Geodesy 2030*

Erdmessung 2030

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Summary
Geodesy plays a central role in monitoring changes of our planet on all relevant spatial and temporal scales using dedicated measurement systems. It applies sophisticated analysis techniques to provide various products to the user community. This paper reports the current status of its activities and identifies future tasks of Geodesy towards 2030. In this context, a key task will be the realization of an innovative, integral and interdisciplinary approach.

Keywords: Geodesy, future developments, observing systems, modeling, applications

Zusammenfassung
Die Erdmessung trägt maßgeblich dazu bei, die Veränderungen unseres Planeten auf allen relevanten Skalen in Raum und Zeit messtechnisch zu quantifizieren und mit geeigneten Analysetechniken für den Nutzer aufzubereiten. Das vorliegende Papier dokumentiert den aktuellen Stand und nennt die wichtigsten Zukunftsaufgaben, die die Erdmessung in Deutschland mit einem zeitlichen Horizont bis 2030 identifiziert hat. Wesentliche Aufgabe ist dabei die Verwirklichung eines innovativen, integrierten und interdisziplinären Ansatzes.

Schlüsselwörter: *Erdmessung, künftige Entwicklungen, Beobachtungssysteme, Modellbildung, Anwendungen*

1 Geodesy – Executive Summary

Geodesy comprises the continuous measurement of the time-varying geometry of land and sea surfaces, the Earth's gravitational field, its rotation and orientation in space. Since measurement signals propagate through the neutral atmosphere and ionosphere, the latter are also included in the wider definition. Geodesy, through its observatories and reference stations, provides the highly accurate global reference frame that positioning systems such as GPS and Galileo require.

One focus of Geodesy is on monitoring physically induced process components and their interactions in the Earth system in near real-time. In particular, it provides observations such as changes in mass, volume, and angular momentum that cannot be obtained in other disciplines. Thus, Geodesy contributes substantially to the solution of numerous Grand Challenges of our society, such as the detection of causes and effects of climate change, risks of natural hazards and measures against the loss of biodiversity, habitat and ecosystem functions. A global geodetic observing system, which allows to measure relevant quantities for addressing these Grand Challenges at any place on Earth at any time and with a resolution of a few kilometers, should be operational by 2030. In this context, German scientists should continue to play an international leading role due to their expertise. This also requires the support of major research institutions.

This document identifies challenges in the areas of (1) technological development (observing systems), (2) methodology, analysis, and modeling, and (3) data products and applications to achieve the ambitious goals and to position German research as an international leader in this context.

Based on extensive expertise in the conceptual and technological development of geodetic space techniques, the operation of geodetic observatories, and active participation in satellite missions, the current and future fields of work in the field of *observing systems* include:

- Expansion and further development of geodetic observatories and observing systems for the acquisition of geometric and gravimetric measurement quantities, with increasing inclusion of areal methods, such as SAR/InSAR, and new measurement concepts, such as GNSS reflectometry;
- Integration and linkage of observation methods to provide a global geodetic reference frame in line with the UN resolution "Global Geodetic Reference Frame for Sustainable Development" (UN 2015, 2016);
- Development and application of new sensors, especially provision and transfer of highly accurate time and frequency information.

In the area of *methodology, analysis, and model building*, the following future research areas are emerging:

- Consistent, complete modeling for correct parameterization and modeling of spatially and temporally variable signals at all scales;
- Further development of stochastic models to describe uncertainties;
- Consistent combination and analysis of geometric and gravimetric quantities and integrate them into Earth system models;
- Numerically efficient implementation on massively parallel high-performance computers.

* English version of the article "Erdmessung 2030" in zfv 1/2019, vol. 144, 2019.

DOI 10.12902/zfv-0392-2022

In the area of *data products and applications*, the following challenges arise:

- Creation of integrated and cross-disciplinary products;
- Provision of integrated reference frames in position and elevation through the international services of the International Association of Geodesy (IAG);
- Provision of products in near real-time as part of operational services as a central element of a European research infrastructure.

2 Challenges

The so-called Grand Challenges are fundamental challenges for our society, the solution of which would induce significant progress in societal, social or economic terms. Grand Challenges for society in the geosciences include natural hazards and disaster risk reduction, climate change and climate protection, freshwater and industrial water availability, ensuring the sustainability of natural resources, and the use and design of the Earth as a habitat. These are embodied, for example, in the UN Sustainable Development Goals 13 (climate change), 14 (oceans), and 15 (terrestrial ecosystems).

> Geodesy contributes substantially to solving these "Grand Challenges", such as causes and effects of global change, causes and risks of natural hazards. Thus, it supports measures against loss of biodiversity, habitat and ecosystem functions.

In the following, the contributions of Geodesy are first explained exemplarily for some of the most important challenges:

a) Causes and effects of global change

Climate change is already having a dramatic impact on our environment and our daily life. For example, global warming is believed to be associated with more frequent and severe heat waves. The 2003 heat wave in Western Europe is held to be accountable for estimated additional 35,000 deaths (Dixon 2017, § 2). Ocean warming and sea-level rise will contribute to more frequent flooding and stronger hurricanes – the most destructive natural disasters. Geodesy provides a hypothesis-free quantification of sea level rise that is independent of assumptions made by numerical models (WCRP Global Sea Level Budget Group 2018). It accounts for the mass balance of glaciers and ice sheets (Shepherd et al. 2018) and changes in terrestrial water reservoirs. Geodesy thus provides essential baseline data to better understand the interaction between changes in the Earth system and global warming. Among others, these data are used to calibrate numerical models to improve forecasting capabilities.

