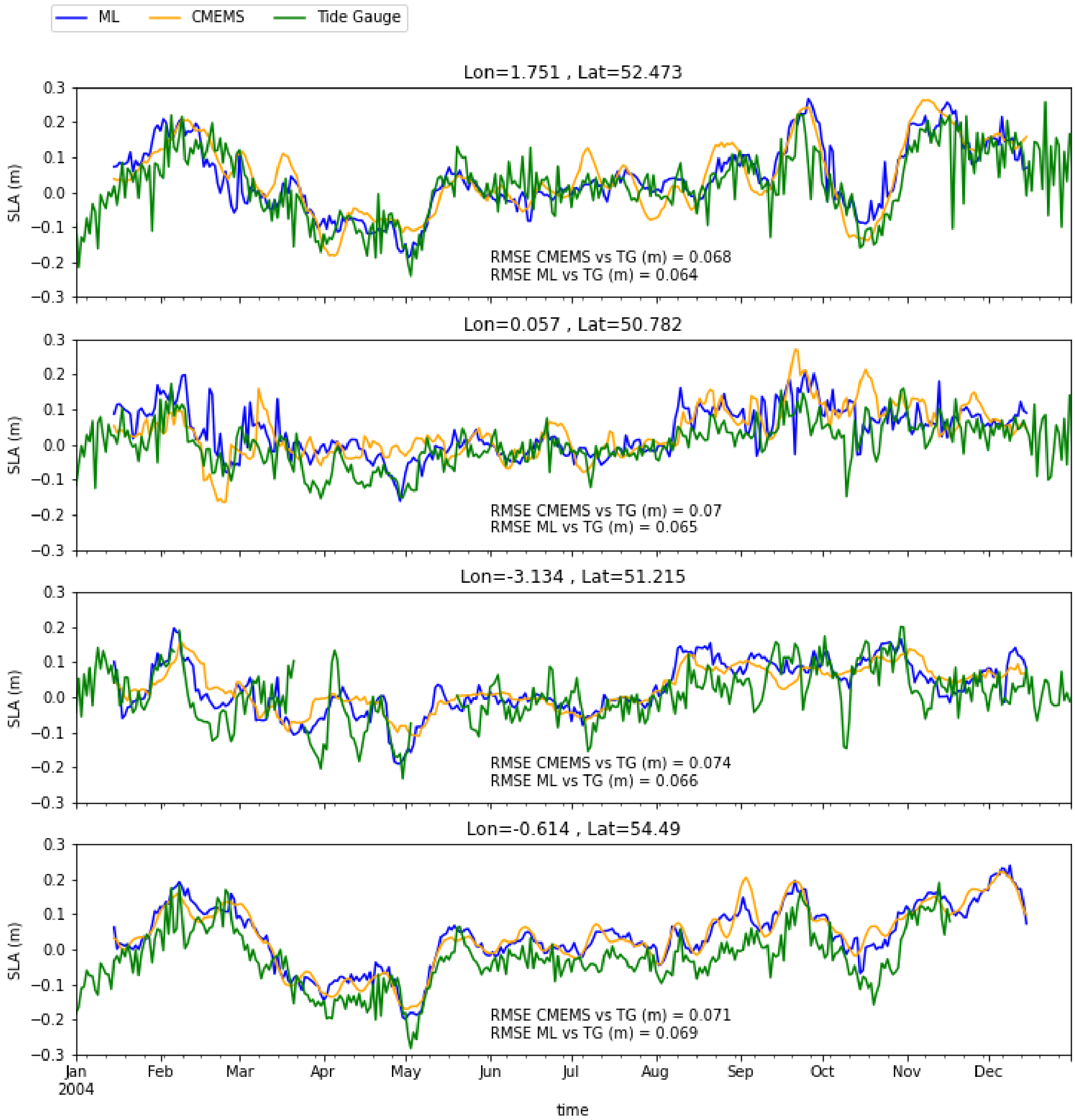

Figure 2.5: *Time series from satellite altimetry from this study (ML, blue) and CMEMS (orange) at the closest point to four tide gauges (green), whose coordinates are shown at the top of each panel. RMSE values are given relative to the tide gauge observations.*

Improved sea level and surface circulation in coastal and shelf ocean

The **DFG project CIRCOS** (Circulation from In-situ and Remote-sensing data in Coastal and Shelf ocean) aims to improve grids of sea level anomalies (SLA) in coastal and shelf regions. Spatially and temporally homogeneous data sets are needed for comprehensive ocean research. When interpolating along-track to grid data, the variability of the SLA is often lost. But this variability is of particular interest for the investigation of marine processes in coastal and continental shelf regions.

In order to increase the variability of the gridded data, CIRCOS combines satellite altimetry observations with wind data, as these are linked to the SLA on different temporal scales. Ongoing research within the project is focused on gaining insights into the impact of wind on the project's study region, the Southwest Atlantic Continental Shelf (SWACS). We have evaluated CMEMS's state-of-the-art gridded SLA product 'Global Ocean Gridded Level-4 (L4) Sea Surface Heights and Derived Variables' in terms of its performance in the SWACS region and the impact of wind stress on the continental shelf SLA.

The results of this regional study[24] led to the conclusion that wind-driven SLA occur in the study region from diurnal to annual time scales and may be partially connected with shelf circulation due to the correspondence with geostrophic velocities. It was also demonstrated that the ability of existing gridded data to resolve SLA variability is limited to $>$20 days. Nevertheless, wind stress data, e.g. measured remotely with scatterometers, provide variability at higher frequencies.

Further investigations of the project include the development of methods for mapping SLA on the SWACS to evaluate the most appropriate interpolation method for preserving fine-scale variability using correlated variables such as wind on the continental shelf using spatio-temporal Co-Kriging. This approach enables the creation of valuable regional data sets and thus a more in-depth analysis of coastal and shelf regions.

Monitoring the Arctic Ocean

The Arctic Ocean is one of the Earth's most vulnerable regions to climate change. Increased temperatures and freshwater influx from glacial melt cause sea level changes and affect regional and global ocean circulation. In this area, satellite altimetry observations are degraded by seasonally changing sea ice cover and challenging ocean conditions, resulting in patchy observations and reduced data reliability.

DGFI-TUM's research in the Arctic Ocean focuses on the dedicated processing of altimeter observations under the prevailing conditions and the determination of reliable parameters derived from them, such as tides in the sea-ice-covered ocean and dynamic ocean topography for circulation studies. However, the first prerequisite for this is the identification of altimeter observations over small water openings such as leads. This is done on the basis of machine learning methods.

In 2023, progress was made in extending the algorithms for the unsupervised classification of radar waveforms (see previous annual reports) to the detection of thin ice. The classification results were compared with the thickness of thin ice derived from thermal images (Müller et al., 2023). The open water classification provides robust measurements of sea surface height that can be used - among other applications - to generate improved tidal corrections required for sea level studies and also to better assess the impact of tides on circulation.

The DGFI-TUM Empirical Ocean Tide (EOT) model (see below) does not yet include the polar oceans, but thanks to the inclusion of Cryosat-2 data, tidal estimation is now also possible in these regions. In collaboration with DTU, a study on the usability of Cryosat-2 for tidal estimation across the Arctic and Antarctic was published, highlighting positive findings from the updated Cryosat-2 processing (Andersen et al. 2023). Following this study, considerable efforts were made to develop a so-called EOT-Polar model. Initial results demonstrated the importance of a multi-mission approach in these regions and showed improved accuracy compared to FES2014[25] provided in the higher latitudes within EOT20. This model was used in comparison with several other tidal models in a case study of the Foxe Basin in North America to demonstrate the limitations of current tidal models in regions of high sea ice concentration and poorly known bathymetry[26]. Efforts will continue over the next years, and it is anticipated that a more advanced version of EOT-Polar will be created.

[24] Juhl M.-C., Passaro M., Dettmering D., Saraceno M. (2024): *Evaluation of sub-annual satellite-based SLA in the continental shelf of the Southwestern Atlantic*, Ocean Dynamics, doi:10.1007/s10236-024-01621-y

[25] Lyard, F. et al. (2021): *FES2014 global ocean tide atlas: design and performance*, Ocean Science, doi: 10.5194/os-17-615-2021

[26] Hart-Davis M., Andersen O., Ray R., Dettmering D. (2023): *Altimetry-derived ocean tides in the Arctic: a Foxe Basin case study*. Presented at OSTST2023

In the framework of the **IGSSE project AROCCIE** (Arctic Ocean Surface Circulation in a Changing Climate and its Possible Impact on Europe), DGFI-TUM aims to create a novel altimetry dataset of ocean currents based on long-term observations by applying the above-mentioned advanced algorithms to distinguish radar echoes over sea ice and leads and to determine the sea surface height in the ice-covered ocean. In a first step, the sea surface heights, the dynamic ocean topography and the geostrophic currents over the Chukchi and Beaufort Seas were calculated and analyzed (Fig.2.6).

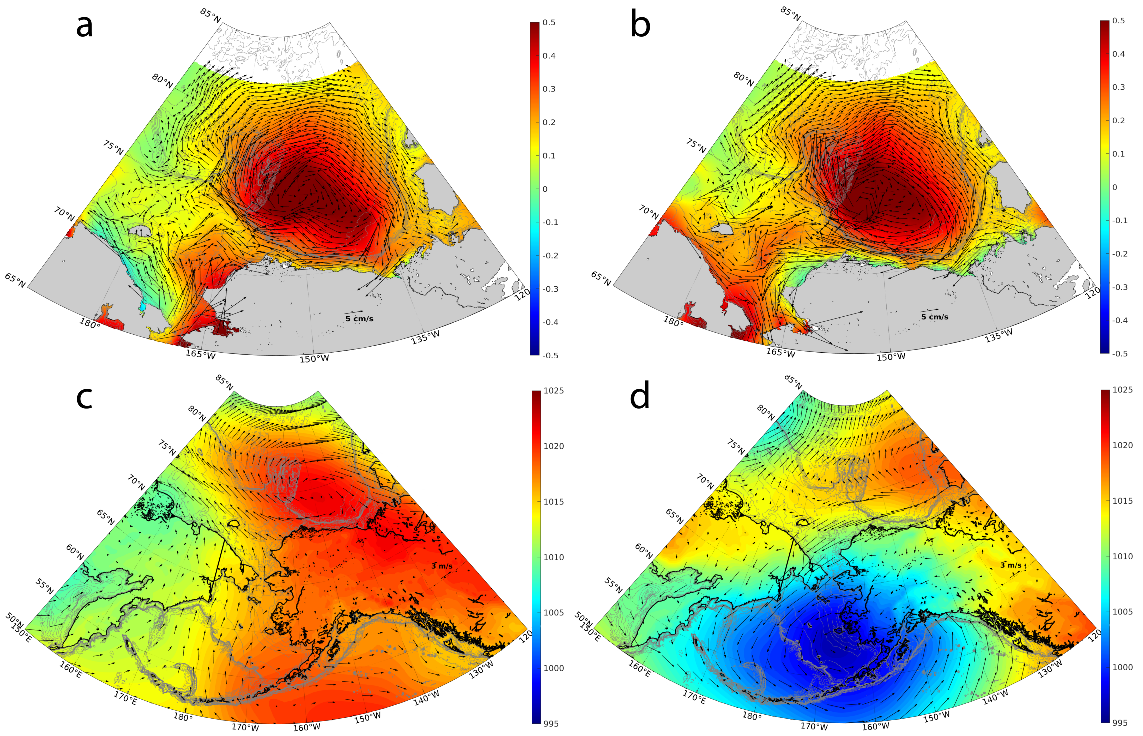

Figure 2.6: *Geostrophic currents (cm/s, vectors) overlaid on dynamic ocean topography (m, color) for (a) 21-30 September 2018 and (b) 15-24 October 2018. Below, 10-m ERA5 winds (m/s, vectors) overlaid on sea level pressure (mb, color) for the months of (c) September and (d) October 2018 are displayed.*

The Chukchi Sea is an important transition region for Pacific-origin waters flowing north through the Bering Strait into the Arctic Ocean. The inflowing waters bring heat and freshwater and influence the structure and variability of the entire Arctic Ocean. Monitoring the processes in the Chukchi Sea is crucial to understand the variability of the Arctic Ocean, especially in a changing climate. While difficult accessibility leads to a lack of oceanographic in-situ measurements in the region, satellite altimetry provides precise information on the sea surface at different spatial and temporal scales and can be used for studies of current patterns.

In the first analysis, the reversals of the northward flow through the Bering Strait were investigated and linked to the anomalously strong northeasterly wind events over the Chukchi Shelf. The pressure gradient between Beaufort High and Aleutian Low leads to northeasterly winds over the shelf, which oppose the northward flow in the strait. In the events of anomalously strong winds, an Ekman transport of the surface waters can be triggered, which leads to higher dynamic ocean topography at the Siberian Coast, which in turn is followed by the reversal of the flow in the Bering Strait and is evident from the satellite altimetry data (as seen in Figure 2.6). While this phenomenon was previously described in oceanographic studies, the altimetry-based dataset made it possible to assess its development, forcing and variability with a higher temporal-spatial resolution (10d/8km) between 2013 and 2023.

Integration of the Empirical Ocean Tide Model (EOT) into ocean models

In 2023, a regional version of the Empirical Ocean Tide Model (EOT) of the Northwestern European Continental Shelf (EOT-NECS) was published[27]. The main objective of this model was to provide improved spatial resolution with respect to our global model EOT20, by the incorporation of additional altimetry orbits provided by the Sentinel-3 missions and SARAL drifting phase. In addition, EOT-NECS, for the first time, estimated constituents empirically and semi-empirically to determine additional constituents to those already provided by the reference model FES2014. The results demonstrated an improved estimation of all common constituents compared to both EOT20 and FES2014, with EOT-NECS being the best-performing tide model with respect to in-situ measurements from TICON-3[28].

The additional constituent selection aimed at providing these constituents for operational forcing of the ocean model DCSM-FM developed by Deltares in the Netherlands. DCSM-FM is operationally used by the Dutch Ministry of Public Works and Water Management, Rijkswaterstaat, to predict water levels in order to reduce the impacts of flooding events. Accurate tidal forcing is of great importance for the model's application as it allows authorities to better prepare for flooding events by putting in place mitigation methods along the coast. Water level predictions by DCSM-FM were improved by 0.42 cm with respect to in-situ measurements when using constituents from EOT-NECS, with some regions experiencing improvements exceeding 1 cm (Fig. 2.7). This application demonstrates the potential of EOT and regional model refinements for interdisciplinary and routine applications and lays the foundation for further research to improve the representation of tides in numerical model estimates (Hart-Davis et al. 2023).

