

Terrestrial Reference Frames: The Fundament for Geodetic Earth Observation and all Positioning Applications

Terrestrische Referenzrahmen: Die Grundlage für die geodätische Erdbeobachtung und alle Positionierungsanwendungen

Detlef Angermann, Manuela Seitz, Mathis Bloßfeld, Florian Seitz

Global reference systems and their implementations such as the International Terrestrial Reference Frame (ITRF) provide the foundation for determining positions on Earth and in space as well as for reliably quantifying our planet's changes due to geodynamic processes and ongoing climate change. The ITRF ensures a uniform basis for all positioning and satellite navigation applications, and thus plays an elementary role in our modern society. The ITRF is the standard reference recommended by a number of international scientific organizations, including the International Union of Geodesy and Geophysics (IUGG) and the International Association of Geodesy (IAG) for positioning, satellite navigation and Earth science applications, as well as for the definition and alignment of national and regional reference frames. In 2015, the United Nations adopted the resolution "Global Geodetic Reference Frame for Sustainable Development", which clearly expresses the importance of a global geodetic reference frame for society, economy and science. Four geodetic space techniques are currently used for the ITRF computation: Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). The current realization of the International Terrestrial Reference System (ITRS), the ITRF2020, comprises 3D coordinates and velocities of around 1900 globally distributed observing stations.

Keywords: International Terrestrial Reference Frame (ITRF), International Terrestrial Reference System (ITRS), ITRS combination centers, space geodetic observation techniques, VLBI, SLR, GNSS, DORIS, geodetic observatories

Globale Referenzsysteme und ihre Implementierungen, wie der Internationale Terrestrische Referenzrahmen (ITRF), bilden die Grundlage für die Bestimmung von Positionen auf der Erde und im Weltraum sowie für die zuverlässige Quantifizierung von Veränderungen unseres Planeten durch geodynamische Prozesse und den fortschreitenden Klimawandel. Der ITRF gewährleistet eine einheitliche Grundlage für alle Anwendungen der Positionsbestimmung und Satellitennavigation und spielt damit eine elementare Rolle in unserer heutigen Gesellschaft. Der ITRF ist die Standardreferenz, die von einer Reihe internationaler wissenschaftlicher Organisationen, darunter die Internationale Union für Geodäsie und Geophysik (IUGG) und die Internationale Assoziation für Geodäsie (IAG), für Positionierung, satellitengestützte Navigation und geowissenschaftliche Anwendungen sowie für die Definition und Festlegung nationaler und

regionaler Bezugsrahmen empfohlen wird. Im Jahr 2015 verabschiedeten die Vereinten Nationen die Resolution „Globaler geodätischer Bezugsrahmen für nachhaltige Entwicklung“, in der die Bedeutung eines globalen geodätischen Bezugsrahmens für Gesellschaft, Wirtschaft und Wissenschaft deutlich zum Ausdruck kommt. Derzeit werden vier geodätische Raumberechnungsverfahren für die ITRF-Berechnung verwendet: Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS) und Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). Die derzeitige Realisierung des Internationalen Terrestrischen Referenzsystems (ITRS), der ITRF2020, umfasst 3D-Koordinaten und Geschwindigkeiten von etwa 1900 weltweit verteilten Beobachtungsstationen.

Schlüsselwörter: Internationaler Terrestrischer Referenzrahmen (ITRF), Internationales Terrestrisches Referenzsystem (ITRS), ITRS-Kombinationszentren, geodätische Raumberechnungsverfahren, VLBI, SLR, GNSS, DORIS, geodätische Observatorien

1 INTRODUCTION

With the technological progress of global Earth observation systems and sensors during the last decades, geodesy provides the potential to determine the geometric shape of land, ice and ocean surfaces as well as the rotation and gravity field of the Earth as global functions of space and time with increasingly higher precision and resolution. Thus, geodesy plays a vital role in Earth system research and for reliably monitoring climate change phenomena (e.g., sea level variations, melting of ice sheets, continental water storage changes). In order to be able to relate the measurement data of different observation systems to each other and to integrate them, they must be referenced consistently. The elementary backbone for this is a uniform global reference system. Moreover, for a meaningful interpretation of changes, it is necessary that this system is highly accurately defined and realized. Special requirements regarding the accuracy and long-term stability of the reference frames arise because even smallest and slowest processes in the Earth system are to be reliably quantified.

One prominent example is the monitoring of global sea level rise. This climate-related phenomenon is of high societal relevance and subject of numerous media reports. About 30 years of satellite

altimetry measurements prove beyond any doubt that the global sea level is rising. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2021), the current mean sea level rise is 3.7 mm per year, whereas over the last century it was “only” approximately 1.5 mm per year. This significant increase in mean sea level rise is induced by the melting of ice masses and the thermal expansion of ocean water due to global warming. However, the sea level is changing not in a homogeneous way: there are large regional differences. As shown in Fig. 1, the sea level is even falling in some regions, but there are much larger regions where the sea level is rising by up to one centimeter per year. Such a rapid sea level rise affects many densely populated coastal regions and islands. The associated risks of flooding and loss of habitats represent an enormous threat to millions of people and can result in major migration movements and social conflicts. Thus, precise knowledge of sea level rise is essential for decision-makers and society. But how do we know sea level rise so precisely?

The principle of satellite altimetry is based on scanning the ocean with an active radar or laser system that transmits microwave or laser pulses to the ground and receives the return signals after reflection at the ocean surface. From the travel time of the pulses the distance between the satellite and the water surface can be determined with centimeter precision. Precise orbits of altimetry satellites are therefore a prerequisite for a reliable determination of sea level variations, and this requires an accurate and long-term stable global reference frame as a fundamental basis. Fig. 2 shows how an inaccurate reference frame can lead to an incorrect determination of sea level. If the ground station moves without being correctly described by the parameters of the reference frame, the same laser measurement will lead to an erroneous satellite orbit. This results in an apparent rise in sea level, although in reality the observation station has changed (Angermann et al. 2021, 2022, 2023). In practice, such a measurement setup is of course not sufficiently accurate.