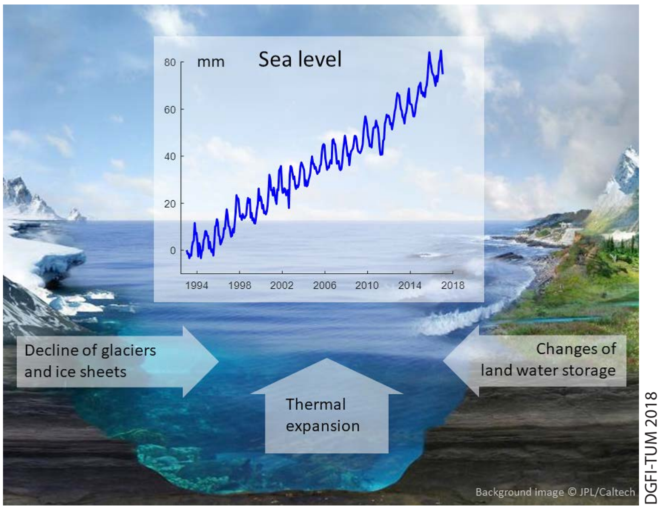

Fig. 1: Change in global mean sea level. The curve shows results of satellite altimetry.

b) Causes and risks of natural hazards

High-precision geodetic monitoring in real-time is necessary for imminent volcanic eruptions, for example, to detect the uplift of the Earth's surface due to the expansion of magma chambers (Dvorak and Dzurisin 1997). For other natural hazards, such as those present in earthquake zones, geodetic measurements provide information on the slow increase of stress in the Earth's crust. Recently, GNSS[1] measurements in near real-time and high temporal resolution offer new possibilities for monitoring earthquakes. Alpine natural hazards, such as landslides, rockslides, debris flows, and avalanches, have cost more than 4,000 lives and caused about 50 billion euros in damage in the area of the European Alps over the past 50 years (Pfurtscheller and Thieken 2013). Shrinking permafrost in the high mountains leads to slope deepening and increased risk of damage. Permanent high-precision monitoring of risk zones is a prerequisite for prediction models. Another example is given with the monitoring of space weather and especially extreme events, such as solar storms, with geodetic space techniques. Such events pose major risks to satellite-based communication and navigation infrastructure. Geodetic measurements also contribute to the understanding of the physical processes underlying natural hazards in many other cases. A major challenge is to transfer the understanding of processes to the prediction capabilities of, e.g., tsunamis and earthquakes.

c) Measures against the loss of biodiversity, habitat and ecosystem functions

About 60 % of the world's population live in coastal regions and almost all megacities are located at coasts. The global rise in sea level and accompanying effects, such as increasing erosion, salinization or more frequent and stronger storm surges, are associated with an immense loss

1 Global Navigation Satellite Systems

of biodiversity and ecosystem functions. The economy of affected countries can be stricken significantly, too. Measures such as adaptation or abandonment of coastal regions require not only global but also regional projections of sea level rise (Cazenave and Le Cozannet 2014). It is Geodesy that enables permanent areal sea level monitoring on regional and global scales using altimeter satellites (Legeais et al. 2018) in conjunction with coastal tide gauge measurements and coastal crustal deformation monitoring (Karegar et al. 2017). Using gravitational determination of ocean mass variations, the individual contributions causing sea-level changes can be separated and a comprehensive understanding of the process can be achieved (Rietbroek et al. 2016).

3 Observation of the Earth System 2030

International organizations and political processes are setting frameworks that pose new challenges for Geodesy. The UN resolution "Global Geodetic Reference Frame for Sustainable Development" (UN 2015, 2016) adopted in 2015 obliges member states to internationally coordinated efforts for the further development of the global geodetic infrastructure and the sustainable use of data. The assessment reports of the Intergovernmental Panel on Climate Change (IPCC 2014) have become milestones and pacesetters for research on climate change. German geodesists play a decisive role in shaping these international developments through numerous key positions in organizations, committees and working groups, and generate core geodetic products as a long-term task within the framework of numerous international services of the IAG.

Global reference systems, accurate satellite orbits, and precise topography and gravity field models provide both a geometric and physical reference frame. They are the prerequisite to quantitatively measure process components in the Earth system. Numerous applications that rely on a global or regional reference frame (positioning, navigation, GIS[2], telecommunications) require consistency and near real-time availability. The current IAG Global Geodetic Observing System (GGOS; Plag and Pearlman 2009) needs to be developed along these lines, including input from other disciplines. It should be developed into an integral part of GEOSS (Global Earth Observing System of Systems), and it should thus realize the Global Geodetic Reference Frame (GGRF) as requested by the UN Committee of Experts on Global Geospatial Information Management. The consistent combination and interpretation of geometric and gravimetric observation methods plays a central role in this process (IAG 2016).

> A global geodetic observation system should be operational by 2030. It should make it possible to measure relevant quantities for dealing with the major challenges at any place on Earth at any time and with a resolution of a few kilometers.

Such a system consists of ground-based as well as space-based observatories and measurement systems and the infrastructures necessary for their operation, data management, distribution, and analysis.