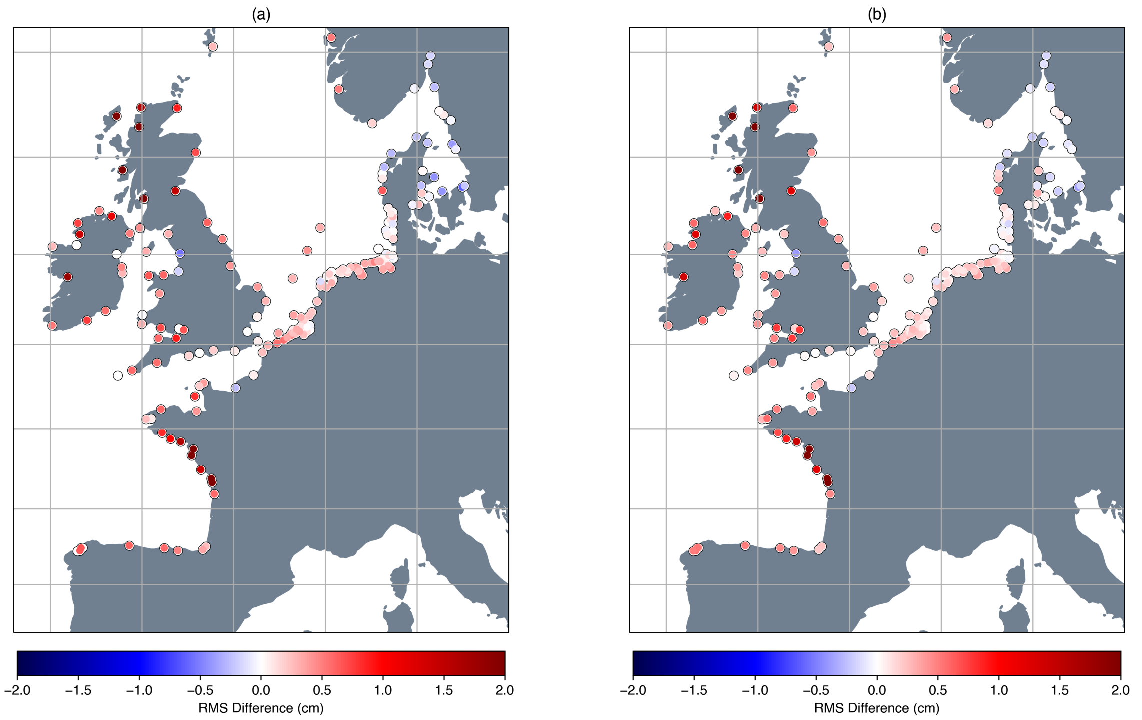

Figure 2.7: *Overall RMS changes with respect to tide gauge observations in (a) tidal heights and (b) water levels from DCSM-FM without EOT-NECS to DCSM-FM with EOT-NECS. Red values indicate a reduction in RMS when using EOT-NECS.*

[27] Hart-Davis M., Schwatke C., Dettmering D., Passaro M., Seitz F. (2023): *EOT-NECS Ocean Tide Model.* SEANOE [Data], doi:10.17882/94705

[28] Hart-Davis M., Dettmering D., Seitz F. (2022): *TICON-3: Tidal Constants based on GESLA-3 sea-level records from globally distributed tide gauges including gauge type information.* PANGAEA, doi:10.1594/PANGAEA.951610

Ocean tide uncertainty information to improve satellite gravity field recovery

Ocean tides are a crucial component in gravity field determination from gravity field observations of dedicated missions like GRACE and GRACE-Follow-on (FO). Within the **DFG project TIDUS-2** (Improved Tidal Dynamics and Uncertainty Estimation for Satellite Gravimetry), part of the **DFG Research Unit 2736 NEROGRAV** (New Refined Observations of Climate Change from Spaceborne Gravity Missions, https://www.asg.ed.tum.de/iapg/nerograv/), an emphasis was placed on the consideration of tide-related errors in the space-based determination of gravity fields with GRACE(-FO).

In cooperation with the GFZ and the FU Berlin, experiments were carried out to take into account errors of the global ocean tide models within the GRACE processing. This requires the uncertainty information of the ocean tide models, but no modern global ocean tide model provides such uncertainties. Therefore, an alternative approach was introduced, which aims to create an ocean tide variance-covariance matrix (OTVCM) from five global tide models for the eight major tidal constituents[29].

As part of the GRACE data analysis, the results incorporating the OTVCM were evaluated in several experiments (Hauk et al., 2023). The study demonstrated that the root mean square error of the GRACE water mass retrievals was improved by 20% by including the OTVCM correction. In addition, when applying the OTVCM and co-estimating the tidal constituents, the effect of tidal aliasing on the retrieval of the gravity field was reduced by 75%, with the largest improvements in the Antarctic and Arctic regions. Further experiments are planned as part of NEROGRAV to further reduce the tidal aliasing errors in GRACE.

Lagrangian ocean analysis for the study of sea turtle dispersion

In 2023, in collaboration with Mercator Ocean International (France), Deltares (Netherlands), the Nelson Mandela University and the University of Cape Town (both South Africa), a study was conducted with the aim of exploring the pathways of juvenile turtles in the Western Indian Ocean. Using Lagrangian ocean analysis tools, experiments were conducted with the global reanalysis product of the Copernicus Marine Service. Various parameters were investigated to study the survivability of turtle hatchlings. As juvenile turtles are extremely small, they cannot be tracked by eye or with modern GPS trackers, so not much is known about the first years of their lives, known as the ‘lost years’.

From the combination of ocean model and Lagrangian tracking tools, possible pathways for these turtles were explored. This provides an indication of where they end up and how likely they are to survive their journey. These results will serve management and conservation policies along the African coast and will be instrumental in limiting human-induced damage to turtles throughout their lifespan (Le Gouvello et al., 2024).

[29] Sulzbach R., Hart-Davis M., Dettmering D., Thomas M. (2023): *Regularized empirical variance-covariance-matrices for stochastic gravity modeling of 8 major ocean tides (data).* GFZ Data Services, doi:10.5880/nerograv.2023.003

2.3 Inland Altimetry

Integration of SWOT into DAHITI

The Surface Water and Ocean Topography (SWOT) mission, launched in December 2022, is the first wide-swath altimetry mission in orbit and follows a complete new and innovative measurement principle. SWOT is equipped with two altimeter instruments: a classical radar nadir altimeter, comparable to Jason-3, and a Ka-band Radar Interferometer, called KaRIn. KaRIn applies the principle of SAR (Synthetic Aperture Radar) inferferometry, which now makes it possible to monitor almost all continental surface waters down to very narrow rivers and small lakes. After launch, SWOT flew in a fast sampling orbit meant for calibration and validation of the measurements. This phase lasted from January 2023 to July 2023 and consisted of 28 passes with daily repeat. Afterwards, SWOT was placed in its final science orbit with a repeat cycle of 21 days and 584 passes.

Even though the KaRIn data has not yet been officially released due to ongoing quality checks and reprocessing, we have started to prepare our public database DAHITI (Database for Hydrological Time Series of Inland Waters; https://dahiti.dgfi.tum.de/, see Section 4.6) for SWOT. SWOT nadir data is now regularly used for water level determination, and the interface

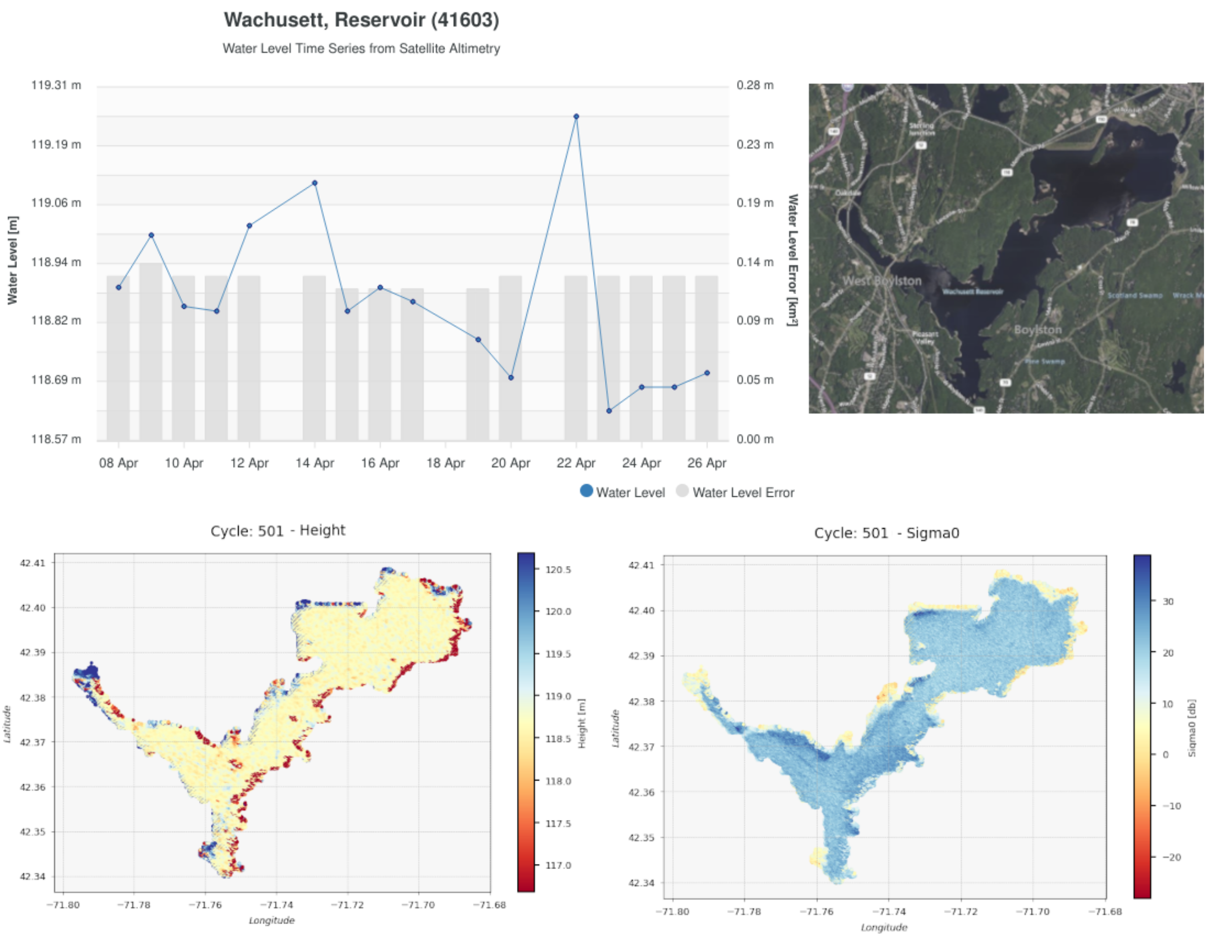

__Figure 2.8:__ First water level time series from SWOT KaRIn for the Wachusett Reservoir (USA): Water level time series (top left) and, as an example, water heights measured on April 25, 2023 (bottom left) together with the standard deviation (bottom right).

for KaRIn data has been set up. As part of the SWOT Science Team, we could access several weeks of beta pre-validated KaRIn data. Preliminary water level time series derived from these data look very promising. Figure 2.8 shows the results for the Wachusett Reservoir (USA) with an area of approx. 15 km². As soon as the validated KaRIn data is released to the public, water level time series will be made available via DAHITI.

Global River Surface Slopes from ICESat-2: IRIS version 2

DGFI-TUM has developed a method for determining river surface slopes based on observations from the ICESat-2 laser altimeter over the last few years[30]. In 2023, the dataset 'ICESat-2 River Surface Slope' (IRIS, Scherer et al., 2023) was published. IRIS comprises global reach-scale average and extreme water surface slopes (WSS) derived from ICESat-2 observations as a supplement to the 'SWOT Mission River Database' (SWORD)[31]. WSS is an important variable that can be applied as a correction to water level time series from satellite altimetry (as shown in Halicki et al., 2023), and it is essential to derive river discharge.

ICESat-2 was launched in October 2018 and carries a unique sensor with six parallel lidar beams that can measure water surface elevation with high precision and accuracy. WSS is instantaneously derived from these lidar measurements to capture spatial and temporal variations. This is not possible with radar altimetry or digital elevation models. An update of IRIS (version v2) incorporates an update of the input ICESat-2 ATL13 dataset from version v5 to v6 including a new improved water mask with additional data and ice flags. In addition, the SWORD dataset was updated from version v2 to v16.

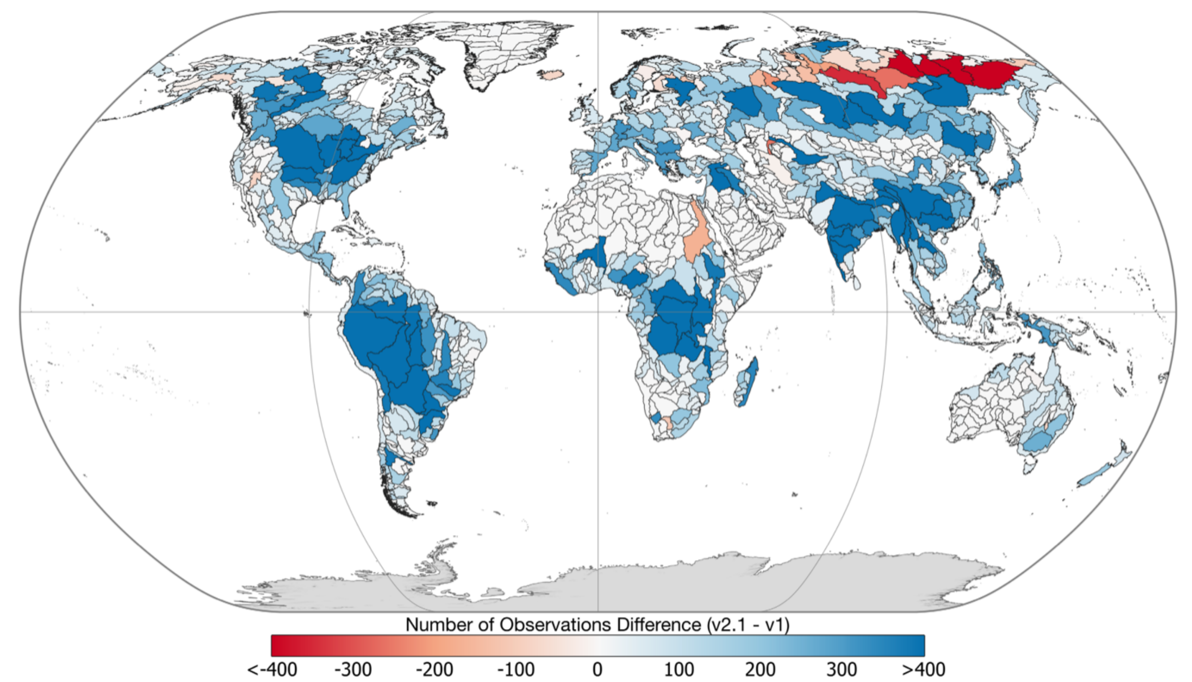

Figure 2.9: *Difference in the number of WSS observations between IRIS versions v2.1 and v1 per basin*

[30] Scherer D., Schwatke C., Dettmering D., Seitz F. (2022): ICESat-2 Based River Surface Slope and Its Impact on Water Level Time Series From Satellite Altimetry. Water Resources Research, doi:10.1029/2022WR032842

[31] Altenau et al. (2021): SWOT river database (SWORD). Zenodo, doi:10.5281/zenodo.4917236

Further IRIS versions are released regularly with the addition of new ICESat-2 observation cycles or updates to the SWORD database. Overall, the number of WSS observations has increased by 50% from 2,303,548 in IRIS version v1 to 3,465,941 in v2.2. The increasing number of observations facilitates to study the temporal changes in WSS and improves the confidence in the average WSS values. Figure 2.9 shows the number of new and removed observations with the updated ICESat-2 ATL13 data and additional cycles. The updated ice flags led to a significant decrease in north-eastern Siberia, while most new observations were added in the major river basins. The development of IRIS was carried out as part of the **DFG project ARISAS**, which is part of the **DFG Research Unit 2630 GlobalCDA** (Understanding the global freshwater system by combining geodetic and remote sensing information with modelling using a calibration/data assimilation, `https://globalcda.de/`).