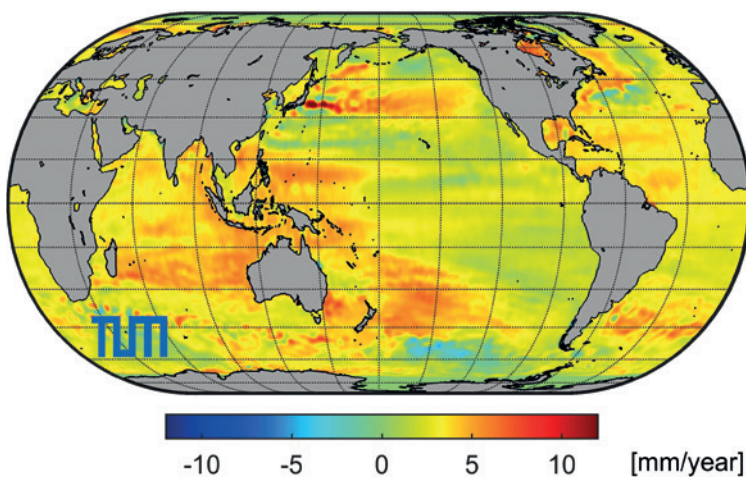


Fig. 1 | Regional sea level rise

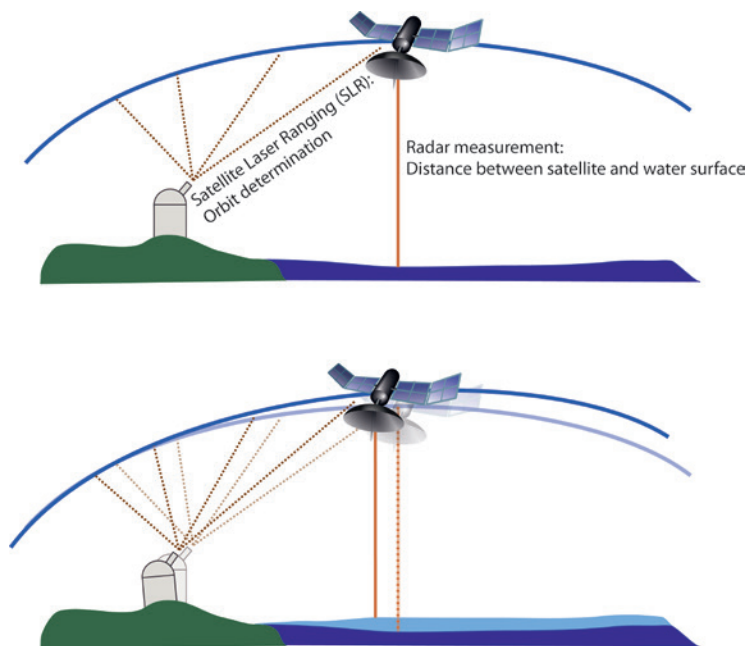


Fig. 2 | Illustration of the effect of an inaccurate reference frame on the determination of sea level

Therefore, the determination of the orbits is based on the use of different space techniques (e. g., SLR, DORIS, and GNSS) operated at several stations, which allows redundancy and validation of the results.

So far, we have looked at the change in sea level in absolute terms in relation to a fixed reference surface. However, to assess the impact of sea level rise in a particular region, it is important to know the sea level change in relation to the coast. In other words, we need to know whether the land is rising or subsiding. This again requires an accurate and stable reference as a metrological basis. Fennoscandia, for example, is rising as result of relaxation after the melting of ice masses of the last ice age (postglacial uplift), while other coastal regions are subsiding, for instance due to plate tectonics or anthropogenic influences such as extensive groundwater withdrawal. An alarming example for the latter effect is Jakarta, the capital of Indonesia, which is considered one of the fastest sinking cities in the world and half of which is already below sea level /Gilmartin 2019/, /Smith 2023/.

Sea level change is not only a prominent example of its societal impact, but also illustrates the high accuracy requirements of the global geodetic reference frame. Depending on the region, tectonic processes also cause changes of the Earth's surface in the order of a few millimeters up to centimeters per year. Viewed over short periods of time, such changes may not be serious. Nevertheless, their reliable determination is very important because they can lead to specific hazardous situations in the longer term (e.g., floods, landslides or earthquakes). However, to be able to reliably determine changes in the millimeter range, the reference frame must have a long-term stability that is at least one order of magnitude better. In accordance with these requirements, the aim of the International Association of Geodesy (IAG) and its Global Geodetic Observing System (GGOS, /Plag & Pearlman 2009/) is a frame accuracy of one millimeter, and a long-term stability of 1 mm per decade.

In addition to monitoring sea level changes and other geodynamic processes as well as operating early-warning systems to protect against natural hazards, there are many tasks of modern society that require a precise global reference. The applications include not only geodetic tasks (e. g., surveying, mapping, cadaster, engineering, land and resource management, photogrammetry, geoinformation), but also other geosciences (e. g., geophysics, oceanography, meteorology, hydrology, climatology) and astronomy. And the GNSS market has been growing explosively (more than six billion GNSS devices are in use today) and is increasingly affecting our daily life. The economic impact is dominated by the so-called consumer sector (i. e., location-based services through mobile devices and tablets) and the automotive industry. Important applications such as autonomous driving, automatic control of industrial and agriculture machinery, traffic and fleet management, transport logistics are dependent on satellite navigation and thus on precise global terrestrial reference frames as its fundamental basis.