The sustainable operation and further development of geodetic measurement techniques and observatories as well as data management, data distribution and data analysis are central tasks for the future. Geodetic observatories, where all relevant observing techniques are operated, play a central role in the realization of global reference systems. With the Geodetic Observatory Wettzell, technological pioneer and core station in the global GGOS observation network for many years, Germany plays a leading role on the international level. This also results from the fact that the entire process chain from raw observation to the (geodetic) end product is covered by the expertise of German Geodesy.

> Based on its existing geodetic expertise, Germany should continue to strive for an international leadership role in the realization of a global geodetic observing system.

2 Geographical Information System

Courtesy Urs Hugentobler, München

Fig. 2: Wettzell Geodetic Observatory

4 Geodesy as a Scientific Discipline: Status and Problem Areas

Paradigm shifts in Geodesy have always resulted from the development of new technologies, which in turn have enabled the detection of previously unobservable phenomena and thus the development of new applications and even entirely new subfields in other geosciences (Kaula 1969, Plag and Pearlman 2009). Such leaps in technology have most often resulted in the development of new directions and in new insights in Geodesy. Examples include the direct measurement of plate tectonics, the accurate detection of continental motion and plate deformation with space geodetic techniques in the 1980s (Carter and Robertson 1992), the development of the GPS system into a global monitoring system in the 1990s, and the areal monitoring of the sea level with mm accuracy since the turn of the millennium. The gravity field missions to measure global mass transport processes (Kusche et al. 2014), the measurement of height and potential differences using high-precision clocks and corresponding optical links, and the precise transmission of time and frequency worldwide (Flury 2017, Müller 2017) are exemplary for the first two decades of the 21st century.

> Physical Geodesy contributes significantly to the monitoring of physically induced processes in the Earth system, in near real-time and on all relevant spatial scales. In particular, it provides observations (changes in mass, volume, angular momentum) that are important fundamental information for other disciplines.

By integrating and assimilating observations into high-resolution Earth system models, Geodesy systematically unlocks information about Earth system processes, serving various application fields with high societal, economic, and scientific benefits (Kumar et al. 2016, Schumacher et al. 2018).

There are a number of challenges that German Geodesy must address in order to maintain or even further expand its international leadership position against the backdrop of the "Grand Challenges" addressed in Section 1 and the goal of consistent observation of the Earth system by 2030 outlined in Section 2.

(1) *Interaction with the public:* The scientific community does not always succeed sufficiently in bringing the social significance of the discipline of Geodesy and its undeniable international successes to the attention of the public and to the politics and media. Terms such as "realization of a global reference system" are precise but highly abstract. In addition, the infrastructure of this reference system is invisible to most citizens. If one were to speak, for example, of the "continuous provision of a globally distributed high-precision network of high-tech observation stations to which any user can connect," the meaning would become more visible.

(2) *Economic value of geodetic products:* Geodetic products are made freely available to public and commercial users on a regular basis through international services in the Global Geodetic Observing System. They are used in a variety of ways, often on a daily basis, without their knowledge of the extensive observational infrastructure and expertise required to derive these products. With the exception of a few approaches, the scientific community has not yet attempted to quantify the economic value of this information.

(3) *Communicating difficult relationships:* Geodesists are used to stating their results and requirements in terms of uncertainties. This scientific approach is generally difficult for non-scientists to understand. In this context, it is complicated by the fact that the global reference frame must be kept available with very high accuracy, and it must be communicated why mm-accuracy is required for reference stations and satellite antennas. Thus, it is easier to communicate that one wants to distinguish between a predicted sea level rise of 20 cm or 50 cm for a 50-year planning period, because this is associated with massive economic consequences. A simple calculation shows that the global reference frame must be realized with an accuracy of 0.1 mm per year for this purpose. Furthermore, it has to be pointed out that it is an enormous challenge to realize mm-accuracy on a highly dynamic Earth body.

(4) *Young scientists:* Geodesy in Germany is relatively broadly based, with eight universities running their own Geodesy degree programs. Nevertheless, the lack of qualified young scientists is one of the most pressing problems at universities and research institutions, since the German science system is known to offer only few permanent research positions to young scientists.

5 Steps to Geodesy 2030

5.1 Technological development (observation systems)

Definition and motivation

Measuring the Earth as a dynamic object on all spatial and temporal scales, with the goal of describing the process drivers as well as the exact positioning of satellites, airplanes, ships up to autonomous motor vehicles, requires observing systems for the homogeneous and continuous measurement of geometric and physical quantities with high accuracy and long-term stability. These observing systems can only be realized by long-term observatories, where different, complementary measurement techniques are combined.

Satellite measurements are the only source of independent information of geodetic quantities in many regions of the world where terrestrial observing systems cannot be operated at all, or are hampered by economic or political reasons. Radar altimetry for monitoring inland waters can be considered as an example here (Schwatke et al. 2015).

Status in Germany and in the international context

Germany has a comparatively large observing capacity with instrumentation covering most areas of global geodetic research. Thus, all point-based geometric space techniques (VLBI[3], GNSS, SLR/LLR[4] and DORIS[5]) are run at German observatories and are processed by dedicated research institutions and universities. They can be used for further scientific applications and analysis. The Geodetic Observatory Wettzell in the Bavarian Forest, which is operated jointly by the Federal Agency for Cartography and Geodesy and the Technical University of Munich, is particularly worth to be mentioned due to its excellent performance (data rate and reliability). At this fundamental station and also at other German observatories, such as the SLR station of the German Research Center for Geosciences in Potsdam, accuracies of a few millimeters can be achieved on a global scale.