Related publications

Andersen O.B., Rose S.K., Hart-Davis M.G.: *Polar Ocean Tides - Revisited Using Cryosat-2.* Remote Sensing, 15(18), 4479, doi:10.3390/rs15184479, 2023

Dettmering D., Schwatke C.: *Comparison of different methods to account for the plasmaspheric electron content in GNSS-derived ionospheric altimeter corrections and their impact on sea level trend estimation.* Earth, Planets and Space, 75(7), doi:10.1186/s40623-023-01764-0, 2023

Ehlers F., Schlembach F., Kleinherenbrink M., Slobbe C.: *Validity assessment of SAMOSA retracking for fully-focused SAR altimeter waveforms.* Advances in Space Research, 71(3), 1377-1396, doi:10.1016/j.asr.2022.11.034, 2023

Halicki M., Schwatke C., Niedzielski T.: *The impact of the satellite ground track shift on the accuracy of altimetric measurements on rivers: A case study of the Sentinel-3 altimetry on the Odra/Oder River.* Journal of Hydrology, 128761, doi:10.1016/j.jhydrol.2022.128761, 2023

Hart-Davis M.G., Laan S., Schwatke C., Backeberg B., Dettmering D., Zijl F., Verlaan M., Passaro M., Seitz F.: *Altimetry-derived tide model for improved tide and water level forecasting along the European continental shelf.* Ocean Dynamics, doi:10.1007/s10236-023-01560-0, 2023

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Laignel B., Vignudelli S., Almar R., Becker M., Bentamy A., Benveniste J., Birol F., Frappart F., Idier D., Salameh E., Passaro M., Menendez M., Simard M., Turki E.I., Verpoorter C.: *Observation of the Coastal Areas, Estuaries and Deltas from Space.* Surveys in Geophysics, doi:10.1007/s10712-022-09757-6, 2023

Le Gouvello D., Heye S., Harris L., Temple-Boyer J., Gaspar P., Hart-Davis M.G., Louro C., Nel R.: *Dispersal corridors of neonate sea turtles from dominant rookeries in the Western Indian Ocean.* Ecological Modelling, 487, 110542, doi:10.1016/j.ecolmodel.2023.110542, 2024

Magalhaes J., Lapa I.G., Santos-Ferreira, A., da Silva, J., Piras F., Moreau T., Amraoui S., Passaro M., Schwatke C., Hart-Davis M.G., Maraldi C., Donlon C.: *Using a Tandem Flight*

Configuration between Sentinel-6 and Jason-3 to Compare SAR and Conventional Altimeters in Sea Surface Signatures of Internal Solitary Waves. Remote Sensing, 15(2), 392, doi:10.3390/rs15020392, 2023

Müller F.L., Paul S., Hendricks S., Dettmering D.: *Monitoring Arctic thin ice: a comparison between CryoSat-2 SAR altimetry data and MODIS thermal-infrared imagery.* The Cryosphere, 17(2), 809-825, doi:10.5194/tc-17-809-2023, 2023

Passaro M., Juhl M.-C.: *On the potential of mapping sea level anomalies from satellite altimetry with Random Forest Regression.* Ocean Dynamics, 73(2), 107-116, doi:10.1007/s10236-023-01540-4, 2023

Passaro M., Schlembach F., Oelsmann J., Dettmering D., Seitz F.: *Coastal Assessment of Sentinel-6 Altimetry Data during the Tandem Phase with Jason-3.* Remote Sensing, 15(17), 4161, doi:10.3390/rs15174161, 2023

Rudenko S., Dettmering D., Zeitlhöfler J., Alkahal R., Upadhyay D., Bloßfeld M.: *Radial orbit errors of contemporary altimetry satellite orbits.* Surveys in Geophysics, 44, 705-737, doi:10.1007/s10712-022-09758-5, 2023

Scherer D., Schwatke C., Dettmering D., Seitz F.: *ICESat-2 river surface slope (IRIS): A global reach-scale water surface slope dataset.* Nature Scientific Data, 10(1), 359, doi:10.1038/s41597-023-02215-x, 2023

Schlembach F., Ehlers F., Kleinherenbrink M., Passaro M., Dettmering D., Seitz F., Slobbe C.: *Benefits of fully focused SAR altimetry to coastal wave height estimates: A case study in the North Sea.* Remote Sensing of Environment, 289, 113517, doi:10.1016/j.rse.2023.113517, 2023

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3 Cross-Cutting Research Topics

The three overarching research topics Atmosphere, Regional Gravity Field, and Standards and Conventions are closely interlinked with the DGFI-TUM Research Areas Reference Systems and Satellite Altimetry.

The atmosphere (Section 3.1) is crucial for the analysis of all geodetic space observations. Satellite orbits are perturbed by atmospheric drag, and measurement signals are affected by refraction and propagation delay. Such effects must be adequately taken into account in precise orbit determination and geodetic data analysis, and the optimisation of respective correction models is an important research task. Vice versa, geodetic space observations also provide valuable information about the state and dynamics of the atmosphere. This information can be used to study atmospheric processes and the impacts of space weather. In recent years, space weather has become an emerging topic and increasingly attracted the attention of society and politics. It can severely impact or damage modern infrastructures, including navigation systems, power supply and communication facilities. Conclusions about space weather can be drawn from variations in the upper atmosphere. Over the past years, DGFI-TUM has built up strong expertise in modeling and forecasting global and regional structures of the electron and neutral density in the Earth's upper atmosphere through the joint evaluation of geodetic space observations using problem-adapted data representations and estimation techniques. DGFI-TUM is strongly involved in space weather research in Germany and has cooperated with the German Space Situational Awareness Center (Weltraumlagezentrum) and DLR for many years. At the international level, DGFI-TUM has chaired the Focus Area on Geodetic Space Weather Research (FA-GSWR) of the Global Geodetic Observing System (GGOS) under the umbrella of the IAG since 2017.

A wide range of applications in geodesy require precise knowledge of the Earth's gravity field (Section 3.2), including the realization and unification of height systems and the determination of precise satellite orbits. The latter are a prerequisite for the calculation of accurate reference frames or for reliable estimates of water levels from satellite altimetry. Temporal changes of the gravity field contain information about mass transports in the Earth system and are of interest, for example, for the study of dynamic processes in the Earth's interior or in the hydrosphere. DGFI-TUM primarily focuses on theoretical and practical aspects of regional gravity field determination with the goal to create high-resolution potential fields by combining different data types, such as space- and airborne gravity measurements, satellite altimetry, terrestrial and ship gravimetry.

Uniform standards and conventions (Section 3.3) are essential to ensure the highest possible consistency of geodetic parameters and science data products. At the international level, DGFI-TUM is deeply involved in the activities of the relevant bodies for defining standards in geodesy and monitoring their implementation. DGFI-TUM chairs the GGOS Bureau of Products and Standards (BPS) and operates it jointly with several partners. Within the United Nations Global Spatial Information Management (UN-GGIM), DGFI-TUM provides the IAG representative for the key area 'Data Sharing and Development of Standards' in the UN-GGIM Subcommittee 'Geodesy'.

3.1 Atmosphere

The Earth's atmosphere can be structured according to its charge state into the neutral lower atmosphere up to about 50 km altitude and the charged upper atmosphere, which comprises the ionosphere up to about 1000 km altitude and the plasmasphere above. Both the ionosphere and the plasmasphere can be characterized by the number of free electrons (i.e. the electron density) and play a key role in monitoring space weather. In 2023, the **DFG project MuSE** (Multi-Satellite ionosphere-plasmasphere Electron density reconstruction) within the **DFG priority programme (SPP) 1788 Dynamic Earth** and the **DAAD project ML-IonoCast** (Machine Learning for Forecasting the Ionospheric Total Electron Content) covered most of the research work at DGFI-TUM on modeling the ionosphere and plasmasphere.

The ionosphere can be sub-divided into different layers, namely – from bottom to top – the $D-$, the $E-$, the F_1- and the F_2-layer, with the latter being the most dominant one. Therefore, the ionosphere is also split into the bottomside part up to the peak of the F_2-layer and the topside part above the F_2-peak including the transition to the plasmasphere. In the last decades, modelling of the ionosphere has concentrated on the bottomside part, as this has the strongest impact on geodetic space observations in form of signal bending and delay. In this context, a model of the ionospheric electron density including a simplified approach for the plasmasphere was developed at DGFI-TUM, based on an optimization approach with equality and inequality constraints for selected key parameters. This approach is described in detail in the PhD thesis of Lalgudi Gopalakrishnan (2023). In recent years, ionosphere research has shifted more towards the topside ionosphere and the plasmasphere. Numerous studies have shown that, depending on the daytime, there is also a significant impact of the topside ionosphere and the plasmasphere on the bending and delay of L-band signals, as observed in GNSS applications.

The classical alternative to electron density modelling within the ionosphere and plasmasphere is modelling the vertical total electron content (VTEC), i.e. the integral of the electron density along the vertical. Consequently, the modelling approaches for VTEC do not consider the height dependency. VTEC values are directly observable by GNSS multi-frequency measurements. In the DGFI-TUM Annual Report 2022, we presented a procedure for constructing a regional, high-resolution and high-precision VTEC model from a global VTEC model using a densification approach based on both two-dimensional (2D) B-spline series expansions and terrestrial GNSS observations. Jeres et al. (2023) reported about a comparison study of various global and regional models over Brazil and confirmed that the two regional VTEC models developed at DGFI-TUM show the best performances with respect to ionosonde measurements and in precise point positioning (PPP). As an alternative to 2D B-spline expansions, VTEC can regionally be modelled by a 2D Taylor series expansion. Natras et al. (2023a) developed a regional VTEC model for the Western Balkans by using an artificial neural network that combines 2D Taylor series coefficients estimated from CORS data with spatiotemporal (latitude, longitude, hour of day), solar (F10.7) and geomagnetic (Kp, Dst) parameters. The following provides an overview of the results achieved in 2023 within MuSE and ML-IonoCast, and also on the current status of the GGOS Focus Area on Geodetic Space Weather Research (FA-GSWR).

Electron density reconstruction within topside ionosphere and plasmasphere

Knowing the electron density distribution within the ionosphere (bottomside and topside) and the plasmasphere as precisely as possible is important for applications such as PPP, autonomous driving, precision agriculture and the detection of space weather events. An electron density model of the topside ionosphere and the plasmasphere was developed at DGFI-TUM within the **DFG project MuSE** by applying an Ensemble Kalman Filter (EnKF) based on slant total electron content (STEC) measurements of low-Earth-orbiting (LEO) satellites of the Swarm and the Formosat-3/COSMIC (F3/C) mission as well as TerraSAR-X, MetOp-A and MetOp-B[32]. Since we use a 3D discretization of the topside ionosphere and plasmasphere, the electon density values of the voxels define the elements of the state vector. For the propagation, i.e., the transition of the state vector from one epoch to the following one, three different approaches have been developed. In the *'Rotation approach' (Rot)* it is assumed that in a geomagnetic Sun-fixed coordinate system the ionosphere remains invariant while the Earth rotates below. In the *'Exponential decay approach' (Exp)* the differences of the electron density values of the voxels and corresponding values from a background model are propagated from one epoch to the next by assuming persistence combined with an exponential decay. As background model we chose the empirical NeQuick model. In the *'Rotation with Exponential decay approach' (Rot and Exp)* the propagation is defined as a combination of both. These three approaches are validated together with the NeQuick model and the simultaneous multiplicative column normalized method plus (SMART+), used as known benchmarks. SMART+ is based on an algebraic reconstruction technique (ART) that is used in the analysis of computed tomography data in medicine and has been extended and adapted here for the analysis of 3D ionospheric tomography data[33]. For the validation we defined a global 3D grid with altitudes between 430 and 20,200 km, for two periods of the year 2015 covering quiet and stormy ionospheric conditions, including the St. Patrick Storm day (March 17, 2015). We investigated the capability of the five approaches to reproduce electron density values derived from the Van Allen Probes (VAP) satellite mission, the in-situ electron density measurements from the Swarm Langmuir Probes (LP) and the ionospheric radio occultation (IRO) profiles from the F3/C mission.

The astrophysical VAP mission was part of NASA's 'Living With a Star' programme and consisted of the twin satellites VAP-A and VAP-B, launched 2012. The mission aimed to study the Van Allen Radiation Belts surrounding the Earth. It provided for around 7 years electron density values derived from electric field measurements at altitudes of up to 5.8 Earth radii along a highly elliptical orbit. The validation of our five approaches with VAP-A and VAP-B data was performed in the altitude range between 5,000 and 20,200 km. One important result is, that independent from the two selected time periods, the NeQuick model must be improved significantly within the plasmasphere. The three EnKF approaches reduce the deviations of NeQuick with respect to the VAP measurements by around 9%, SMART+ reduces them by circa 5%.

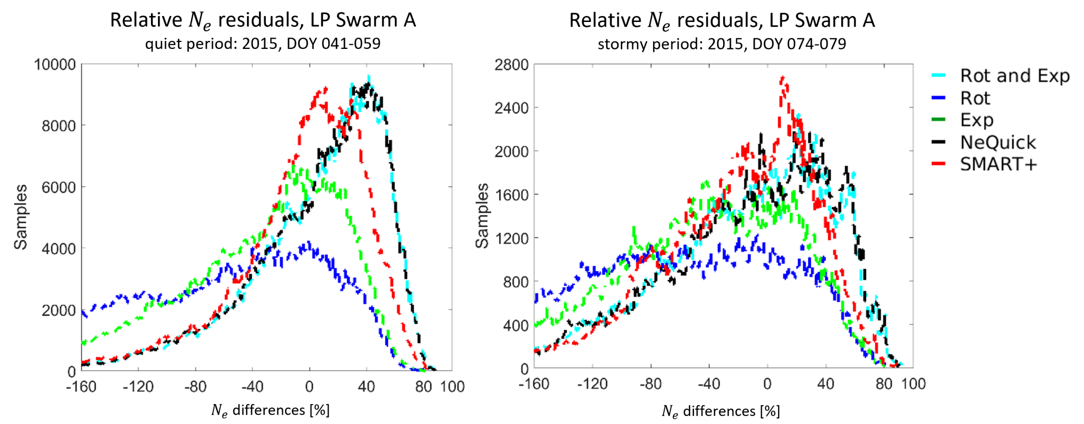


Figure 3.1: *Distribution of the relative electron density residuals derived by the three EnKF propagation methods, NeQuick and SMART+ compared to the Swarm-A LP observations during a quiet (left) and a stormy space weather period (right), both in 2015. The stormy period includes the St. Patrick storm day.*

[32]Gerzen T., Minkwitz D., Schmidt M., Erdogan E. (2020): *Analysis of different propagation models for the estimation of the topside ionosphere and plasmasphere with an ensemble Kalman filter.* Ann. Geophys., doi: 10.5194/angeo-38-1171-2020

[33]Gerzen T., Minkwitz D. (2016): *Simultaneous multiplicative column normalized method (SMART) for 3D ionosphere tomography in comparison with other algebraic methods.* Ann. Geophys., doi:10.5194/angeo-34-97-2016

Figure 3.1 depicts as another validation result the relative residuals between the in-situ LP electron density measurements of Swarm A and the corresponding electron density values calculated by the three EnKF propagation approaches 'Rot', 'Exp' and 'Rot and Exp' as well as NeQuick and SMART+. The results show that SMART+ outperforms the other approaches. This statement applies to almost all of the validation methods used in this study[34].

Uncertainty Quantification for Machine Learning Based Ionosphere Forecasting

Machine Learning (ML) techniques can be used not only to forecast VTEC values, but also to determine realistic and reliable forecast uncertainties or accuracies. In 2023, we studied this issue by adding an uncertainty quantification (UQ) component to the ML-based forecast models either considering only deterministic model uncertainties or both deterministic model uncertainties and stochastic data uncertainties. In this way, we developed and implemented four probabilistic ML-based approaches for 1-day VTEC forecasts including 95% confidence intervals, namely (1) the Super Ensemble (SE), (2) the Bayesian Neural Network (BNN), (3) the Quantile Gradient Boosting (QGB), and (4) the Bayesian Neural Network including Data uncertainty (BNN+D). While the SE and BNN approaches only take model uncertainties into account, the other two approaches, QGB and BNN+D, include both model and data uncertainties; for more details see Natras et al. (2023b) and the PhD thesis of Natras[35].

In a numerical study on VTEC forecast, we applied the aformentioned approaches to a time period from January 2015 to December 2017. The training data are covering the first two years while the testing is performed for the subsequent year 2017. In the 12 panels of Fig. 3.2, we present the 1-day VTEC forecast results in blue for the time interval from September 6 to 10, 2017, i.e. the most intense solar activity period in 2017, for three points P_1, P_2 and P_3, which all have the same longitude ($10°E$) but different latitudes ($70°N$, $40°N$, and $10°N$) and thus, represent areas at high, mid, and low latitudes, respectively. Furthermore, the panels show in light green the 95% confidence intervals along the VTEC axis and in orange the ground truth (GT) VTEC data of the global ionosphere maps (GIM) from the Center for Orbit Determination in Europe (CODE).

The following conclusions can be drawn from the results of the four approaches shown in the four blocks of Fig. 3.2:

1. SE and BNN provide the smallest 95% confidence intervals and thus, provide too optimistic results. In fact, the GT VTEC values are in 50% of the presented time interval outside the forecasted confidence intervals.
2. The approaches capturing data uncertainties, QGB and BNN+D, provide much wider 95% confidence intervals, which contain the GT values for around 95% of the presented time interval. They appear to be much more realistic and reliable.
3. The computationally most demanding method is BNN+D, while QGB is the fastest one.