2 INTERNATIONAL TERRESTRIAL REFERENCE SYSTEM

2.1 ITRS Definition

Conventionally, a terrestrial reference system is a global coordinate system co-rotating with the Earth. Such a coordinate system – in geodesy we speak of a geodetic reference system – is a mathematical construct in which every point on the surface, inside and outside the Earth, can be described with unique coordinates. The fundamental geodetic coordinate system in use today is the International Terrestrial Reference System (ITRS). It has been formally adopted and recommended as the primary global geodetic reference system by the IUGG at its General Assembly 2007 /IUGG 2007/. The ITRS is a Cartesian coordinate system, in which the position of a point is described with three metric values (X , Y , Z) with respect to three coordinate axes perpendicular to each other (Fig. 3).

The ITRS definition is based on the conventions of the International Earth Rotation and Reference Systems Service (IERS). This conventional definition fulfils the following conditions /Petit & Luzum 2010/:

- The origin of the ITRS is the center of mass of the Earth (geocenter), including its atmosphere and oceans.
- The scale (unit length) of the ITRS is the meter (SI).
- The orientation of the ITRS corresponds to the definition of predecessor systems. The axis directions refer to a historical definition of the Greenwich meridian (x -axis), a historical direction of the Earth's mean axis of rotation (z -axis) and the conventional equatorial plane perpendicular to these axes.
- The time evolution of the orientation is ensured by using a no-net-rotation condition with respect to horizontal tectonic motions over the whole Earth.

Since our planet is subject to a variety of geodynamic processes and forces from external bodies, the definition of the ITRS orientation does not correspond to today's actual conditions. For example, the North Pole now deviates from the conventional z-axis of the ITRS by more than ten meters, as it is moving towards Canada at an average rate of about eight centimeters per year, mainly due to post-glacial uplift /Angermann et al. 2021, 2022/. The actual directions of the other two axes also differ from their conventional definition. However, these deviations are by no means critical. The decisive factor is that the reference system is stable over time, so that all changes on our dynamic planet can be related to a stable reference to allow a meaningful interpretation. Furthermore, for a unique relation between the reference system and the points on the Earth's crust, constants (e.g., geometric gravitational constant GM , speed of light c), conventions, (geo-) physical models and model parameters (e.g., Earth and ocean tide models, Love numbers) need to be defined and consistently applied.

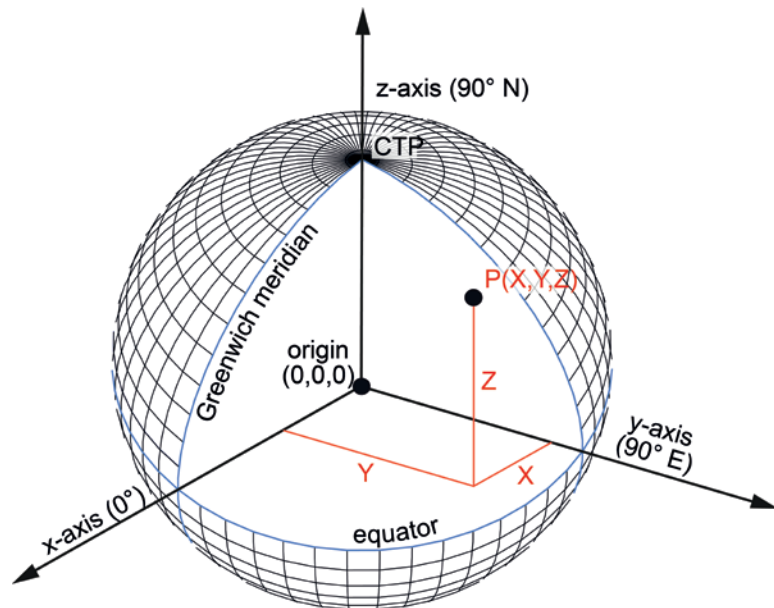


Fig. 3 | Cartesian coordinate system of the Earth

2.2 Positions and Displacements of Reference Points

The ITRS is realized by a set of terrestrial points (reference points of tracking instruments or geodetic markers) attached to the solid Earth crust. These reference points undergo a variety of motions: tidal displacements due to Earth's body tides and ocean tides, tectonic motion, polar motion, loading deformations due to atmospheric and hydrological mass movements, and other motions from internal mass movements and external forces. Reference points located in tectonically active regions can be also affected by seismic events in the form of co-seismic and post-seismic displacements or volcanic effects.

According to the IERS Conventions 2010 /Petit & Luzum 2010/, the positions and movements of reference points are described by a linear model in terms of coordinates at a reference epoch and constant velocities. However, such a linear model is not suitable for describing the motion of the actual (instantaneous) position of the reference points on the Earth's crust, as these are influenced by various effects that cause non-linear variations. For this reason, a so-called regularized position $X_R(t)$ is introduced by applying conventional corrections $\Delta X_i(t)$ to remove high-frequency temporal variations (mainly geophysical ones). The advantage is that a position with a more regular (nearly linear) time variation is obtained. The general model for connecting the instantaneous position of a reference point $X(t)$ on the Earth's crust at epoch t , and a regularized position $X_R(t)$ is

$$X(t) = X_R(t) + \sum \Delta X_i(t). \quad (1)$$

In the conventional secular approach, the regularized station position itself is parameterized by a linear model describing the position at

any epoch t_i by the position at the reference epoch t_0 plus a constant velocity v multiplied by the time difference $(t_i - t_0)$:

$$X_R(t_i) = X_R(t_0) + v \cdot (t_i - t_0). \quad (2)$$

The conventional correction models consider various geophysical effects on the station positions (e.g., Earth tides, ocean loading, rotational deformation caused by polar motion, ocean pole tide loading). Correction models are also applied for effects that directly influence the space geodetic observations such as signal propagation (atmosphere) and technique-specific effects (e.g., GNSS antenna phase center variations, thermal deformation of VLBI telescopes, SLR range biases, etc.). Even if all these effects are corrected by models, it must be kept in mind that model uncertainties (or possible errors) and other effects not considered by the models could influence the corrections of the instantaneous station positions. As a result, deviations of the non-linear part of the real station movements from the correction models become visible as residuals in the reference point coordinate time series /Bloßfeld et al. 2014/. In other words, the instantaneous position of a reference point deviates from the real position estimated from the space geodetic observations at a given epoch. These deviations can be considered as one of the main limiting factors for the accuracy of current realizations of the ITRS. Therefore, the treatment of non-linear station motions is the subject of ongoing research.