In the global observation of the gravity field, German geodetic science is at the origin of developments through extensive participation in the GRACE[6], GOCE[7] and GRACE Follow-On satellite missions. It also plays an international pioneering role in the development of novel future mission concepts and the new and further development of measurement technologies. Nowadays, global gravity field measurements draw their added value from reliable detection and quantification of temporal and spatial changes as well as interpretation capabilities in areas of hydrology (Kusche et al. 2016, Scanlon et al. 2018), glaciology (Shepherd et al. 2012, Farinotti et al. 2015), oceanography (Rietbroek et al. 2016), and geophysics (Pail et al. 2015). The global character of the questions as well as the measurement methods require intensive collaborations with international research groups. The successes are impressively documented by numerous scientific publications and authoritative positions in international research organizations (Geodesist's Handbook, Drewes et al. 2016).

The global observations are complemented by numerous terrestrial observing systems, such as absolute or superconducting gravimeters, which have a very high accuracy but only a punctual global coverage. Germany is very well established in terrestrial gravimetry (Neumeyer et al. 2008, Wilmes et al. 2016). Likewise, the very dense and accurate terrestrial reference station network for GNSS satellite observations in Germany can be mentioned.

In contrast, German Geodesy research is only slowly beginning to explore existing opportunities in the field of Interferometric Synthetic Aperture Radar (InSAR). This is partly due to the fact that previous missions were always operated independently by international space agencies, such as ESA[8] or NASA[9], or national agencies, such as DLR[10] or JAXA[11], and the involvement of university scientists and institutes as well as the availability of data was only possible under certain conditions, also because some data products are used commercially although, e.g., ESA strongly provides an open data policy. A fundamental change in terms of general access to measurements and data has recently been observed in the Sentinel remote sensing satellites, where an open access data policy is generally operated.

The same is true for research in the field of satellite radar altimetry, which has been largely driven internationally by NASA, ESA and the French space agency CNES[12]. With new technologies such as delay Doppler altimetry or Ka-band measurement, further development is currently taking place here, so that there is an opportunity for German research groups to catch up with the world leaders.

Challenges and goals

Certain goals for the technological development and the further development of geodetic observation networks are derived from the future challenges already mentioned or, more specific, from the contribution of Geodesy to their solution. Of course, in many cases this global task cannot be successfully carried out by Germany alone, but only in an international context and collaboration. Nevertheless, based on the existing expertise, a leading role of Germany in international developments should be aspired (Schuh et al. 2016). Current trends and fields of work in this regard include:

(1) *Expansion and further development of geodetic observatories:* For the tasks described at the beginning, various technological improvement possibilities can be used for the four geodetic space techniques – GNSS, SLR/LLR, VLBI, DORIS – which should be implemented at all observatories if possible. The increased construction and further development of geodetic observatories (fundamental stations) as places for the local ties of different measurement techniques, but also as calibration points, will be of even greater importance in the future. This is true for geometric point methods as well as for gravity measurements (Plag and Pearlman 2009).

(2) *Sustainable observing system of the gravity field:* Follow-up missions of the current gravity field satellite missions are essential for continuous and homogeneous global measurement of the Earth's gravity field and its variations. However, even larger spatial and

3 Very Long Baseline Interferometry
4 Satellite/Lunar Laser Ranging
5 Doppler Orbitography and Radiopositioning Integrated by Satellite
6 Gravity Recovery and Climate Experiment
7 Gravity field and Ocean Circulation Explorer
8 European Space Agency
9 National Aeronautics and Space Administration
10 German Aerospace Center
11 Japan Aerospace Exploration Agency
12 Centre national d'études spatiales

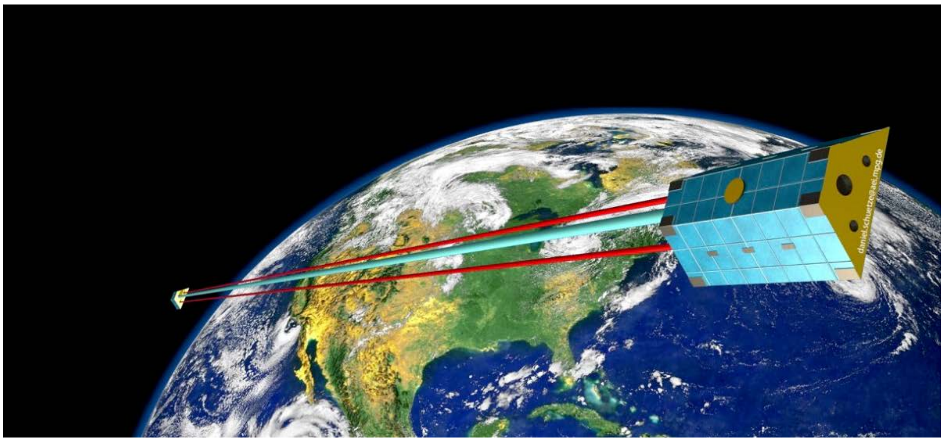

Fig. 3: Global observation of mass transport processes using GRACE/GRACE-FO

temporal scales must be covered. In Germany, corresponding future mission concepts are already under development (Pail et al. 2015, Douch et al. 2018).