Natras et al. (2023b) present further investigations, tests and conclusions on the four approaches. Taking all these individual evaluations into account, QGB appears to have the best performance.

[34] Gerzen T., Minkwitz D., Schmidt M., Rudenko S. (in preparation): *Performance analysis of the NeQuick model, ensemble Kalman filter and SMART+ based estimations of the topside ionosphere and plasmasphere by electron density measurements of Van Allen Probes, Formosat-3/COSMIC IRO and Swarm Langmuir Probes.*

[35] Natras R. (2024): *Machine learning for modeling and forecasting the ionosphere Vertical Total Electron Content, including space weather effects and uncertainty quantification.* Dissertation, Technical University of Munich

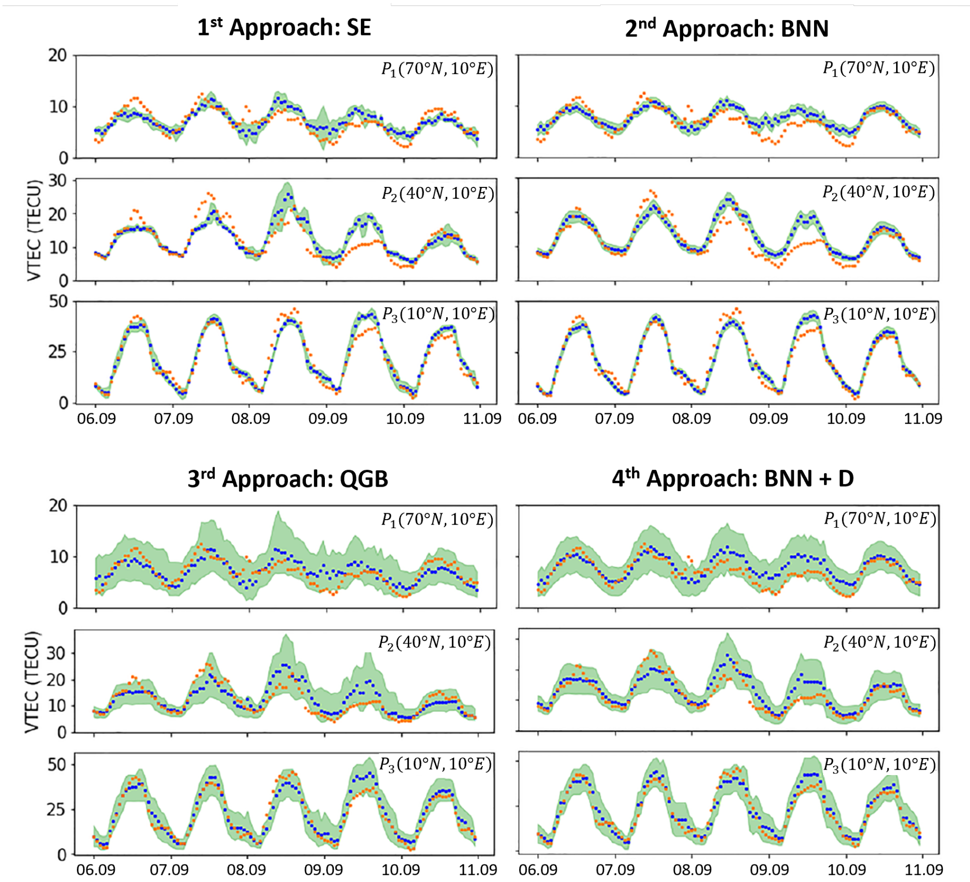


Figure 3.2: *VTEC forecasts (blue dots) from the four probabilistic ML-approaches SE (top left), BNN (top right), QGB (bottom left) and BNN+D (bottom right) computed with a forecast time step of 1 day; 95% confidence intervals are plotted as light green bands. VTEC series of CODE (orange dots) act as ground truth. All data are plotted for the solar active period September 6 to 11, 2017 at the 3 points P_1, P_2 and P_3 located at different latitudes (Natras et al. 2023b).*

GGOS Focus Area on Geodetic Space Weather Research

Since 2017 Geodetic Space Weather Research is a Focus Area (FA-GSWR) within GGOS. The main objectives of the FA-GSWR are the development of (1) improved ionosphere, plasmasphere and thermosphere models, (2) the investigation of the coupling processes between these atmospheric sub-components and (3) a better understanding of space weather events and their possible monitoring by space missions and space observing systems. Figure 3.3 shows in the center the ionosphere/plasmasphere and the thermosphere embedded within the magnetosphere. While in the top part of the figure the most important geodetic and solar observation techniques are displayed, the bottom part shows the science data products of the FA-GSWR that will in a later stage be provided to users for direct application.

In the current period from 2023 to 2027, research will focus on the analysis of coupling processes and the combination of geodetic and solar observation techniques. This also includes the consideration of physical models such as TIE-GCM. Four JSGs have been set up (see Fig. 3.3), which will work together on the following tasks:

- extensive simulation studies to assess the impact of space weather events on technical systems and to define necessary actions in case of severe space weather events,
- development of ionosphere and thermosphere models (maps),

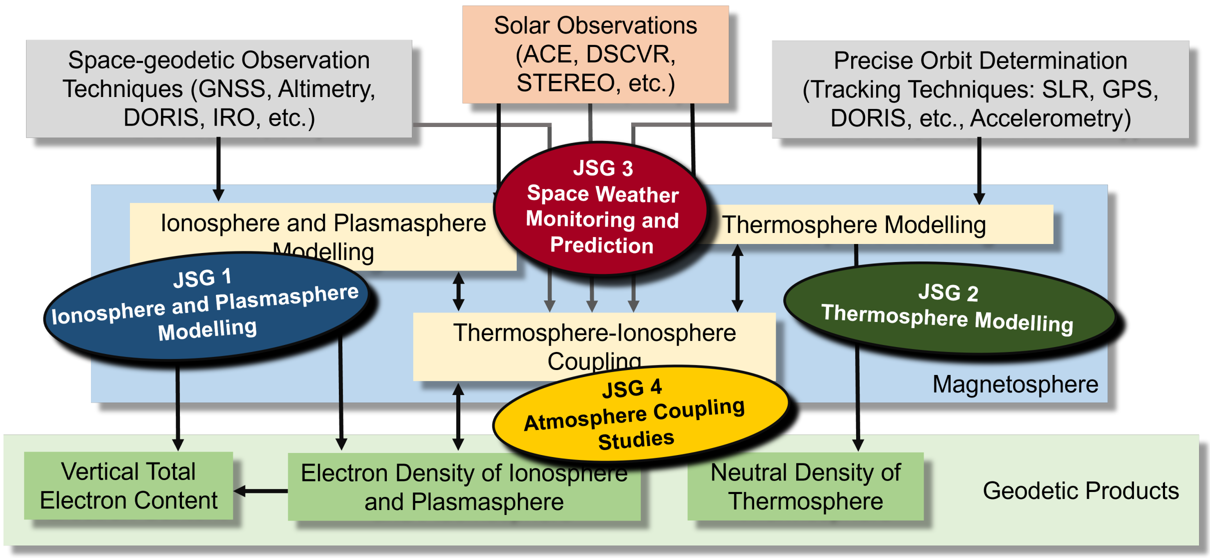


Figure 3.3: Structure of the FA-GSWR for the period 2023 to 2027. The four Joint Study Groups (JSG) are visualized in the chart at the positions according to their scientific tasks.

- establishment of recommendations for the applications of relevant models, e.g., in precise satellite orbit determination, for collision avoidance, in space debris analysis, and for re-entry computations,
- extension of the research from the upper to the lower atmosphere including an integrated analysis of horizontal and vertical (in cooperation with the newly proposed GGOS FA on Combined Tropospheric Products) coupling processes,
- projection of climate change effects from the lower to the upper atmosphere in cooperation with the IAG Intercommission Committee on Geodesy for Climate Research (ICCC),
- organization of focused interdisciplinary workshops, for example with the International Association of Geomagnetism and Aeronomy (IAGA).

More information about the Focus Area and the work within the JSGs is available on the FA-GSWR website: https://ggos.org/about/org/fa/geodetic-space-weather-research/.

Related publications

Jerez G.O., Hernández-Pajares M., Goss A., Prol F.S., Alves D.B.M., Monico J.F.G., Schmidt M.: Two-way Assessment of Ionospheric Maps Performance Over the Brazilian Region: Global Versus Regional Products. Space Weather, 21, doi:10.1029/2022SW003252, 2023

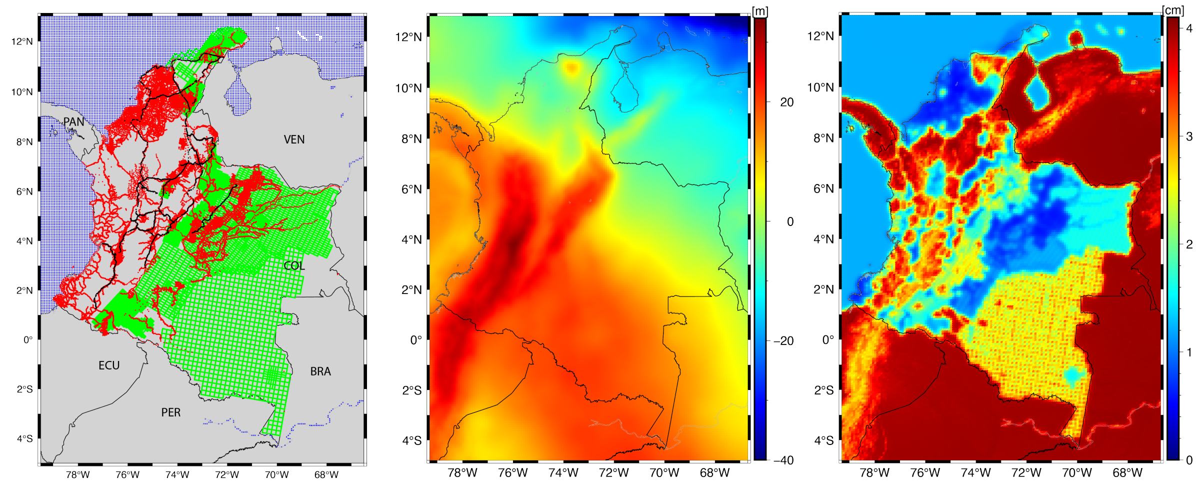
Lalgudi Gopalakrishnan G.: Ionosphere Electron Density Modelling Using a Constrained Optimization Approach. Dissertation, Bayerische Akademie der Wissenschaften, DGK C 924, 2024, ISBN 978-3-7696-5336-6, identical with the TUM online publication, 2023

Natras R., Goss A., Halilovic D., Magnet N., Mulic M., Schmidt M., Weber R.: Regional Ionosphere Delay Models Based on CORS Data and Machine Learning. NAVIGATION: Journal of the Institute of Navigation, 70(3), navi.577, doi:10.33012/navi.577, 2023a

Natras R., Soja B., Schmidt M.: Uncertainty Quantification for Machine Learning-Based Ionosphere and Space Weather Forecasting: Ensemble, Bayesian Neural Network, and Quantile Gradient Boosting. Space Weather, doi:10.1029/2023SW003483, 2023b

3.2 Regional Gravity Field

Regional high-resolution gravity refinement is crucial for many applications in geodesy and geophysics, including the realization of the International Height Reference System (IHRS). DGFI-TUM conducts research in this regard in the framework of the **DFG project Geo-H** (Enhanced geopotential field modeling as basis for the establishment of precise height systems) together with TUM's Chair of Astronomical and Physical Geodesy. To obtain a regional gravity model with high accuracy, different types of gravity measurements such as terrestrial, airborne and shipborne observations need to be combined with satellite gravimetry and altimetry data in an optimal manner (Liu 2023). For this purpose, novel numerical methods have been developed at DGFI-TUM in recent years[36,37]. Besides the advanced modeling methods, another key to a high-precision gravity model is the data coverage and quality, which is why regional gravity field modeling in less developed regions are especially challenging. In a recent work, we tackle this problem in a case study of Colombia.



(a) *(b)* *(c)*

Figure 3.4: *(a) Study area in Colombia and available gravity data, including terrestrial (red points), airborne (green flight tracks), and altimetry (blue points) data, as well as the GNSS/leveling data (black points) for validation, (b) computed quasi-geoid model QGeoidCOL2023, and (c) its standard deviation*

Figure 3.4a shows the available gravity data, including terrestrial and airborne observations provided by the National Mapping Agency, the Colombian Geological Survey, and the oil company Ecopetrol as well as gravity anomaly data from DTU21GRA for the offshore area. Terrestrial data stem from 101 gravity surveys with altogether 65,763 observation points that were conducted between 1941 and 2000. Although the exact measurement accuracy is unknown due to the unavailability of metadata, it is not expected to be high considering that the terrestrial data were collected by different surveys and the positions of older observations were frequently read from maps. Thus, the records are examined for systematic errors and wrong data: outliers in the coordinates are ruled out by comparing the given height values to that from the SRTM terrain model, and outliers in the gravity values are identified by comparing to a global gravity model (XGM2019) plus a topography model (ERTM2160) through a three-sigma rule[38].

[36] Liu Q. et al. (2020): *Determination of the regularization parameter to combine heterogeneous observations in regional gravity field modeling.* Remote Sensing, doi:10.3390/rs12101617

[37] Liu Q. et al. (2022): *Combination of different observation types through a multi-resolution representation of the regional gravity field using the pyramid algorithm and parameter estimation.* J. Geodesy, doi:10.1007/s00190-022-01670-5

[38] Liu Q., Schmidt M., Sánchez L., et al. (2024): *High-resolution regional gravity field modeling in data-challenging regions for the realization of geopotential-based height systems.* Earth, Planets and Space, doi:10.1186/s40623-024-01981-1

Airborne gravity data was collected in 17 airborne campaigns between 2005 and 2010, with mean flight altitudes ranging from 1,200 m to 6,400 m. As the airborne data have been post-processed and the corresponding metadata are not available, inconsistencies are likely between the different campaigns. Thus, a crossover analysis is performed to indicate the accuracy of individual airborne surveys, an along-track Gaussian low-pass filter is applied to reduce high-frequency noise, and a data evaluation in comparison to the SATOP (SAtellite-TOPography) model, which merges the satellite-only global gravity model GOCO06s and the Earth2014 topography model is conducted. This evaluation reveals long-wavelength errors, i.e., biases in the 17 airborne surveys. A bias estimation method is then developed based on the methods of spherical radial basis functions (SRBFs), and the estimated biases are removed from the airborne data before they are combined with the terrestrial and altimetry data for the quasi-geoid modeling.

The calculated $5' \times 5'$ quasi-geoid QGeoidCOL2023 is visualized in Fig. 3.4b. Height anomaly values range from -39.95 m to 33.42 m, which illustrates the high variability of the gravity field in the region. The corresponding standard deviation of the calculated quasi-geoid is shown in Fig. 3.4c. It ranges from a few millimeters to around 4 cm. The values are smaller in areas where denser gravity observations are available (cf. Fig. 3.4a). QGeoidCOL2023 is validated against GPS/leveling data in Colombia (comparison results are given in Section 1.4). It outperforms the latest South American quasi-geoid model QGEOID2021 and the five recent high-resolution GGMs, namely XGM2019, GECO, SGG-UGM-1, EIGEN6C4, and EGM2008.

Related publication

Liu Q.: Regional gravity field refinement for geoid height modeling based on the combination of data from various observation techniques. Dissertation, Bayerische Akademie der Wissenschaften, DGK, C 896, München, ISBN 978-3-7696-5308-3, 2023

3.3 Standards and Conventions

With the technological progress of space- and ground-based Earth observation systems and sensors, geodesy is capable of determining the geometric shape of land, ice and sea surfaces, the Earth's orientation in space, its rotation and gravity field as global functions of space and time with increasingly higher precision and resolution. Geodesy thus provides the metrological basis for the reliable quantification of changes to our planet caused by geodynamic processes and climate change, as well as for numerous applications such as positioning and satellite navigation. However, to ensure consistent results and take full advantage of technological improvements and the high accuracy of geodetic observations, common standards, conventions and models are essential for data analysis and in the creation of high-quality science data products.