3 INTERNATIONAL TERRESTRIAL REFERENCE FRAME

3.1 Introductory Remarks and Fundamentals

For all practical applications, the theoretically defined reference system, the ITRS, must be realized by calculating the coordinates of firmly anchored points on the Earth's surface. These points are globally distributed observation stations whose coordinates are

consistently determined according to the system definition using space geodetic observation techniques. They materialize the reference system and make it accessible. The realization of the ITRS is called the International Terrestrial Reference Frame (ITRF).

The ITRF is recommended by the IAG and the IUGG as the standard terrestrial reference frame to the user community for positioning, satellite navigation and Earth science applications, as well as for the definition and alignment of national and regional reference frames /IAG 2019/, /IUGG 2019/. High accuracy, consistency and long-term stability of the ITRF are required for Earth system research and for precisely monitoring global change phenomena as well as for precise positioning applications on and near the Earth's surface. In view of the high societal relevance of the ITRF, the United Nations adopted the UN resolution "Global Geodetic Reference Frames for Sustainable Developments (GGRF)" on February 26, 2015 (/UN 2015/, https://ggim.un.org/documents/A_RES_69_266_E.pdf). This first UN resolution about geodesy emphasizes the importance of a sustainable global geodetic reference frame and the highly accurate measurement of our planet as a fundamental basis for economy, society and sciences. In March 2023, the UN-GGCE (Global Geodetic Centre of Excellence) has been established at the UN Campus in Bonn /UN-GGCE 2023/. This was an outstanding milestone in safeguarding the infrastructure required for the global geodetic reference frame and at the same time to promote the relevance of geodesy.

The ITRF is a global effort of hundreds of institutions and thousands of individuals around the globe, based on the investments of national mapping agencies, space agencies, universities and research groups in operating geodetic observatories, archiving, analyzing and combining the contributing space geodetic observations. Today, the ITRF consists of about 1900 geodetic observation stations distributed worldwide. The three-dimensional positions and temporal variations of these stations are observed using four space geodetic observation techniques: VLBI, SLR, GNSS, and DORIS. Three ITRS Combination Centers, the Institut national de l'information géographique et forestière (IGN) in Paris (France), the Deutsches Geodätisches Forschungsinstitut of the Technical University of Munich (DGFI-TUM, Germany), and the Jet Propulsion Laboratory (JPL) of NASA in Pasadena (USA) are responsible for the combination of the

data provided by the four technique-specific IAG Services, namely the International GNSS Service (IGS), the International Laser Ranging Service (ILRS), the International VLBI Service for Geodesy and Astrometry (IVS) and the International DORIS Service (IDS). The availability of three ITRF solutions ensures an assessment of the quality of the final ITRF product, which is then released by the ITRS Center at IGN. The ITRS Center is also responsible for the maintenance of the ITRS/ITRF, including network coordination, for the provision of specifications for the ITRS Combination Centers, and for the evaluation of their respective results.

3.2 Four Space Geodetic Techniques: VLBI, SLR, GNSS and DORIS

The four contributing space geodetic observation techniques VLBI, SLR, GNSS, and DORIS form the basis for the realization of the ITRS. These four space techniques provide observations over 27 to 41 years for the current ITRS realization 2020 (Fig. 4).

The corresponding station networks are displayed in Fig. 5. GNSS accounts for the largest number of stations, DORIS stations are most homogeneously distributed around the globe and the SLR and VLBI networks are sparsely distributed with only a few stations in the southern hemisphere but play an important role for the generation of the ITRF. The general picture of the distribution of ITRF stations shows a clear imbalance between the northern and southern hemisphere. In addition to the ocean areas, large parts of Asia and Africa are poorly covered with observing stations. There are currently five stations where all four space geodetic techniques are operated, which are highlighted in Fig. 5.

3.3 The key role of geodetic observatories

One of the biggest challenges in calculating the ITRF is to optimally combine the data from the four observation techniques VLBI, SLR, GNSS, and DORIS. This is where co-location stations (which operate two or more techniques together) come into play, allowing the