(3) *Increased inclusion of SAR/InSAR:* In the future, the determination of individual points must be more supplemented by areal methods. SAR and InSAR should increasingly be used for Geodesy and global monitoring and be combined with reference point measurements. The global measurement data from the Sentinel-1 satellites of the EU's Copernicus project play an important role here.

(4) *Integration of observation techniques:* It will be possible to decisively improve the quality of reference frames if, in addition to local tie measurements between observing techniques on the Earth's surface (co-location), ties realized in space, e. g. on satellites or on the lunar surface, become available. In the future, dedicated (mini-)satellites will be used for this purpose to support the measurement systems of all geometric methods, whereby these must be specially designed according to geodetic principles and findings.

(5) *Height datum:* For the monitoring of natural hazards and the consequences of climate change, the stability of the geodetic height datum, i. e. the height reference, must be improved on a global and regional scale, and existing inhomogeneities and inconsistencies must be minimized (Ihde et al. 2017). This requires the availability of a globally well-distributed station network with adequate measurement instrumentation to consistently connect the different geometric and gravimetric realizations of the reference systems by linking the space geodetic measurement techniques.

(6) *Time and frequency:* A large number of geodetic observing techniques can be traced back to highly accurate measurement of time or time differences, which makes the synchronization of clocks of central importance here. The precise synchronization of measurement systems and observatories made possible by innovative developments in time and frequency transmission techniques (Schreiber and Kodet 2018) will allow time measurement to be used as an additional geodetic observable. In the medium term, these techniques, together with the realization of highly stable clocks, will lead to a global network of synchronized clocks. Completely based on relativistic models, they will allow geodetic space techniques to be operated even more accurately than today.

(7) *New measurement concepts:* GNSS reflectometry, as a new measurement technique with globally distributed observations from aircraft or space missions, will provide contributions to monitoring sea level and other parameters relevant to natural hazards and global change.

(8) *New sensors:* The development of new sensors (Müller 2017), such as quantum gravimeters, optical clocks, quantum gyroscopes, as well as the lossless transmission of time and frequency by means of optical fibers over large distances addressed in (6), opens up a new dimension for gravimetric Earth observation, such as the point-by-point measurement of potential differences by means of clocks using relativistic Geodesy and its combination with corresponding classical measurement methods (Müller et al. 2018).

5.2 Methodology, analysis and modeling

Definition and motivation

The methodological foundations of Geodesy are largely based on the mathematical-physical modeling necessary for a complete and consistent description of the geometry, rotation, and gravity field of the Earth, including the oceans and atmosphere and their interactions. Since the observational quantities of Geodesy range from the rate of high-precision clocks to the propagation of microwave or laser signals in the atmosphere as well as to the motion of satellites and the Moon, or the radiation from quasars, Geodesy is closely related not only to mathematics and physics, but also to astronomy, aerospace, and the neighboring Earth sciences. In addition, the analysis of the measurements is in the foreground, i. e., the optimal interpretation of often huge, occasionally incomplete or contradictory data sets, which are always subject to measurement noise, from the sensor to the integration into numerical process models. Here, too, links to mathematics and numerics as well as to mathematical statistics and information theory are very important.

The breathtaking developments of the last years in the field of sensor technology and space-based observing techniques require in parallel a consequent further development of geodetic methodology and analysis.

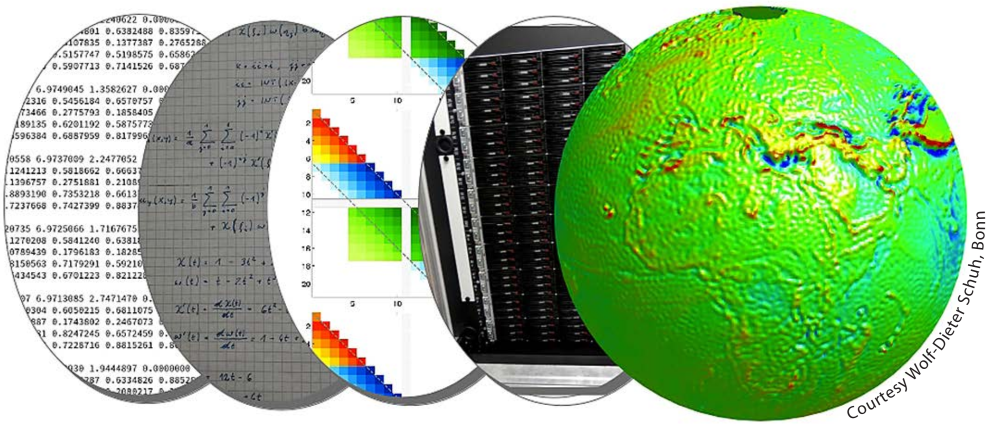

Fig. 4: Schematic processing chain from the raw observations to the gravity field model

The range of Earth system parameters that can be detected and the accuracy of their determination have been significantly increased by new and more precise measurement techniques. However, consistent analysis must now replicate increasingly complex physical interactions in the Earth system, some of which are not well known and can only be represented by even more complex Earth science simulation models.

In addition to model deficiencies, the measurement process itself also contains further shortcomings. Complex measurement systems, unclear interactions between a measurement system and its immediate environment, uncertainties in the reference system but also the attempt to derive latent parameters from the measurements increase the complexity of modeling.