DGFI-TUM is strongly involved in the definition and implementation of unified standards and conventions in geodesy. This important task is carried out at international level by GGOS, where the DGFI-TUM has chaired the Bureau of Products and Standards (BPS), one of the two GGOS Bureaus, since many years (the second one is the Bureau of Networks and Observations, BNO, chaired by the Havard Smithonian Center for Astrophysics, USA). Furthermore, within GGOS, DGFI-TUM also provides the current GGOS President (Laura Sánchez, since 2023) and chairs two of the GGOS Focus Areas (FA Unified Height System, completed in 2023, see Section 1.4; FA Geodetic Space Weather Research, ongoing, see Section 3.1). DGFI-TUM also contributes to the GGOS Affiliate GGOS D-A-CH (established in 2021) which aims to bundle the GGOS-related activities of Germany, Austria and Switzerland in terms of science and infrastructure. The organizational structure of GGOS is shown in Figure 3.5.

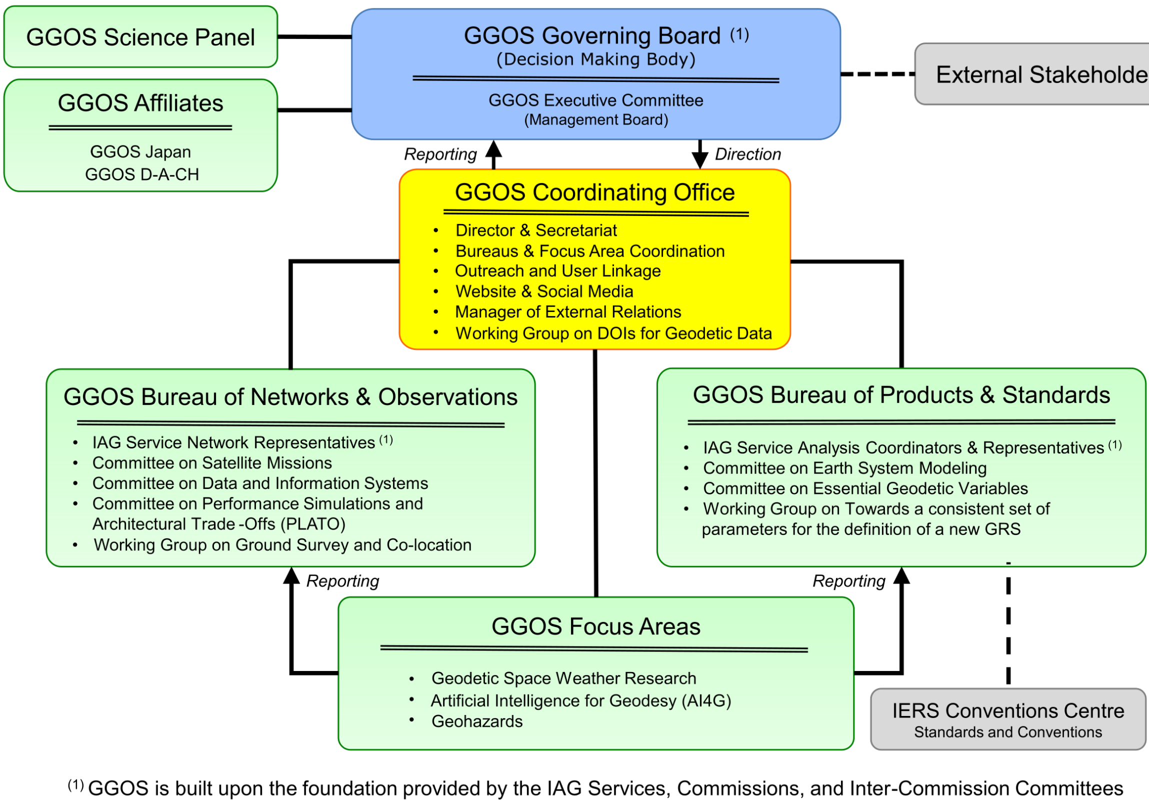


Figure 3.5: *Organizational structure of IAG's Global Geodetic Observing System (GGOS).*

GGOS Bureau of Products and Standards

The BPS is chaired by DGFI-TUM and operated jointly with TUM's Chair of Astronomical and Physical Geodesy within the Research Group Satellite Geodesy (Forschungsgruppe Satellitengeodäsie, FGS). Further involved partners are GFZ (German Research Centre for Geosciences, Potsdam) and DLR (German Aerospace Centre, Oberpfaffenhofen).

The following GGOS entities are associated to the BPS:

- Committee 'Contributions to Earth System Modeling';
- Committee 'Definition of Essential Geodetic Variables (EGVs)';
- Working Group 'Towards a consistent set of parameters for the definition of a new GRS'.

The BPS supports GGOS in its goal to obtain high-quality science data products for science and society. Figure 3.6 illustrates the integration of the different geodetic observation techniques to determine geodetic parameters as the basis for Earth system studies[39]. On the other hand, physical processes in the Earth system influence geodetic measurements in many ways. Thus, the development and unified implementation of enhanced correction and reduction models improves geodetic data analysis and results in more precise and consistent geodetic parameters.

[39] Angermann D., Sánchez L. (2024): *Global Geodetic Observing System (GGOS)*. In: Encyclopedia of Geodesy. Book series: Encyclopedia of Earth Sciences Series, doi:10.1007/978-3-319-02370-0

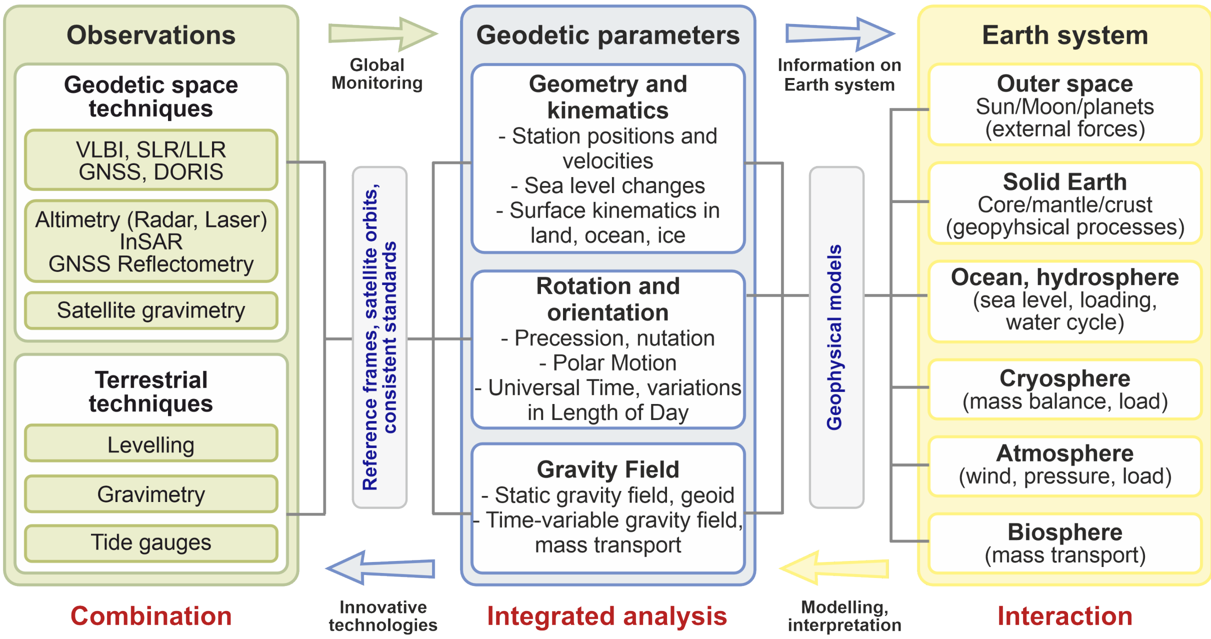


Figure 3.6: *Integration of geodetic observation techniques to determine consistent geodetic parameters as the basis for Earth system studies.*

Unification of geodetic standards and conventions

A continuous task of the BPS is to keep track and foster the homogenization of adopted geodetic standards and conventions across all components of the IAG. The BPS has compiled an inventory of standards and conventions in geodesy, which presents the current status, identifies gaps and inconsistencies, and provides open issues and recommendations regarding the consistent application of standards and conventions[40].

To accomplish its tasks, the BPS closely collaborates with the IAG Scientific Services, the IERS Conventions Center and other entities involved in standards and conventions, such as the IAU Commission A3 'Fundamental Standards', the International Organization for Standardization (ISO/TC 211) and the United Nations Global Geospatial Information Management (UN-GGIM) Subcommittee on Geodesy (SCoG) Working Group 'Data Sharing and Development of Geodetic Standards'. In the framework of the revision of the IERS Conventions, the BPS contributes to the renewal of Chapter 1 'General definitions and numerical standards' in its function as Chapter Expert.

Promotion of geodetic science data products

In collaboration with the IAG and other GGOS components, the BPS has created user-friendly descriptions for geodetic science data products, which have been implemented at the GGOS website (`www.ggos.org`). In this way, GGOS contributes to promote geodetic results to other disciplines and to make geodesy visible in the geoscientific community and beyond[41] (Angermann et al., 2023a, 2023b). The BPS also supports the GGOS Coordinating Office in the development of the GGOS Portal[42] that serves as a unique search and access point (one-stop shop)

[40] Angermann D. et al. (2020): *Bureau of Products and Standards: Inventory of standards and conventions used for the generation of IAG products*. J. Geodesy, doi:10.1007/s00190-020-01434-z

[41] Angermann D., et al. (2022): *GGOS Bureau of Products and Standards: Description and promotion of geodetic products*. IAG Symposia, doi:10.1007/1345_2022_144

[42] Sehnal M., Sánchez L, Angermann D., et al. (2024):*Emphasizing the value of geodesy to science and society through IAG-GGOS*. IAG Symposia, doi:doi.org/10.1007/1345_2024_243

for geodetic data and products to ensure better accessibility, user-friendly interfaces, easy-to-understand descriptions, and a comprehensive overview of data sources. Furthermore, the BPS contributes to GGOS outreach activities in social media, e.g. through the creation of videos about geodesy and geodetic results in non-specialist language (Fig. 3.7).

Figure 3.7: *GGOS videos 'Discover GGOS and Geodesy' and 'Terrestrial Reference Frames - Connecting the World through Geodesy' (www.ggos.org, screenshot taken on 2024-03-05).*

Definition of Essential Geodetic Variables (EGV)

The concept of Essential Variables (EV) is being used by different scientific communities to accurately describe and monitor changes within and between Earth system components using observational data. The EV shall be of high impact, feasible, sustainable and consistent. Within the geoscientific community, UN's Global Climate Observing System (GCOS, https://gcos.wmo.int/ has defined Essential Climate Variables (ECV) that critically contribute to the characterization of the Earth's climate, and the Global Ocean Observing System (GOOS, https://goosocean.org/) has defined Essential Ocean Variables (EOV) that focus on physics, biogeochemistry, biology and ecosystems of the oceans.

Similarly, GGOS is working on the definition and implementation of **Essential Geodetic Earth Observation Variables (EGV)** as a systematic and sustainable contribution of geodesy to the observation of the Earth system. EGV are geometrical and physical variables, or a group of interrelated variables, that are critical to characterizing the geometrical and physical shape of the Earth and to its orientation in space. Led by the BPS, the process of defining the EGV was initiated in 2023.

EGV are determined from geodetic observations and are essential, for example, for the assessment of potential natural and climate-related hazards and the development of mitigation strategies. The EGV also include geodetic parameters that are of fundamental importance for socially and economically relevant applications such as positioning or navigation. By underpinning the relevance of sustainable geodetic services, EGV support the work of the UN-GGCE (United Nations Global Geodetic Centre of Excellence) and other high-level international organizations like the UN-FCCC (United Nations Framework Convention on Climate Change), the IPCC (Intergovernmental Panel on Climate Change) and GEO (Group on Earth Observation).

Related publications

Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler U., Sánchez L., Steigenberger P.: *GGOS Bureau of Products and Standards: BPS Activity Report 2023*. GGOS Days 2023, Acalá de Henares, Spain, doi:10.5281/zenodo.8414290, 2023a

Angermann D., Pail R., Seitz F., Hugentobler U.: *The importance of geodetic reference frames - A uniform basis to tackle current and future challenges*. GIM International, 37(7), 2023b

4 Scientific Transfer

Transfer of knowledge, scientific results and data within the scientific community and to the public is an essential element of scientific work. Strong involvement in scientific organizations and networking in collaborative research programs at national and international level is a long-standing important pillar in the international strategy of DGFI-TUM. Scientific publications and presentations, participation in scientific meetings, guest visits and the operation of internet and data portals are the most important instruments of cross-disciplinary information exchange.

Section 4.1 contains a compilation of the positions and involvement of DGFI-TUM staff in national and international scientific organizations. The institute is intensively networked with other institutions worldwide, in particular through research activities within the International Union of Geodesy and Geophysics (IUGG), the International Astronomical Union (IAU), and the International Association of Geodesy (IAG). DGFI-TUM is a major player in the IAG's Global Geodetic Observing System (GGOS) (cf. Section 3.3) and operates research centers, analysis centers, and data centers, mostly on the basis of long-term commitments (cf. Section 1). Scientists of DGFI-TUM participate in various collaborative projects, working and study groups, and assume numerous key leadership and management positions to actively shape the future direction of international geodetic research.

Section 4.2 lists the scientific publications of the year 2023. Section 4.3 provides the presentations given by DGFI-TUM scientists at the numerous national and international conferences, symposia and workshops displayed in Section 4.4. Guests who visited DGFI-TUM as part of research collaborations in 2023 are listed in Section 4.5. To share scientific information and data with partners and the interested public, DGFI-TUM maintains several websites, public data bases, and social media channels. An overview of the portals operated is given in Section 4.6.

4.1 Functions in Scientific Bodies

United Nations Global Spatial Information Management (UN-GGIM)

- Subcommittee Geodesy, Working Group for a Global Geodetic Reference Frame (GGRF),
  IAG Representative for Key Area Data Sharing and Development of Standards:
  Angermann D.

International Astronomical Union (IAU)

- Commission A.2, Rotation of the Earth,
  Immediate Past President and Senior Advisor: Seitz F., Member: Seitz M.
- Joint IAU CA.2/IAG/IERS Working Group Consistent Realization of TRF, CRF and EOP,
  Co-Chair: Seitz M., Member: Seitz F.
- Joint IAU CA.2/IAG Working Group Improving Theories and Models of the Earth's Rotation,
  Member: Seitz F.

International Union of Geodesy and Geophysics (IUGG)

- *Representative to the Panamerican Institute for Geodesy and History (PAIGH),*
  Sánchez L.

International Association of Geodesy (IAG)

- Executive Committee,
  Member: Sánchez L.
- Global Geodetic Observing System (GGOS),
  President: Sánchez L.
- Global Geodetic Observing System (GGOS) Executive Committee,
  Member: Angermann D., Sánchez L.
- Global Geodetic Observing System (GGOS) Governing Board,
  Member: Angermann D., Kehm A., Sánchez L., Schmidt M.
- Global Geodetic Observing System (GGOS) Strategic Planing Committee,
  Member: Angermann D., Sánchez L.
- Global Geodetic Observing System (GGOS) Bureau of Products and Standards,
  Director: Angermann D., Member: Sánchez L.
- Global Geodetic Observing System (GGOS) Focus Area Unified Height System,
  Lead: Sánchez L.
- Global Geodetic Observing System (GGOS) Focus Area Geodetic Space Weather Research,
  Lead: Schmidt M.
- Global Geodetic Observing System (GGOS) Bureau of Products and Standards, Working Group Towards a consistent set of parameters for the definition of a new GRS,
  Member: Angermann D., IHRF representative: Sánchez L.
- Global Geodetic Observing System (GGOS) Focus Area Unified Height System, Joint Working Group Implementation of the International Height Reference Frame (IHRF),
  Chair: Sánchez L., Member: Liu Q.
- Global Geodetic Observing System (GGOS) Focus Area Geodetic Space Weather Research, Joint Study Group 1 Understanding ionospheric and plasmaspheric processes,
  Member: Gerzen T.
- Global Geodetic Observing System (GGOS) Focus Area Geodetic Space Weather Research, Joint Study Group 2 Thermosphere modelling improvements and applications,
  Member: Schmidt M.
- Global Geodetic Observing System (GGOS) Focus Area Geodetic Space Weather Research, Joint Study Group 3 Improved understanding of space weather events and their monitoring by satellite missions,
  Member: Dettmering D.
- Global Geodetic Observing System (GGOS) Working Group on DOIs for Geodetic Data,
  Member: Angermann D., Schwatke C.
- Global Geodetic Observing System (GGOS) Working Group on Performance Simulations and Architectural Trade-Offs (PLATO),
  Chair: Kehm A., Member: Bloßfeld M.
- Global Geodetic Observing System (GGOS) Working Group Consolidation of a best estimate GRS based on the adopted W0 of the IHRF ,
  Member: Angermann D., IHRF Representative: Sánchez L.
- Global Geodetic Observing System (GGOS) Committee Essential Geodetic Variables,
  Member: Angermann D.