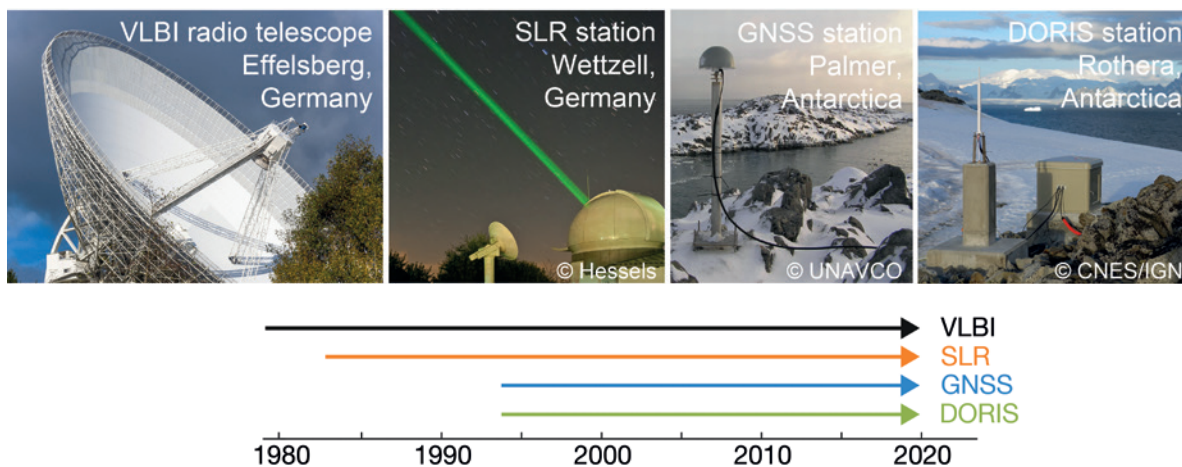


Fig. 4 | Space geodetic observation techniques VLBI, SLR, GNSS and DORIS and their observation time span used for the computation of the current ITRS realization 2020

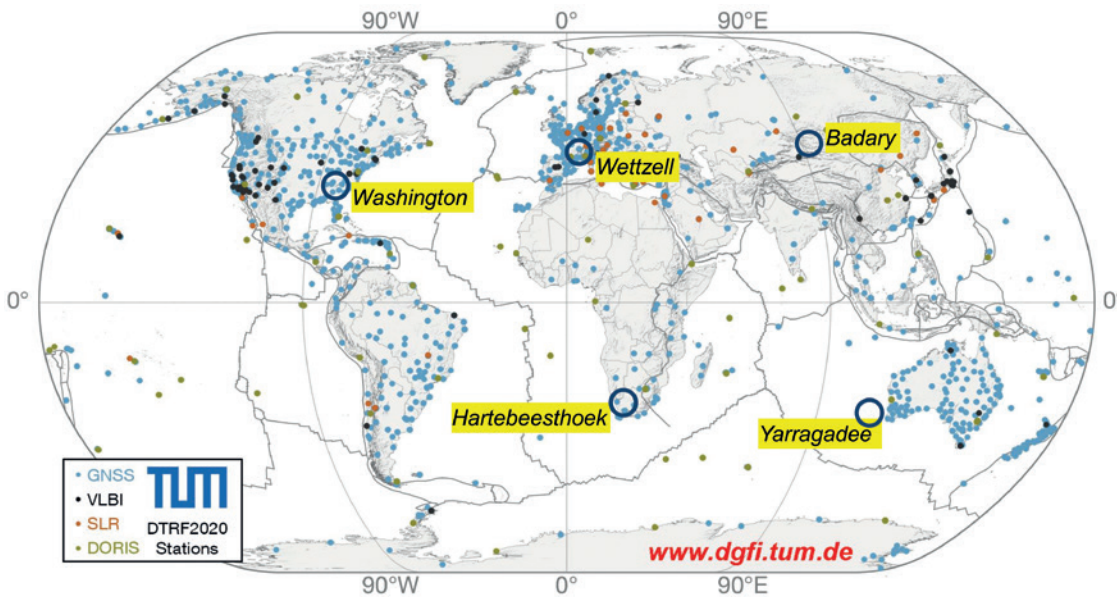


Fig. 5 | Spatial distribution of technique-specific station networks used for the current ITRS realization 2020. Co-location sites operating all four space techniques are highlighted.

individual space techniques to be combined so that their results can be processed into a consistent reference frame. This so-called inter-technique combination is essential to fully exploit the different sensitivities and strengths of the individual techniques (e.g., SLR to realize the origin, VLBI for the orientation of the Earth in space, SLR, VLBI and GNSS for the scale, and GNSS and DORIS for co-location and densification) for the determination of the parameters of the terrestrial reference frame. Of specific relevance are geodetic observatories, where all four techniques are operated together (so-called fundamental or core stations). One of the most important and most accurate core stations of the ITRF is the Geodetic Observatory Wettzell in the Bavarian Forest, Germany. Fig. 6 shows the spatial arrangement of the measurement systems operated at this site.

A prerequisite for the inter-technique combination is the precise knowledge of the connection vectors (3D coordinate differences) between the reference points of the individual observation systems, which are measured with millimeter accuracy using local surveying and height networks. In addition, these connection vectors (so-called local ties) are essential for estimating the accuracy of the different measurement systems and for detecting any discrepancies or technique-specific errors that may exist. For this purpose, the coordinate differences measured with the space geodetic techniques (which refer to the respective reference points of the instruments) are compared with the local tie vectors. In Wettzell, these discrepancies are very small (in the range of a few millimeters), which confirms the high quality of the observation systems and the local tie measurements.