Tailored decorrelation filters and parameter and variance estimation methods must be continuously developed to ensure flexible modeling with millions or even billions of data points. Simulation calculations are used to adaptively adjust and refine models to the data. Despite the use of massively parallel computer systems and optimized algorithms, computing times of several weeks for a single simulation are not uncommon.

Status in Germany and in the international context

German research groups have made internationally visible contributions especially in the areas of construction and combination of global reference frames, modeling of potential fields, and stochastic modeling of complex quantities in Geodesy. This is documented, for example, by the diverse participation of German groups in the analysis centers of the international services of the IAG.

High-performance computers with hundreds of thousands of cores are available today. High performance computing and massively parallel programming allow the processing of realistic models as well as the construction of simulation environments. The extended use of these systems requires the consistent formulation of all algorithms for parallel processing, taking into account distributed storage. In the field of Geodesy, the first approaches to high-performance computing on distributed systems have already been made in the areas of gravity field processing and the modeling of dynamic ocean topography. Young scientists in Germany are very well trained to use these innovative computing architectures.

In cooperation with the other disciplines of Earth system research (hydrology, oceanography, meteorology, …), integrated model systems are developed and implemented on high-performance computers in geodetic Earth system research. At present, the focus is often on coupled forward systems, and the fit between measurements and simulation model is used to correct the model parameters. In addition to data assimilation methods, there are very advanced approaches in Geodesy in the area of inverse modeling, where parameters are derived directly from measurements. There is still a considerable need for research in the merging of these approaches.

Since geodetic products are usually derived directly from the measured data by inverse modeling, it is also possible to estimate their uncertainties and correlations and make them available, so that users can estimate their reliability and also specify these for products derived from them. However, only the consistent description of all measurement and model uncertainties allows a complete integration of the different models and measurements.

Challenges and goals

In the area of methodology, analysis, and modeling, the following future research areas are emerging:

(1) *Consistent description of uncertainties:* While it is possible to capture internal or formal uncertainties in the model, it is often extremely difficult to estimate external uncertainties caused by model deficits (Vishwakarma et al. 2017). When evaluating individual observation types, model deficits could be hidden by latent parameters that are not well-determined by observations. Often, over-parameterization is even done deliberately. It turns out that the estimated values for such parameters are systematically distorted. Integrating complementary observation types into a combined model effectively reduces this degree of freedom. Consequently, there is an inconsistency of the incorrectly assigned information and the complementary observation types. This needs to be resolved by a consistent uncertainty description.

(2) *Modeling:* Additional care is required in modeling, especially for complex models with heterogeneous data types. There are often very extensive data sets with different reference systems and complex histories of provenience. Consistent, complete models require both

a careful parameterization of the functional relationships between the data types and the model parameters as well as a complete stochastic description of the uncertainties of the data and the model errors.

(3) *Spatial-temporal modeling:* There is still a need for research in approximation and interpolation in one- to four-dimensional space, with particular emphasis on scalar and multivariate applications, description of potential fields, or solution of partial differential equations using global and local basis functions, such as spherical functions, radial basis functions, finite elements, or splines (Tourian et al. 2017). This usually leads to high-dimensional dynamical systems with sparse grids or sparse function systems.

(4) *Improved space-time parameterization:* A correct parametric description of the space-time behavior is of central importance in many sub-areas of geodetic Earth system modeling, in global gravity models as well as in terrestrial reference frames, in order to describe the true system behavior, sampled by geodetic observations, sufficiently well by the model parameters and to avoid systematic errors, such as leakage effects.

(5) *Stochastic modeling:* Further developments in the representation of stochastic relationships are necessary in order to be able to model multivariate, time-variable effects in a targeted manner. Here, approaches via covariance functions as well as via discrete-time processes are to be investigated. Process analyses in the spatial domain as well as in the spectral domain should provide additional insights into the stochastic behavior. The flexibility thus gained in the modeling of correlations can then be used for tailored modeling of the system.

(6) *Consistent combination:* A central task is the consistent combination of geometric and gravimetric measurement quantities into high-quality results consistently related to geometric and gravimetric reference surfaces in the sense of the Global Geodetic Observing System of the IAG (Wu et al. 2017). This requires extensive further methodological developments.

(7) *Integrated models and model systems:* Numerical modeling of Earth system components, i. e., the atmosphere, oceans, hydrosphere, cryosphere, and solid Earth, is evolving toward an increasingly complete, consistently coupled description of the mass fluxes within individual components and the interactions between them within the context of the system as a whole (Bierkens et al. 2015). Existing model systems for geodetic Earth system research, which include numerical models of the ocean, atmosphere, and terrestrial water cycle, as well as mechanical models of crustal elasticity and the viscoelastic response of the Earth's body to glacial cycles, are not yet capable today of predicting and interpolating geodetic observations with sufficient accuracy. They therefore need to be further developed in close collaboration with neighboring disciplines.

(8) *High-Performance Computing:* Particular attention should be paid to the numerically efficient implementation of analysis and modeling processes on massively parallel high-performance computers, with special emphasis on the parallelization of algorithms. This makes it possible to represent complex model correlations parametrically, to perform a coupling of subsystems and to carry out the estimation process consistently in a single cast, taking into account correlations between the subsystems.