- IAG Symposia Series,
  Assistant Editor-in-Chief: Sánchez L.
- Commission 1, Sub-Commission 1.2 Global reference frames,
  Chair: Bloßfeld M.
- Commission 1, Sub-Commission 1.4 Interaction of celestial and terrestrial reference frames,
  Member: Seitz M.
- Commission 1, Working Group 1.2.1 Impacts of loading on reference frame realizations,
  Member: Seitz, M.
- Commission 2, Joint Working Group 2.1.1 Establishment of the International Gravity Reference Frame,
  Corresponding member, IHRF representative: Sánchez L.
- Commission 2, Joint Working Group 2.2.2 Error assessment of the 1 cm geoid experiment,
  Member: Liu Q., Sánchez L.
- Commission 2, Sub-Commission 2.5.4: International Altimeter Service Planning Group,
  Member: Dettmering D., Schwatke C.
- Commission 3, Steering Committe ,
  Member, GGOS Representative: Sánchez L.
- Commission 4, Sub-Commission 4.3 Atmosphere Remote Sensing,
  Chair: Schmidt M.
- Commission 4, Working Group 4.3.3 Ionosphere Scintillations,
  Member: Schmidt M.
- International Altimetry Service (IAS) Pilot Service,
  Member: Dettmering D.
- Inter-Commission Committee on Geodesy for Climate Research (ICCC),
  Steering Committee member: Sánchez L.
- Inter-Commission Committee on Theory (ICCT), Joint Study Group T.26 Geoid/quasi-geoid modelling for realization of the geopotential height datum,
  Member: Sánchez L.
- Inter-Commission Committee on Theory (ICCT), Joint Study Group T.29 Machine learning in geodesy,
  Member: Natras R.
- Inter-Commission Committee on Theory (ICCT), Joint Study Group T.33 Time series analysis in geodesy and geodynamics,
  Member: Schmidt M.

International Association for the Physical Sciences of the Oceans (IAPSO)

- Best Practice Study Group on Tidal Analysis,
  Member: Hart-Davis M.G.

International Earth Rotation and Reference Systems Service (IERS)

- Directing Board,
  Associate member: Angermann D., Bloßfeld M.
- ITRS Combination Center,
  Chair: Seitz M., Member: Bloßfeld M.

- Working Group on SINEX Format,
  Member: Seitz M.
- Working Group on Site Coordinate Time Series Format,
  Member: Seitz M.

International Laser Ranging Service (ILRS)

- Governing Board,
  Member: Bloßfeld M., Schwatke C.
- Analysis Center,
  Chair: Bloßfeld M., Member: Kehm A.
- Analysis Standing Committee,
  Co-Chair: Bloßfeld M., Member: Kehm A., Schwatke C.
- EUROLAS Data Center (EDC),
  Chair: Schwatke C.
- Operations Center,
  Chair: Schwatke C.
- Data Formats and Procedures Standing Committee,
  Chair: Schwatke C.
- Networks and Engineering Standing Committee,
  Member: Schwatke C.
- Study Group on Data Format Update,
  Member: Schwatke C.
- Study Group on ILRS Software Library,
  Member: Schwatke C.
- ILRS Representative to the World Data System,
  Schwatke C.

International VLBI Service for Geodesy and Astrometry (IVS)

- Operational Analysis Center,
  Chair: Glomsda M., Member: Seitz M.
- IVS Combination Center,
  Member: M. Seitz

International DORIS Service (IDS)

- Governing Board,
  Member: Dettmering D., Sánchez L.
- Associate Analysis Center,
  Co-Chairs: Bloßfeld M., Rudenko S.
- DORIS Analysis Working Group,
  Member: Rudenko S.
- Working Group on NRT DORIS data,
  Chair: Dettmering D., Member: Schmidt M.

International GNSS Service (IGS)

- Governing Board,
  Member, GGOS Representative: Sánchez L.
- Regional Network Associate Analysis Center for SIRGAS,
  Chair: Sánchez L.
- Infrastructure Committee,
  Member: Sánchez L.
- Working Group Reference Frame,
  Member: Sánchez L.
- Ionosphere Working Group,
  Member: Schmidt M.

International Gravity Field Service (IGFS)

- Advisory Committee,
  Member: Sánchez L.
- International Height Reference Frame (IHRF) Combination Coordination,
  Co-Chair: Sánchez L.

International Service for the Geoid (ISG)

- *Scientific Advisor: Sánchez L.*

International Organization for Standardization (ISO)

- ISO/TC211,
  IAG Representative to ISO/TC211: Angermann D.

International Space Science Institute (ISSI)

- Team Understanding the connection between coastal sea level and open ocean variability through space observations,
  Member: Oelsmann J., Passaro M.

European Commission (EC) / European Space Agency (ESA)

- Copernicus POD Quality Working Group,
  Member: Dettmering D.

European Space Agency (ESA)

- Copernicus New Generation Topography Constellation Ad-Hoc Expert Group,
  Member: Passaro M.
- Copernicus Sentinel-3 Next Generation Topography Mission Advisory Group,
  Member: Passaro M.
- CryoSat Expert Group,
  Member: Passaro M.
- Coastal Altimetry Workshop Organizing Committee,
  Member: Passaro M.
- Hydrospace Scientific Committee,
  Member: Schwatke C.

European Space Agency (ESA) / European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)

- Sentinel-3 Validation Team, Altimetry Sub-Group,
  Member: Dettmering D.
- Sentinel-6 Validation Team,
  Member: Dettmering D., Oelsmann J., Passaro M., Schlembach F., Schwatke C.

Centre National d'Etudes Spatiales (CNES) / National Aeronautics and Space Administration (NASA)

- Ocean Surface Topography Science Team,
  Member: Dettmering D., Oelsmann J., Passaro M., Schlembach F., Schwatke C.
- SWOT Science Team,
  Member: Dettmering D., Schwatke C.
- SWOT Science Team Working Group Global Hydrology and Remote Sensing,
  Member: Schwatke C.
- SWOT Science Team Working Group River Science,
  Member: Schwatke C.
- SWOT Science Team Working Group Science for Lakes and Wetlands,
  Member: Schwatke C.

Sistema de Referencia Geocéntrico para las Américas (SIRGAS)

- Scientific Committee,
  Member: Sánchez L.
- SIRGAS Analysis Center,
  Chair: Sánchez L.

Forschungsgruppe Satellitengeodäsie (FGS)

- *Deputy Speaker: Seitz F.*
- Managing Board,
  Member: Bloßfeld M., Schmidt M., Seitz F.

Nansen Tutu Center for Marine Environmental Research

- Associate Researcher,
  Member: Hart-Davis M.G.

Deutsche Gesellschaft für Polarforschung (DGP)

- Working Group Polar Geodesy and Glaciology,
  Member: Müller F.L.

Deutsche Gesellschaft für Geodäsie, Geoinformation und Landmanagement (DVW)

- Working Group 7: Experimentelle, Angewandte und Theoretische Geodäsie,
  Member: Schmidt M., Seitz F.

Bayerische Akademie der Wissenschaften

- Ausschuss Geodäsie (Deutsche Geodätische Kommission, DGK),
  Member: Seitz F.

4.2 Publications

Andersen O.B., Rose S.K., Hart-Davis M.G.: *Polar ocean tides - revisited using Cryosat-2*. Remote Sensing, 15(18), 4479, doi:10.3390/rs15184479, 2023

Angermann D., Pail R., Seitz F., Hugentobler U.: *The importance of geodetic reference frames - A uniform basis to tackle current and future challenges*. GIM International, 37(7), 43-45, 2023

Costa S., Sánchez L., Piñón D., Tarrio-Mosquera J., Guimarães G., Gómez D., Drewes H., Mackern-Oberti M., Antokoletz E., de Matos A., Blitzkow D., da Silva A., Inzunza J., España D., Rodríguez O., Rozas-Bornes S., Guagni H., González G., Paucar-Llaja O., Pampillón J., Alvarez-Calderón A.: *Status of the SIRGAS Reference Frame: Recent developments and new challenges*. International Association of Geodesy Symposia, doi:10.1007/1345_2023_227, 2023

Delva P., Altamimi Z., Blazquez A., Bloßfeld M., Böhm J., Bonnefond P., Boy J.-P., Bruinsma S., Bury G., Chatzinikos M., Couhert A., Courde C., Dach R., Dehant V., Dell'Agnello S., Elgered G., Enderle W., Exertier P., Glaser S., Haas R., Huang W., Hugentobler U., Jäggi A., Karatekin O., Lemoine F., Le Poncin-Lafitte C., Lunz L., Männel B., Mercier F., Métivier L., Meyssignac B., Müller J., Nothnagel A., Perosanz F., Rietbroek R., Rothacher M., Schuh H., Sert H., Sosnica K., Testani P., Ventura-Traveset J., Wautelet G., Zajdel R.: *GENESIS: co-location of geodetic techniques in space*. Earth, Planets and Space, doi:10.1186/s40623-022-01752-w, 2023

Dettmering D.: *Working Group NRT DORIS data*. In: Soudarin L., Ferrage P. (Eds.), International DORIS Service Activity Report 2021, International DORIS Service and CNES, 67-68, doi:10.24400/312072/i02-2023.001, 2023

Dettmering D., Wang N.: *Using near-real-time DORIS data for validating real-time GNSS ionospheric maps*. IDS Newsletter 10, 2023

Dettmering D., Schrama E.J.O.: *Preface: New results from DORIS for science and society*. Advances in Space Research, doi:10.1016/j.asr.2023.04.027, 2023

Dettmering D., Schwatke C.: *Comparison of different methods to account for the plasmaspheric electron content in GNSS-derived ionospheric altimeter corrections and their impact on sea level trend estimation*. Earth, Planets and Space 75(7), doi:10.1186/s40623-023-01764-0, 2023

Ehlers F., Schlembach F., Kleinherenbrink M., Slobbe C.: *Validity assessment of SAMOSA retracking for fully-focused SAR altimeter waveforms*. Advances in Space Research, 71(3), 1377-1396, doi:10.1016/j.asr.2022.11.034, 2023

Glomsda M., Seitz M., Angermann D.: *Comparison of simultaneous VGOS and legacy VLBI sessions*. In: Armstrong K. et al. (Eds.), IVS 2022 General Meeting Proceedings, 2023

Glomsda M., Seitz M., Bloßfeld M., Angermann D.: *Investigating the datum parameters of new solutions by IVS AC DGFI-TUM*. In: Haas R. et al. (Eds.); Proceedings of the 26th European VLBI Group for Geodesy and Astrometry Working Meeting, 2023

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Wang N., Dettmering D., Li Z., Liu A., Schmidt M.: *DORIS NRT data: an independent data source for GNSS-based ionospheric maps validation and combination*. EGU General Assembly 2023, Vienna, Austria, 2023

Wang N., Dettmering D., Li Z., Schmidt M., Liu A.: *DORIS NRT data for validating and combining GNSS-based ionospheric maps*. 28th IUGG General Assembly, Berlin, Germany, 2023

Wang N., Dettmering D., Liu A., Schmidt M.: *Near-Real-Time DORIS Data for GNSS-based Ionospheric Maps Validation and Combination*. IDS Analysis Working Group Meeting 2023, Saint-Mandé, France, 2023

Zeitlhöfler J., Bloßfeld M., Rudenko S.: *Current status of DORIS POD at DGFI-TUM*. IDS Analysis Working Group Meeting 2023, Saint-Mandé, France, 2023

4.4 Participation in Meetings, Symposia, Conferences

2023-01-11/12 : **Ocean Prediction Decade Kick-Off Meeting, online**
Hart-Davis M.G.

2023-01-13 : **Sea Level Climate Change Initiative, Progress Meeting, online**
Oelsmann J., Passaro M.

2023-01-20 : **GGOS Strategic Plan Committee Meeting, online**
Angermann D., Sánchez L.

2023-01-24/25 : **Sentinel-3 Next Generation Topography MAG, online**
Passaro M.

2023-01-27 : **HYDROCOASTAL Progress Meeting 10, online**
Dettmering D.

2023-01-31 : **ESA S6-JTEX Progress Meeting 5, online**
Passaro M.

2023-02-01 : **GGOS Strategic Plan Committee Meeting, online**
Angermann D., Sánchez L.

2023-02-13 : **IDS Governing Board Meeting, online**
Dettmering D., Sánchez L.

2023-02-15 : **IGS Infrastructure Committee Meeting, online**
Sánchez L.

2023-02-21 : **GGOS Strategic Plan Committee Meeting, online**
Angermann D., Sánchez L.

2023-03-01/02 : **GlobalCDA ECR Gender Equality Workshop on Negotiation, Stuttgart, Germany**
Scherer D.

2023-03-01/03 : **Second Earth Orientation Parameters Prediction Comparison Campaign, Alicante, Spain**
Kehm A.

2023-03-02 : **SWOT Working Group 'River Science', online**
Schwatke C., Scherer D.

2023-03-03 : **GlobalCDA status meeting, Stuttgart, Germany**
Dettmering D., Scherer D.

2023-03-08/09 : **NEROGRAV Status Meeting, Munich, Germany**
Dettmering D., Hart-Davis M.G., Seitz F.

2023-03-28/29 : **2nd ICCC Workshop on 'Geodesy for Climate Research' , online**
Passaro M., Dettmering D.

2023-03-29 : **OPTIMAP Final Presentation, online**
Schmidt M., Seitz F., Dettmering D.

2023-03-29/31 : **First meeting of the International Advisory Committee of the UN Global Geodetic Centre of Excellence (UN-GGCE), Bonn, Germany**
Angermann D., Sánchez L.

2023-03-29/31 : **Third Plenary Meeting of the UN Subcommittee on Geodesy, Bonn, Germany**
Angermann D., Sánchez L.

2023-04-03 : **Sea Level Climate Change Initiative+, Progress Review Meeting Q1 2023, online**
Passaro M.

2023-04-18 : **IDS Analysis Working Group Meeting, online**
Bloßfeld M., Rudenko S., Sánchez L., Zeitlhöfler J.

2023-04-18/19 : **Sentinel-3 Next Generation Topography MAG, ESA, online**
Passaro M.

2023-04-19 : **IDS Governing Board Meeting, online**
Dettmering D., Sánchez L.

2023-04-22 : **GGOS Coordinating Board Meeting, Vienna, Austria**
Angermann D., Sánchez L., Schmidt M.

2023-04-23 : **GGOS Strategic Plan Committee Meeting, Vienna, Austria**
Angermann D, Sánchez L.

2023-04-24/28 : **EGU General Assembly 2023, Vienna, Austria**
Bloßfeld M., Hart-Davis M., Kehm A., Oelsmann J., Passaro M., Scherer D., Rudenko S., Seitz M., Seitz F.

2023-04-26 : **ILRS Analysis Standing Committee Meeting, Vienna, Austria**
Bloßfeld M., Kehm A., Rudenko S., Schwatke C., Seitz M.

2023-05-10 : **CLIMATE-SPACE Information Day, ESA, online**
Passaro M.