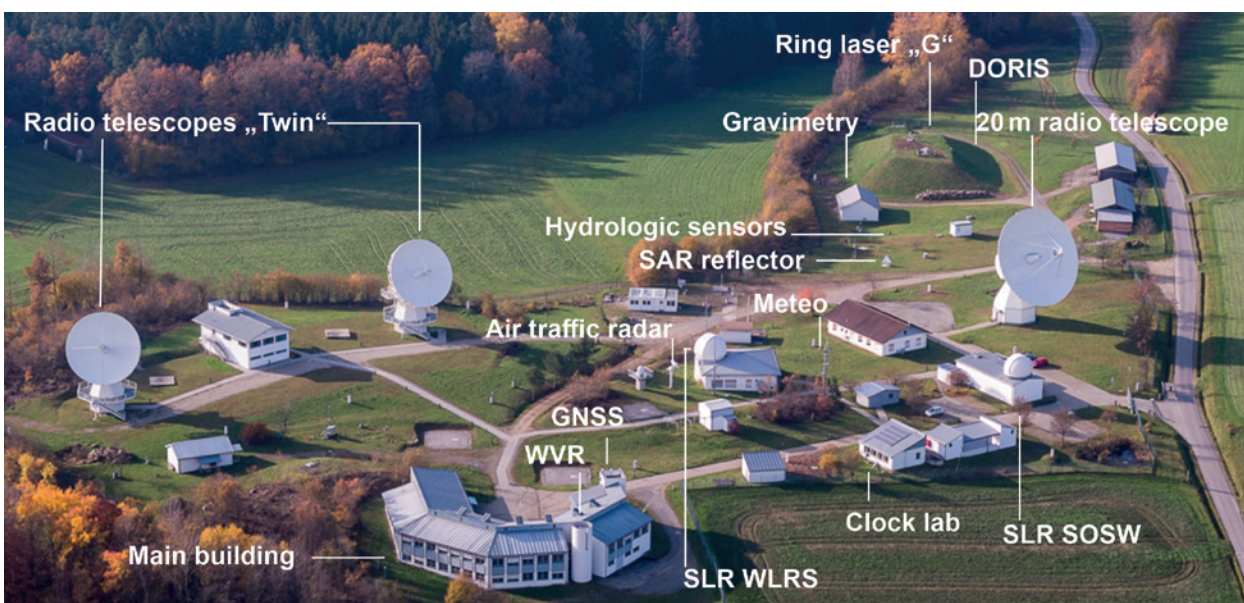


Fig. 6 | Measurement systems at the Geodetic Observatory Wettzell in the Bavarian Forest, Germany (Image courtesy: BKG, Hessels)

Technique/ IAG Service	Time Span	Sampling	Solution Type	Constraints	Reference
VLBI/IVS	1980.0 – 2021.0	Session-wise	Normal Eq.	None	/Hellmers et al. 2022/
SLR/ILRS	1983.0 – 1993.0	15-days	Solution	Loose	/Pavlis & Luceri 2022/
	1993.0 – 2021.0	Weekly			
GNSS/IGS	1994.0 – 2021.0	Daily	Solution	Minimum	/Rebischung 2022/
DORIS/IDS	1993.0 – 2021.0	Weekly	Solution	Minimum	/Moreaux et al. 2022/

Tab. 1 | Input data sets for the ITRS realization 2020

However, a shortcoming of the ITRF calculation is that there are still not enough fundamental stations on the globe, and that their geographical distribution is rather sparse to consistently link the different space techniques with the required precision.

4 THE CURRENT REALIZATION OF THE INTERNATIONAL TERRESTRIAL REFERENCE SYSTEM: ITRF2020

4.1 Input Data and General Overview for the ITRS Realization 2020

In 2022, the latest ITRS realization ITRF2020 was released by the responsible ITRS Center in Paris /Altamimi et al. 2023/ as successor to the previous realization, the ITRF2014 /Altamimi et al. 2016/. The input data for the ITRS realization 2020 are VLBI, SLR, GNSS, and DORIS time series of station positions and Earth orientation parameters (EOP), which are provided by the IAG Scientific Services. The time series for the four techniques were reprocessed by using the latest technique-specific and geophysical background models as specified in the IERS Conventions 2010 /Petit & Luzum 2010/. The major characteristics of the input data for the ITRS realization 2020 are summarized in Tab. 1.

Compared to the previous ITRS 2014 realizations /Altamimi et al. 2016/, /Abbondanza et al. 2017/, /Seitz et al. 2022/, six more years of observation data, new stations and satellites are available for the ITRS realization 2020. Moreover, technical improvements at various stations, an improved modeling and a homogenized parameterization of the techniques have been performed. The input data for the ITRS realization 2020 were used by the three ITRS Combination Centers to compute the current ITRS realizations, the ITRF2020 /Altamimi et al. 2023/, the DTRF2020 /Seitz et al. 2023/ and the JTRF2020 /Gross et al. 2023/. While DTRF2020 and ITRF2020 are secular frames providing station positions at a reference epoch and constant velocities according to the conventional ITRS definition, the JTRF2020 is based on a Kalman filter approach delivering time series of station positions. Thus, the two conventional multi-year solutions computed at IGN and DGFI-TUM are not directly comparable with the JTRF2020 time series of weekly station position and EOP solutions. However, there are also differences between the two secular frames, the ITRF2020

and the DTRF2020: IGN performs the combination of the four space techniques at the solution level, while the combination strategy of DGFI-TUM is based on the combination of normal equation systems (NEQs). Another difference is the handling of non-linear station motions. The ITRF2020 models seasonal station variations by estimating periodic (e. g., annual and semi-annual) signals, while DTRF2020 considers geo-physically modeled atmospheric, oceanic and hydrological NTL (non-tidal loading) corrections at the NEQ level. Both secular frames have in common that PSD (post-seismic deformation) models are used for sites impacted by major earthquakes.

4.2 DTRF2020 solution calculated at DGFI-TUM

The DTRF2020 solution is the ITRS realization of the ITRS Combination Center at DGFI-TUM /Seitz et al. 2023/. Two main innovations compared to the previous realization, the DTRF2014 /Seitz et al. 2022/ are:

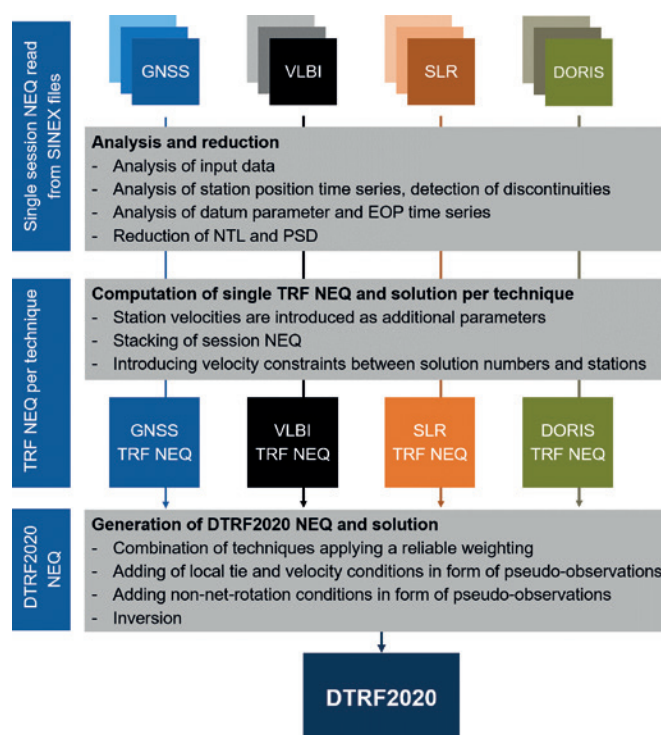


Fig. 7 | DGFI combination strategy based on a two-step approach: In the first step, the observations are analyzed and stacked per technique, and secondly, the resulting long-term NEQs of the four techniques are combined to the DTRF2020.

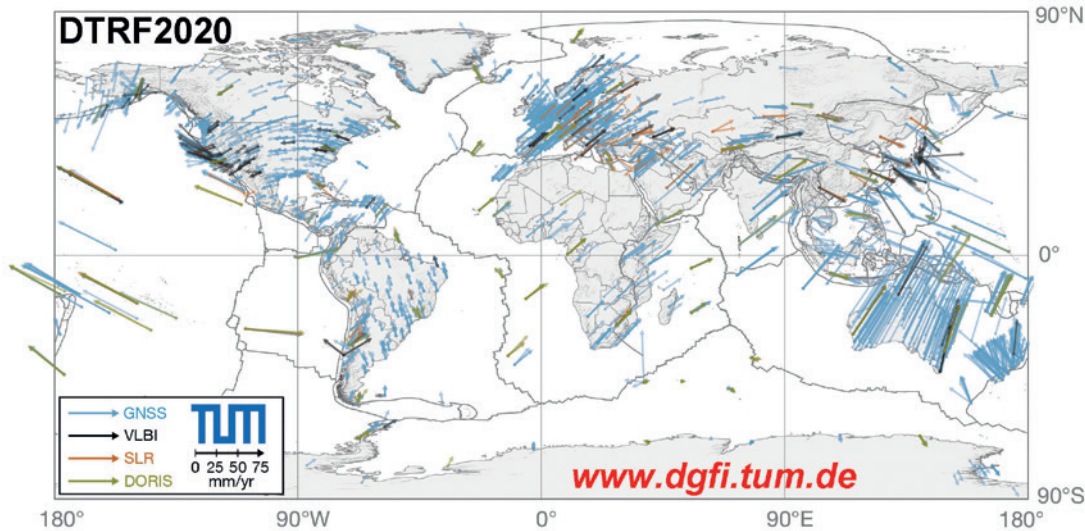


Fig. 8 | Horizontal station velocities of DTRF2020

- DTRF2020 considers for the first time all three components of NTL corrections /Glomsda et al. 2022/. The atmospheric, hydrological and oceanic components provided by the IERS Global Geodetic Fluid Center (GGFC; <https://geophy.uni.lu>) cover the full observation time span of the space geodetic techniques.
- PSD signals of stations that are strongly affected by earthquakes are modeled and considered in the DTRF computations for the first time.

The DGFI-TUM strategy is based on the combination at the normal equation level by applying a two-step approach (Fig. 7). In the first step, the time series of station positions and EOP are analyzed, the NTL and PSD signals are reduced, and the normal equation systems are stacked per technique. The second step comprises the combination of the technique-specific NEQs, the so-called inter-technique combination.

The main DTRF2020 results comprise station coordinates at the reference epoch 2010.0, the corresponding velocities, and EOP. DTRF2020 is available via Zenodo /Seitz et al. 2023/. The DTRF website <https://dtrf.dgfi.tum.de/en/dtrf2020/> provides detailed information about the DTRF2020 combination strategy, released files and DTRF2020 application. Fig. 8 depicts the horizontal position changes (velocities) of about 1900 globally distributed observing stations. The signature of plate tectonics is clearly visible (the boundaries of lithospheric plates are indicated by grey lines).

5 CONCLUSIONS AND OUTLOOK

The global terrestrial reference frame is a geodetic result of high societal and scientific impact. It ensures a uniform reference for all geospatial data and for a multitude of tasks in modern society such as satellite navigation, positioning applications, geoinformation systems, engineering, cadaster, land and resource management. In addition, a reliable monitoring of changes of our planet caused by geodynamic effects and climate change phenomena as well as the operation of early-warning systems to protect against natural hazards require a highly accurate global reference as fundamental ba-

sis. With a position accuracy of approximately 5 mm and a stability of 5 mm per decade, current ITRF solutions surpass all previous versions /Altamimi et al. 2023/. However, the ambitious targets of the IAG are not achieved yet, and probably exceeded by a factor of about 5. A major limiting factor for the accuracy of the ITRF and the integration of the different space techniques is the rather inhomogeneous and sparse distribution of co-location sites. In this context, the observed discrepancies (3-dimensional coordinate differences) between the local tie measurements and the space geodetic solutions, which exceed the level of 5 mm for about half of the co-locations /Altamimi et al. 2023/, /Seitz et al. 2022/, provide an important measure for the accuracy of the different techniques. This result clearly shows that the local tie residuals need to be reduced by improved modeling of the techniques and more accurate measurements of the local ties. Another issue is an improved handling of non-linear station motions. Although a significant progress has been achieved in the framework of the ITRS realization 2020, further improvements are necessary to reach the ITRF accuracy requirements. The fact that the three ITRS Combination Centers applied different approaches to account for non-linear station motions is beneficial to do comparisons between them and to perform detailed studies on this issue.