5.3 Data products and applications

Definition and motivation

Geodesy plays a central role in a value chain for data products and applications. Its addressees range from experts in Geodesy, e. g. for global reference frames, to users from neighboring scientific disciplines, e. g. for measuring sea level change, to users of operational services, e. g. for disaster management, and political decision-makers. Since new data, findings, and applications are continuously emerging, also driven by technological advancements and the development of new analysis methods, this chain must be designed in a flexible way.

Status in Germany and in the international context

Research in Germany has been pioneering the definition and realization of global and regional reference systems (Nothnagel et al. 2010, Seitz et al. 2016, see Journal of Geodesy Special Issue on Reference Systems 2018). In this topic area, scientists from Germany are significantly involved in projects and committees of international organizations, including the United Nations.

The research is primarily focused on the following key areas:

- the determination of highly accurate and long-term stable coordinates of geodetic observatories by combining different measurement techniques,
- the description of temporal changes in station positions due to geodynamic processes (Bloßfeld et al. 2014, Sanchez and Drewes 2016),
- the realization of terrestrial reference systems with high temporal resolution (Bloßfeld et al. 2016) and in near real-time to determine station movements (e. g. after earthquakes) with utmost accuracy,
- the improved realization of the geodetic datum (coordinate origin, orientation, and scale) (Wu et al. 2017),
- the linking (orientation) of regional and global reference frames with the highest accuracy,
- the joint realization of the global terrestrial reference system and the celestial reference system including the associated Earth orientation parameters (Kwak et al. 2018),
- the use of new observing technologies to increase accuracies and expand the parameter space.

Due to its crucial contribution to the planning, operation, and analysis of the previous gravity satellite missions, Geodesy in Germany has great merits in providing global gravity field solutions, both for the spatially high-resolution static gravity field (Pail et al. 2011, Scheinert et al. 2016; Pail et al. 2018) and for temporal gravity field changes. Based on gravity field modeling, the goal is to achieve the highest possible consistency between height systems obtained from gravimetric leveling on the one hand and from combining geometric heights with gravity field models on the other. As examples, physical height reference systems, in Germany the quasigeoids GCG2016 and EGG2016, can be mentioned.

The integration of geodetic results into interdisciplinary Earth system research has a long tradition, driven and coordinated among others by the DFG priority program "Mass Transport and Mass Distributions in the Earth System", the DFG research groups "Earth Rotation and Global Dynamical Processes" as well as "Space-Time Reference Systems for Monitoring Global Change and for Precise Navigation in Space" and currently the DFG priority programs "Dynamic Earth" and "Regional Sea Level Change and Society". Improved hydrological models that assimilate data from GRACE and radar altimetry (Androsov et al. 2018) can be listed as examples of products that have been generated under these coordinated programs, among others, and have benefited substantially from Geodesy. Additionally important are:

- time series of ocean masses and global sea level (Legeais et al. 2018),
- geostrophic ocean currents from purely geodetically determined ocean topography and their societal and climatic implications (Wouters et al. 2014),
- water vapor profiles from GNSS measurements that operationally feed into weather forecasting, observations and forecasts of space weather (Erdogan et al. 2017) and its security-related implications, e. g., on navigation, telecommunication, and power systems,
- mass balance estimates for ice sheets (Shepherd et al. 2018) and glacier systems,
- improved (e. g., inverse) modeling of lithosphere (Bouman et al. 2016) and solid Earth processes, such as glacial-isostatic balancing (Groh et al. 2012, Sasgen et al. 2017), or earthquake processes.

Increasing demands are placed on products and applications from Geodesy, such as provision on an operational basis and consistency over time. Free availability and easy accessibility are increasingly required. The Sentinel missions of the Copernicus program of the EU and ESA as well as the Earth Explorer missions of ESA fulfill this demand with the free provision of remote sensing and Earth observation data on an unprecedented scale. The volumes of data to be processed are growing enormously. This places new demands on data infrastructures and processing procedures. However, it also opens up the potential to gain added information value from the abundance of available data ("Big Data").

Challenges and goals

(1) *Integrated products:* The analysis of geodetic observation data from different methods must be done in an integrated approach, together with "non-geodetic measurements", because the various measurements reflect the same Earth system processes in different and complementary ways. Integrated analysis improves the reliability and consistency of data products and allows novel data products to be developed. For example, a wide range of geodetic observation types must be consistently linked to provide a comprehensive picture of the global water cycle. These include satellite altimetry measurements, time-varying and static gravity field measurements, GNSS-measured deformations of the solid Earth that may be particularly caused by loading effects, and measurements of the atmospheric state.