2023-05-23 : **Tour de IGS, 6th Stop 'Galileo Constellation Spotlight', online**
Rudenko S.

2023-06-12/15 : **26th EVGA Meeting and IVS Analysis Workshop, Bad Kötzting, Germany**
Glomsda M.

2023-06-13/14 : **GEO Symposium 2023, Geneva, Switzerland**
Sánchez L.

2023-06-14 : **Ocean Prediction Regional Team Meeting for African Seas, online**
Hart-Davis M.G.

2023-06-21 : **ESA S6-JTEX Progress Meeting 7, online**
Passaro M.

2023-06-28/29 : **HYDROCOASTAL Acceptance Review, Frascati, Italy**
Dettmering D.

2023-06-29 : **EUMETSAT COPAS Project Kick-Off, online**
Passaro M.

2023-07-06 : **Sea Level Climate Change Initiative, Progress Meeting, online**
Oelsmann J., Passaro M.

2023-07-11/20 : **28th IUGG General Assembly, Berlin, Germany**
Bloßfeld M., Sánchez L., Müller F.L., Pisareva M., Dettmering D., Passaro M., Schmidt M., Angermann D., Hart-Davis M.G.

2023-07-13 : **IAPSO Tidal Analysis Best Practice Study Group Meeting, online**
Hart-Davis M.G.

2023-07-14 : **GGOS BPS and BNO joint meeting, Berlin, Germany**
Angermann D., Sánchez L.

2023-07-18 : **GGOS Strategic Plan Committee Meeting, Berlin, Germany**
Sánchez L.

2023-07-20 : **IAG Executive Committee Meeting, Berlin, Germany**
Sánchez L.

2023-09-12 : **HYDROCOASTAL Final Review Meeting, Frascati, Italy**
Scherer D.

2023-09-19/22 : **SWOT Science Team Meeting, Toulouse, France**
Dettmering D., Scherer D., Schwatke C.

2023-09-20/22 : **GGOS Days 2023, Acalá de Henares, Spain**
Angermann D., Kehm A., Müller F.L., Sánchez L., Schmidt M.

2023-09-26/28 : **CryoSat QWG Meeting, Porto, Portugal**
Dettmering D., Hart-Davis M.G.

2023-10-05 : **GlobalCDA ECR Gender Equality Workshop on 'How to write compelling proposals', Munich, Germany**
Scherer D.

2023-10-06 : **GlobalCDA status meeting, Munich, Germany**
Dettmering D., Scherer D., Schwatke C., Seitz F.

2023-10-12 : **GeoSymposium: Geodesy and Geophysics for Sustainable and Scientific Development, Bogotá, Colombia**
Sánchez L.

2023-10-12/13 : **DFG Research Unit FOR5456 'Clock Metrology for Earth System Research' Status Seminar, Munich, Germany**
Angermann D., Bloßfeld M., Glomsda M., Kehm A., Schmidt M., Seitz F., Seitz M., Zeitlhöfler J.

2023-10-16/20 : **ILRS 2023 Virtual International Workshop on Laser Ranging, online**
Bloßfeld M., Kehm A., Rudenko S., Zeitlhöfler J.

2023-10-26 : **ILRS Analysis Standing Committee Meeting, online**
Bloßfeld M., Kehm A., Rudenko S., Seitz M., Zeitlhöfler J.

2023-11-06/07 : **Nansen-Tutu Centre Symposium 2023, Cape Town, South Africa**
Hart-Davis M.G.

2023-11-06/09 : **The Nansen Legacy Symposium 'Towards the new Arctic Ocean - Past, Present, Future', Tromso, Norway**
Müller F.L.

2023-11-07/11 : **Ocean Surface Topography Science Team (OSTST) Meeting 2023, San Juan, Puerto Rico**
Juhl M.-C., Rudenko S.

2023-11-16 : **ILRS Networks and Engineering Standing Committee Meeting, online**
Kehm A.

2023-11-20 : **IERS Directing Board Meeting, online**
Angermann D., Bloßfeld M., Seitz M.

2023-11-27 : **IGS Associate Member Meeting, online**
Sánchez L.

2023-11-27/12-01 : **5th Space for Water Cycle and Hydrology Workshop, HYDROSPACE 2023, Lisbon, Portugal**
Scherer D., Schwatke C.

2023-11-27/28 : **IAPSO Best Practice Study group meeting on Tidal Analysis, Liverpool, UK**
Hart-Davis M.G.

2023-11-28 : **UN-GGCE Listening World Tour, Virtual Meeting between IAG and UN-GGCE , online**
Angermann D., Bloßfeld M., Müller F., Kehm A., Liu Q., Sánchez L., Seitz F.

2023-11-28/29 : **IDS Analysis Working Group Meeting, Saint-Mandé, France**
Rudenko S., Sánchez L., Zeitlhöfler J.

2023-11-29 : **IDS Governing Board Meeting, Saint-Mandé, France**
Sánchez L.

2023-11-29/30 : **Colloquium Geodäsie und Fernerkundung, Bundesanstalt für Gewässerkunde (BfG), Koblenz, Germany**
Dettmering D.

2023-11-30 : **IERS Directing Board Meeting, online**
Bloßfeld M., Seitz M.

2023-11-30 : **IGS Governing Board Meeting, online**
Sánchez L.

2023-12-04 : **DVW AK7 meeting, online**
Bloßfeld M., Dettmering D., Seitz F.

2023-12-10 : **IAG Executive Committee Meeting, San Francisco, USA**
Sánchez L.

2023-12-11/15 : **AGU Fall Meeting 2023, San Francisco, USA**
Liu Q.

4.5 Guests

2023-01-01/12-31 : Dr. Stephan Paul, AWI, Bremerhaven, Germany

2023-01-01/09-30 : Dr. Yuliia Semenova, Institute of Geophysics, National Academy of Sciences of Ukraine

2023-02-07 : Prof. Dr. Andreas Güntner, Section Hydrology, German Research Centre for Geosciences (GFZ), Potsdam, Germany

2023-02-13/04-21 : Tadea Veng, DTU, Denmark

2023-02-13/05-12 : Hergeir Teitsson, DTU, Denmark

2023-06-20/30 : Prof. Xiaoli Deng, University of Newcastle, Australia

2023-07-03/07 : Annika Walter, HCU, Hamburg, Germany

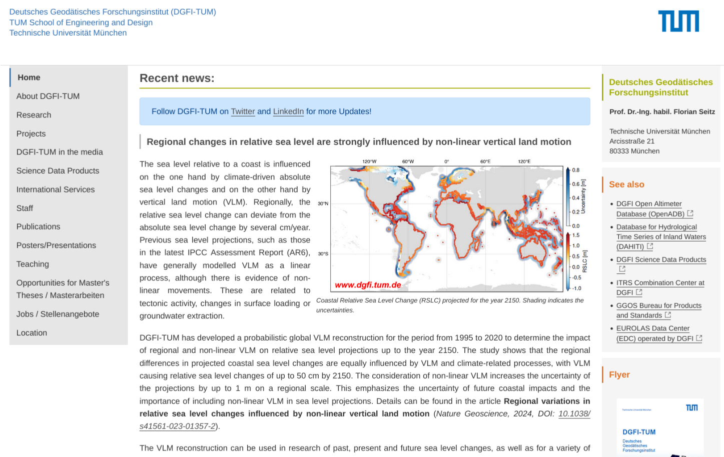
2023-07-31 : Dr. Jan Kodet, Dr. Johann Eckl, Geodetic Observatory Wettzell, Germany

2023-10-17/12-15 : Joanna Najder, Wroclaw University of Environmental and Life Sciences, Poland

4.6 Internet Portals

For the exchange of scientific knowledge, results and data with national and international partners, interested parties and the public, DGFI-TUM maintains the following internet portals and public databases:

Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM)



The DGFI-TUM website at www.dgfi.tum.de highlights the latest research results and provides information on the structure and research of the institute. It presents the national and international projects as well as the institute's involvement in various international scientific organizations. The website contains complete lists of publications, reports and presentations since 1994 and provides the scientific data products of DGFI-TUM. It has a media section and presents information on teaching.

For contact with the public, the scientific community and students, DGFI-TUM is represented on social media channels. Among others, on X (Twitter) (x.com/DgfiTum), Facebook (facebook.com/dgfitum), and LinkedIn (linkedin.com/company/dgfi-tum), current results, job offers, and opportunities for scientific work are published. Posts are met with considerable response and reach several hundred followers.

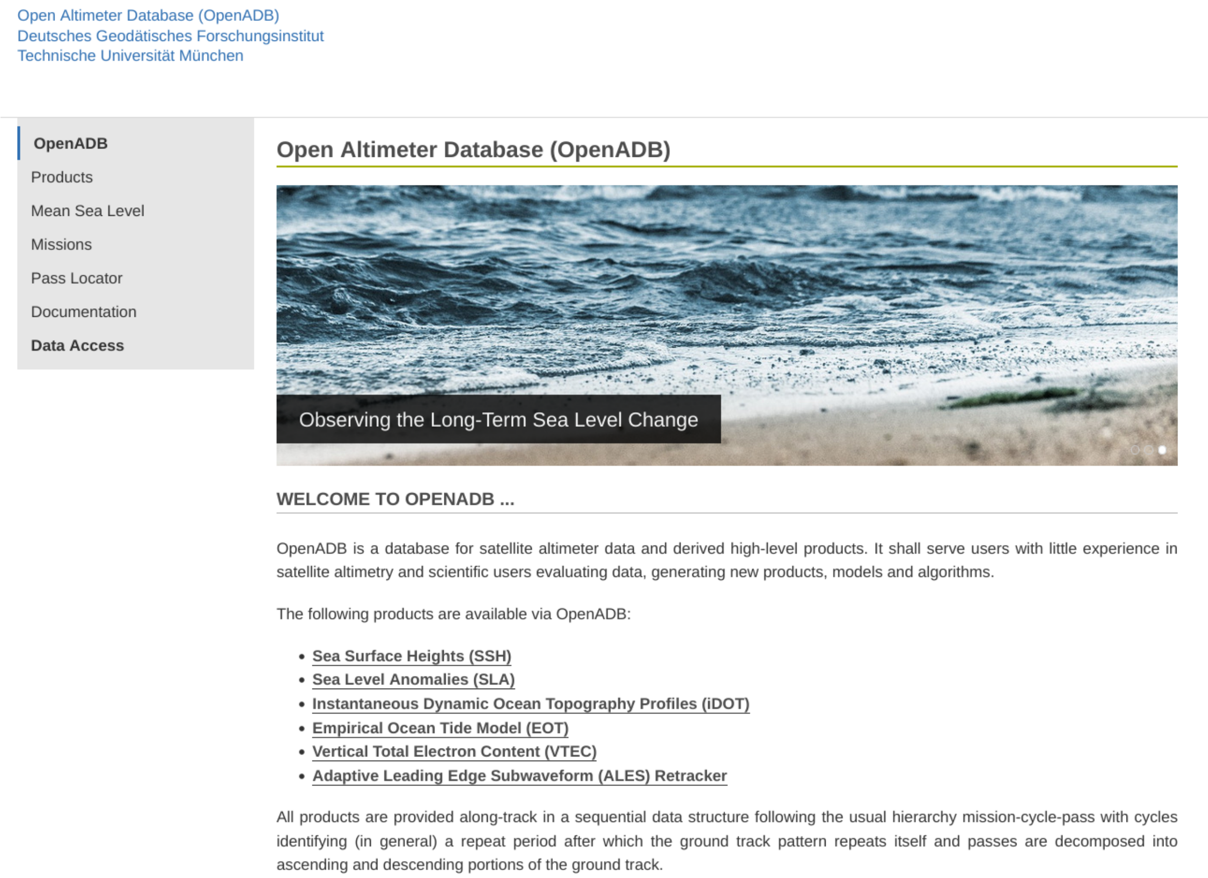
Open Altimeter Database (OpenADB): Ocean science data from space

OpenADB (openadb.dgfi.tum.de) is the DGFI-TUM platform for the dissemination of multi-mission altimetry data and derived high-level science products of oceanic and atmospheric quantities (Schwatke et al., 2023). It serves scientists across disciplines as well as users in research and practice. OpenADB data are widely used for the study of ocean and climate processes, for monitoring purposes, or for the creation and validation of new products, models, and algorithms.

Currently, OpenADB provides the following data:

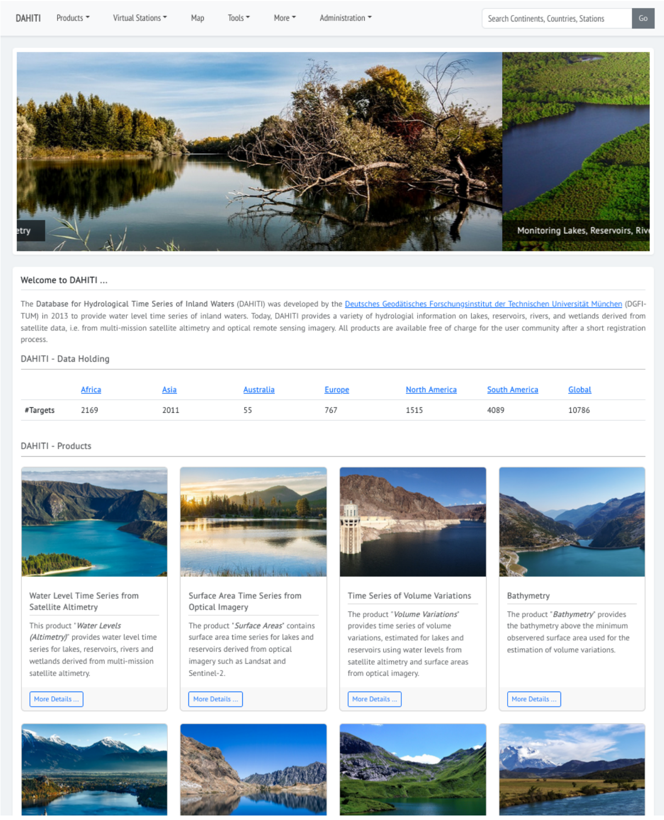
- Sea Surface Heights (SSH)
- Sea Level Anomalies (SLA)
- Adaptive Leading Edge Subwaveform (ALES) Retracker heights
- Instantaneous Dynamic Ocean Topography Profiles (iDOT)
- Empirical Ocean Tide Model (EOT)
- Vertical Total Electron Content (VTEC)

All altimetry data are provided free of charge to registered users in standard data formats. The data in OpenADB are preprocessed and already corrected with the latest geophysical models. In addition, data from all missions have been carefully harmonized and cross-calibrated so that observation data from different missions can be combined and analyzed jointly.



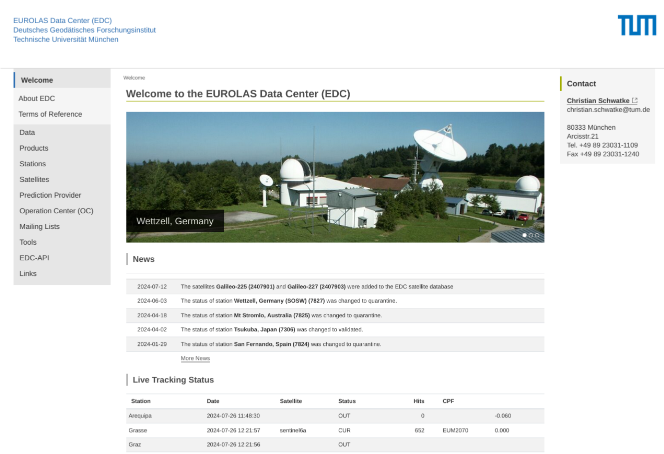
Database for Hydrological Time Series of Inland Waters (DAHITI)

DAHITI (dahiti.dgfi.tum.de) is the DGFI-TUM database for satellite-based hydrological parameters. To date, DAHITI provides water level time series from multi-mission satellite altimetry for more than 10,000 locations at lakes, reservoirs, rivers and wetlands worldwide. The data are continuously and automatically updated with the latest satellite information.



For many of these targets, DAHITI provides additional hydrological parameters that are calculated from optical Landsat/Sentinel-2 images and satellite altimetry. With respect to lakes and reservoirs, DAHITI offers time series of surface water extent, changes in water storage (volume changes), bathymetry and water occurrence masks. For rivers, DAHITI provides discharge information and high-resolution water surface slopes, which were greatly expanded in 2023 (front page and section 2.3).
With several thousand registered users and almost four million data requests in recent years, DAHITI is a widely used data source for numerous applications in science and practice. The Global Climate Observing System (GCOS) lists the database as an openly accessible data source for the Essential Climate Variable (ECV) 'Lakes'.

EUROLAS Data Center (EDC)



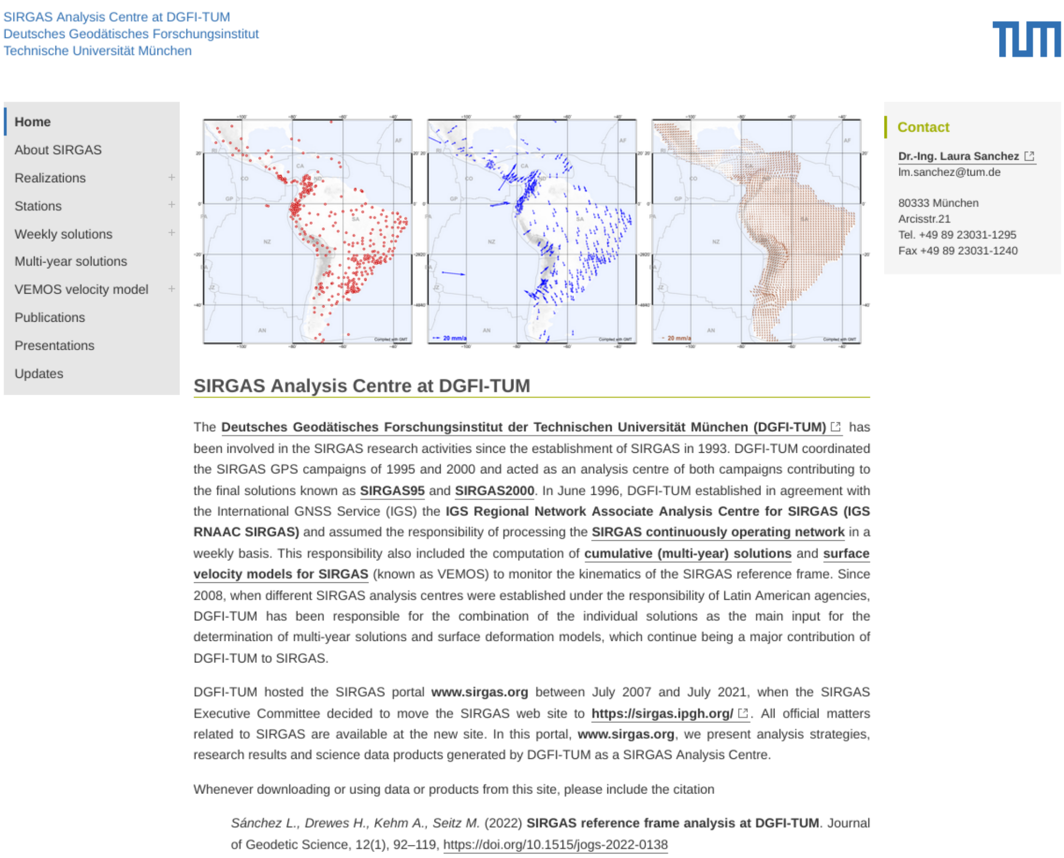
The EUROLAS Data Center (EDC) is - along with NASA's CDDIS - one of two global Data Centers of the International Laser Ranging Service (ILRS). The EDC has been operated by DGFI-TUM since 1998. The website edc.dgfi.tum.de provides the ILRS community with access to all SLR original observations and derived results. In addition, the EDC website provides information about real-time data management in the ILRS Operations Center (OC) at EDC and about the Data Center's data holding.

GGOS Focus Area Unified Height System

DGFI-TUM has chaired the GGOS Focus Area *Unified Height System* from 2015 until 2023. Its main objective is the implementation of a global vertical reference system in accordance with the International Association of Geodesy (IAG) Resolution No. 1, 2015 for the definition and realization of an International Height Reference System (IHRS). The Focus Area website (ihrs.dgfi.tum.de), maintained by DGFI-TUM, summarizes the actions, plans, and recent achievements, and provides an inventory of work documents, publications and presentations.

Geocentric Reference System for the Americas (SIRGAS)

DGFI-TUM has been involved in SIRGAS research activities since the establishment of SIRGAS in 1993. The institute coordinated the 1995 and 2000 SIRGAS GPS campaigns and acted as an analysis center, contributing to the final solutions SIRGAS95 and SIRGAS2000. In 1996, DGFI-TUM established the International GNSS Service (IGS) Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIRGAS) and assumed responsibility for the weekly processing of the continuously operating SIRGAS network. This also includes the computation of cumulative (multi-year) solutions and surface velocity models (known as VEMOS) to monitor the kinematics of the SIRGAS reference frame. Since 2008, DGFI-TUM has focused on the computation of the SIRGAS core network and on the combination of this network with the solutions provided by the Latin American data centers for national SIRGAS densification. DGFI-TUM also plays a central role in the determination of SIRGAS reference frame multi-year solutions and surface deformation models. DGFI-TUM's SIRGAS website www.sirgas.org presents analysis strategies, research results and data products generated by DGFI-TUM as SIRGAS Processing and Combination Centre and as IGS RNAAC SIRGAS.


SIRGAS Analysis Centre at DGFI-TUM
Deutsches Geodätisches Forschungsinstitut
Technische Universität München

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Updates

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SIRGAS Analysis Centre at DGFI-TUM

The **Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM)** has been involved in the SIRGAS research activities since the establishment of SIRGAS in 1993. DGFI-TUM coordinated the SIRGAS GPS campaigns of 1995 and 2000 and acted as an analysis centre of both campaigns contributing to the final solutions known as **SIRGAS95** and **SIRGAS2000**. In June 1996, DGFI-TUM established in agreement with the International GNSS Service (IGS) the **IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIRGAS)** and assumed the responsibility of processing the **SIRGAS continuously operating network** in a weekly basis. This responsibility also included the computation of **cumulative (multi-year) solutions** and **surface velocity models for SIRGAS** (known as VEMOS) to monitor the kinematics of the SIRGAS reference frame. Since 2008, when different SIRGAS analysis centres were established under the responsibility of Latin American agencies, DGFI-TUM has been responsible for the combination of the individual solutions as the main input for the determination of multi-year solutions and surface deformation models, which continue being a major contribution of DGFI-TUM to SIRGAS.

DGFI-TUM hosted the SIRGAS portal **www.sirgas.org** between July 2007 and July 2021, when the SIRGAS Executive Committee decided to move the SIRGAS web site to **https://sirgas.ipgh.org/**. All official matters related to SIRGAS are available at the new site. In this portal, **www.sirgas.org**, we present analysis strategies, research results and science data products generated by DGFI-TUM as a SIRGAS Analysis Centre.

Whenever downloading or using data or products from this site, please include the citation

Sánchez L., Drewes H., Kehm A., Seitz M. (2022) **SIRGAS reference frame analysis at DGFI-TUM**. Journal of Geodetic Science, 12(1), 92–119, https://doi.org/10.1515/jogs-2022-0138

5 Projects

A large part of DGFI-TUM's research activities is financed through third-party funds from various sources. Funding of the following projects is gratefully acknowledged (in alphabetic order):

AROCCIE Arctic Ocean surface circulation in a changing climate and its possible impact on Europe (IGSSE)

CIRCOS Circulation from In-situ and Remote Sensing Data in Coastal and Shelf Ocean (DFG)

COPAS Copernicus Altimetry Services: Polar Ice and Snow Topography Mission CRISTAL (EUMETSAT)

CPOD Copernicus Sentinels Precise Orbit Determination (ESA)

FOR 2630, ARISAS Advances in remote sensing of inland waters by satellite altimetry with special focus on SWOT (DFG)

FOR 2736, TIDUS-2 Improved tidal dynamics and uncertainty estimation for satellite gravimetry (DFG)

FOR 5456, P7 The application of time in closure as a novel strategy towards error-free space geodetic observations (DFG)

FOR 5456, P9 Novel clock technologies for combination on ground and in space: Real data and simulation (DFG)

Geo-H Enhanced geopotential field modelling as basis for the establishment of precise height systems (DFG)

Hydrocoastal Sentinel-3 and Cryosat SAR/SARIn radar altimetry for coastal zone and inland waters (ESA)

MEPODAS Mitigation of the current errors in precise orbit determination of altimetry satellites (DFG)

ML-IonoCast Machine learning for forecasting the ionospheric total electron content (DAAD)

PROGRESS Pro- and retrospective highly accurate and consistent Earth Orientation parameters for geodetic research within the Earth system sciences (DFG)

PSD-ITRS Analysis, approximation and interpretation of post-seismic deformations determined at GNSS observing stations for the improvement of the ITRS realisation (TUM Institute of Advanced Study, IAS)

S6-JTEX Sentinel-6 Michael Freilich and Jason-3 tandem flight exploitation (ESA)

SPP 1788, MuSE Multi-satellite reconstruction of the electron density in ionosphere and plasmasphere (DFG)

SL-CCI Plus Sea Level Climate Change Initiative Plus (ESA)

SS-CCI Plus Sea State Climate Change Initiative Plus (ESA)

6 Personnel

6.1 Lectures and Courses at Universities

Angermann D.: Lecture ‘Satellite Geodesy: Global Geodata for Society and Politics’, TUM, SS 2023

Bloßfeld M.: Lecture ‘Realization and Application of Global Geodetic Reference Systems’, TUM, SS 2023

Bloßfeld M.: Lecture ‘Geokinematics’, TUM, WS 2022/23 and WS 2023/24

Dettmering D.: Lecture ‘Hydrogeodesy: Monitoring Surface Waters from Space’, TUM, WS 2022/23 and WS 2023/24

Glomsda M., Bloßfeld M.: Lecture ‘Data Analysis of Geodetic Space Techniques’, TUM, SS 2023

Müller F.L.: Seminar ‘Climate Signatures in the Hydrosphere’, TUM, SS 2023

Passaro M.: Lecture ‘Satellite Altimetry and Physical Oceanography’, TUM, WS 2022/23 and WS 2023/24

Sánchez L.: Lecture ‘Advanced Aspects of Height Systems’, TUM, WS 2022/23 and WS 2023/24

Schmidt M.: Lecture ‘Numerical Modeling’, TUM, WS 2022/23 and WS 2023/24

Schmidt M.: Lecture ‘Numerical Methods in Satellite Geodesy’, TUM, SS 2023

Schmidt M.: Lecture ‘Ionosphere Monitoring and Modeling’, TUM, WS 2022/23 and WS 2023/24

Schmidt M., Seitz F., Müller F.L., Glomsda M.: Lecture ‘Numerical Methods’, TUM, WS 2022/23 and WS 2023/24

Seitz F.: Lecture ‘Seminar ESPACE’, TUM, SS 2023

Seitz F.: Lecture ‘Earth Rotation’, TUM, WS 2022/23 and WS 2023/24

Seitz F.: Lecture ‘Satellite Geodesy for Earth System Applications’, TUM, WS 2022/23 and WS 2023/24

Seitz F.: Lecture ‘Climate Change and Agriculture’, TUM, WS 2022/23 and WS 2023/24

Seitz F.: Lecture ‘Introduction to Geodesy and Geoinformation’, TUM, WS 2022/23 and WS 2023/24

Seitz F.: Seminar for Doctoral Candidates at DGFI-TUM, TUM, WS 2022/23, SS 2023 and WS 2023/24

6.2 Academic Program Coordination and Study Advice

Müller F.L.: Master and Bachelor programmes 'Geodesy and Geoinformation'

6.3 Lectures at Seminars, Schools, and Public Relations

Angermann D.: 'Was ist Geodäsie?'. TUM Open Campus Day, 2023-03-10

Müller F.L.: Exhibition/fair stand, TUM Open Campus Day, 2023-03-10

Müller F.L.: 'Geodesy and Geoinformation'. TUM Master's Days 2023, 2023-03-22

Angermann D., Müller F.L.: 'Geodäsie und Geoinformation'. MINT Informationstag (online), TUM, 2023-05-04

Angermann D.: 'Geodäsie und Geoinformation'. Explore TUM, Jakob-Brucker-Gymnasium Kaufbeuren, 2023-07-24

Müller F.L., Angermann D.: 'Geodäsie und Geoinformation'. Unitag, TUM, 2023-12-01

6.4 Thesis Supervision

Master theses

Seitz F., Rudenko S., Zeitlhöfler J.: Thesis Alkahal R., TUM: Impact of refined geophysical models on orbits of altimetry satellites. 2023-05-05

Seitz F., Hart-Davis M.G.: Thesis Li Y., Wuhan University/TUM: Correlation between tidal variations and the El Nino Southern Oscillation (ENSO). 2023-06-26

Passaro M.: Thesis Usoltseva M., TUM: Effect of coral reefs on wave height and wave energy. 2023-11-02

Schmidt M.: Thesis Cayhan S., TUM: Feature extraction for ionospheric space weather forecasting with machine learning. 2023-12-01

Doctoral theses

Seitz F. (supervisor)**:** Thesis Glomsda M., TUM: Improvement of geodetic reference frame and Earth orientation parameters by reduction of non-tidal loading effects in Very Long Baseline Interferometry. 2023-03-27

Passaro M. (supervisor)**, Seitz F.** (co-supervisor)**:** Thesis Oelsmann J., TUM: The role of vertical land motion in past, present, and future relative sea level changes. 2023-07-05

Schmidt M. (supervisor)**:** Thesis Natras R., TUM: Machine learning for modeling and forecasting the ionosphere vertical total electron content, including space weather effects and uncertainty quantification. 2023-12-08

Passaro M. (supervisor)**, Seitz F.** (co-supervisor)**:** Thesis Schlembach F., TUM: Development of a novel coastal retracking algorithm for SAR satellite altimetry. 2023-12-18

6.5 Conferral of Doctorates

Glomsda M.: Improvement of geodetic reference frame and Earth orientation parameters by reduction of non-tidal loading effects in Very Long Baseline Interferometry.
Examiners: Prof. Dr.-Ing. F. Seitz (TUM), Prof. Dr.techn. J. Böhm (TU Wien, Austria), Prof. Dr. B. Soja (ETH Zurich, Switzerland).
Day of defense: 2023-03-27
Institution: TUM

Oelsmann J.: The role of vertical land motion in past, present, and future relative sea level changes.
Examiners: PD. Dr. M.Passaro (TUM), Prof. Dr.-Ing. F. Seitz (TUM), Prof. Dr. S. Dangendorf (Tulane University, USA).
Day of defense: 2023-07-05
Institution: TUM

Natras R.: Machine learning for modeling and forecasting the ionosphere vertical total electron content, including space weather effects and uncertainty quantification.
Examiners: Prof. Dr.-Ing. M. Schmidt (TUM), Prof. Dr. U. Hugentobler (TUM), Prof. Dr. B. Soja (ETH Zurich, Switzerland).
Day of defense: 2023-12-08
Institution: TUM

Schlembach F.: Development of a novel coastal retracking algorithm for SAR satellite altimetry.
Examiners: PD. Dr. M.Passaro (TUM), Prof. Dr.-Ing. F. Seitz (TUM), Prof. Dr. J. Gomez-Enri (Universidad de Cadiz, Spain).
Day of defense: 2023-12-18
Institution: TUM

6.6 Research Stays

TUM Graduate School

Pisareva M.: Alfred-Wegener-Institut, Bremerhaven, Germany
Duration: 2023-06-12 until 2023-06-16
Collaboration: Dr. C. Wekerle

Hart-Davis M.G.: Technical University of Denmark, Copenhagen, Denmark
Duration: 2023-06-16 until 2023-06-30
Collaboration: Prof O. Andersen

6.7 Awards

Halicki M., Schwatke C., Scherer D.: *Best Poster Award*, 40. International School of Hydraulics, Polish Academy of Sciences, Katy Rybackie, Poland