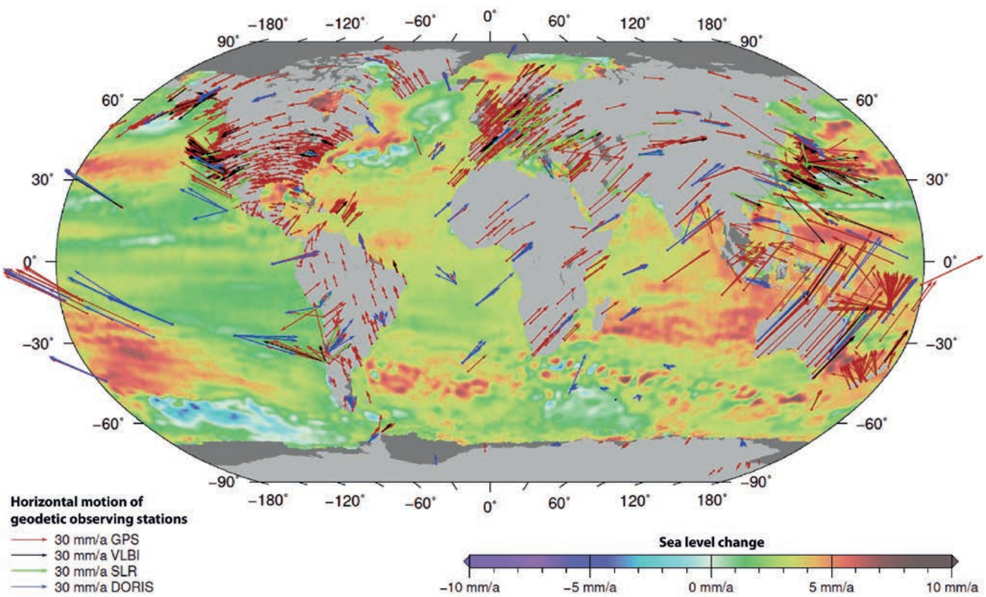

Fig. 5:
Processes in the Earth system observed with geodetic methods: sea level change and drift of continental plates

Courtesy: DGFI-TUM

(2) *Integrated reference systems:* For the consistent combination of geodetic techniques, the separation between purely geometric reference frames and height reference frames must be overcome in favor of a consistent geometric-gravimetric reference system in the sense of the GGRF position paper of the IAG (IAG 2016).
(3) *Inclusion of complementary techniques and products:* Remote sensing techniques, such as InSAR, can be considered as Earth observation tools and must be included in the integrated analysis. Taking the global hydrologic cycle as an example, remote sensing contributes to the measurement of the extent of water bodies and glaciers, flow velocities of rivers and glaciers, deformations of the solid Earth, soil moisture, and atmospheric parameters. Considering GNSS meteorology, it becomes clear that the transition between geodetic measurement techniques and remote sensing techniques nowadays is smooth.
(4) *Cross-disciplinary products:* In the future, the analysis of geodetic observations will merge far more than in the past with the modeling of Earth system processes as well as with the use of non-geodetic data (Sneeuw et al. 2014). Therefore, it will add significant value to process understanding. From a geodetic perspective, models of Earth system processes have, until recently, in many cases been used purely to correct geodetic data products. However, from a process modeling perspective, raw geodetic data are increasingly being used as original observation data. The role of Geodesy in gaining enhanced information on the Earth system is by far no longer limited to the pure provision of geodetic observations. This is because, on the one hand, only a sound description of uncertainties will allow the analysis process to be optimally designed and the uncertainty of the results, for example in climate research, to be adequately described. On the other hand, only with a deep understanding of the analysis process, the contradictions between geodetic measurement quantities and model prediction can be resolved and the underlying measurement system be better understood and developed. In this context, a key issue of climate-related research and decision-making processes is the separation between natural variability and anthropogenic influences. To this end, it is necessary to compare ensembles of free simulations with and without anthropogenic effects with long, consistent and integrated syntheses (re-analyses, data assimilation) of observed data sets that also include error information.
(5) *Real-time products and operational services:* In particular, the important integration of geodetic measurements into early warning systems means that numerous parameters relevant for analysis must be available in quasi real-time. For example, the Universal Time UT1, which characterizes the variations of the Earth's rotation, must also be determined and made available in near real-time for the accurate real-time analysis of satellite measurements. Water vapor and electron density, measured by geodetic techniques with high spatial and temporal resolution, are needed in near real-time for forecasting weather and space weather. Gravity field products with a short latency of a few days are required for their integration into operational services (e.g., Copernicus), such as flood and drought forecasting and disaster management applications.
(6) *IAG Services:* The operation of or participation in the international services of the IAG is a long-term task with the highest societal relevance, which must be continuously accompanied by research work in order to continue improving the product quality and keeping it at the current state of science. Therefore, the central participation of German scientists and research institutions in these services must also be ensured in the future.

6 Outlook and conclusion

Geodesy conducts basic research to develop methods for monitoring and analyzing change processes in the Earth system. It covers the entire chain from measurement concepts and observation infrastructure to analysis and modeling methods, products and applications. It is connected well with the other geosciences, since many phenomena can be successfully investigated and understood only in interdisciplinary cooperation. Geodesy is increasingly concerned both with anthropogenic effects in the Earth system and their separation from natural variations and with the interactions between anthropogenic and natural effects which require exchange also with the social sciences. Thus, Geodesy does not only make scientific contributions to Earth system modeling, but also significantly supports the formulation of concrete courses of action in addressing societal issues, such as modern infrastructure, resource conservation, water crisis prevention, and disaster management.

In order to continue to perform its far-reaching tasks successfully and sustainably, Geodesy needs:
- Investments to provide geodetic infrastructure (observatories on Earth, satellite missions);
- Financial support to develop innovative technologies, new measurement concepts and satellite techniques;
- Funding programs to develop the necessary analysis and modeling techniques;
- Guaranteed core funding of internationally recognized long-term tasks, such as the provision of a global reference framework;
- Creation of a framework for conducting targeted research at universities, in addition to the larger research institutions;
- Dedicated training and promotion of young scientists;
- Appropriate outreach measures to make the extensive services of Geodesy known to a wider circle.

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