Significant milestones for global geodesy were the adoption of the United Nations resolution “Global Geodetic Reference Frame (GGRF) for Sustainable Development” in 2015 and the establishment of the UN-GGCE at the UN Campus in Bonn in 2023. Main tasks of the UN-GGCE are to raise awareness among Member States of the importance of geodetic reference frames, to build capacity and to enhance the infrastructure needed to ensure the availability of highly accurate reference frames /UN-GGCE 2024/. Another important achievement was the approval of the upcoming ESA satellite mission GENESIS /Delva et al. 2023/. By co-locating DORIS, GNSS, SLR and VLBI in space, the GENESIS mission will strengthen the combination of the different techniques and thus contribute to improving ITRF accuracy.

REFERENCES

- Abbondanza, C.; Chin, T. M.; Gross, R. S.; Heflin, M.; Parker, J.; Soja, B.; van Dam, T.; Wu, X. (2017): JTRF2014, the JPL Kalman filter and smoother realization of the International Terrestrial Reference System. In: *Journal of Geophysical Research: Solid Earth* 122(2017)10, 8474–8510. <https://doi.org/10.1002/2017JB014360>.
- Altamimi, Z.; Rebischung, P.; Métivier, L.; Collilieux, X. (2016): ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions. In: *Journal of Geophysical Research: Solid Earth* 121(2016)8, 6109–6128. <https://doi.org/10.1002/2016JB013098>.
- Altamimi, Z.; Rebischung, P.; Collilieux, X.; Métivier, L.; Chanard, K. (2023): ITRF2020: an augmented reference frame refining the modeling of nonlinear station motions. In: *Journal of Geodesy* 97(2023), 47. <https://doi.org/10.1007/s00190-023-01738-w>.
- Angermann, D.; Pail, R.; Seitz, F.; Hugentobler, U. (2021): *Mission Erde – Geodynamik und Klimawandel im Visier der Satellitengeodäsie*. Springer, Berlin/Heidelberg. <https://link.springer.com/book/10.1007/978-3-662-62338-1>.
- Angermann, D.; Pail, R.; Seitz, F.; Hugentobler, U. (2022): *Mission Earth – Geodynamics and Climate Change Observed Through Satellite Geodesy*. Springer, Berlin/Heidelberg. <https://link.springer.com/book/10.1007/978-3-662-64106-4>.
- Angermann, D.; Pail, R.; Seitz, F.; Hugentobler, U. (2023): The importance of geodetic reference frames – A uniform basis to tackle current and future challenges. In: *GIM International* 37(2023)7, 43–45.
- Bloßfeld, M.; Seitz, M.; Angermann, D. (2014): Non-linear station motions in epoch and multi-year reference frames. In: *Journal of Geodesy* 88(2014)1, 45–63. <https://doi.org/10.1007/s00190-013-0668-6>.
- Delva, P.; Altamimi, Z.; Blazquez, A.; Bloßfeld, M.; Böhm, J.; Bonfond, P.; Boy, J.-P.; Bruinsma, S.; Bury, G.; Chatzinikos, M.; Couhart, 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. G.; Le Poncin-Lafitte, C.; Lunz, L.; Männel, B.; Mercier, F.; Métivier, L.; Meysignac, 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. (2023): GENESIS: co-location of geodetic techniques in space. In: *Earth, Planets and Space* 75(2023), 5. <https://doi.org/10.1186/s40623-022-01752-w>.
- Gilmartin, L. M. (2019): *Jakarta Underwater. Rising Seas as Opportunity*. University of Maryland. <https://doi.org/10.13016/NDVZ-RR4M>.
- Glomsda, M.; Bloßfeld, M.; Seitz, M.; Angermann, D.; Seitz, F. (2022): Comparison of non-tidal loading data for application in a secular reference frame. In: *Earth, Planets and Space* 74(2022), 87. <https://doi.org/10.1186/s40623-022-01634-1>.
- Gross, R.; Abbondanza, C.; Chin, M.; Heflin, M.; Parker, J. (2023): JTRF2020: Results and Next Steps. In: *EGU General Assembly 2023*, 23–28 April, Vienna, Austria. <https://doi.org/10.5194/egusphere-egu23-2117>.
- Hellmers, H.; Modiri, S.; Thaller, D.; Gipson, J.; Bloßfeld, M.; Seitz, M.; Bachmann, S. (2022): The IVS contribution to ITRF2020. In: Tech. Rep., available at the ITRF2020 website. <https://itrf.ign.fr/en/solutions/ITRF2020>.
- IAG – International Association of Geodesy (2019): IAG Resolution No. 1 “The International Terrestrial Reference Frame (ITRF)” at the XXVII IUGG General Assembly 2019. https://iag-aig.org/doc/GH2020/209_IAG%20Resolutions.pdf (23.09.2024).
- IPCC – Intergovernmental Panel on Climate Change (2021): *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S. L.; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M. I.; Huang, M.; Leitzell, K.; Lonnoy, E.; Matthews, J. B. R.; Maycock, T. K.; Waterfield, T.; Yelekçi, O.; Yu, R.; Zhou, B. (Eds.)). Cambridge University Press, Cambridge, UK/New York, NY, USA. <https://doi.org/10.1017/9781009157896>.
- IUGG – International Union of Geodesy and Geophysics (2007): Resolution of the XXIV IUGG General Assembly No. 2 “Geocentric and International Terrestrial Reference Systems (GTRS and ITRS)”. <https://iugg.org/wp-content/uploads/2022/03/perugia07.pdf> (23.09.2024).
- IUGG – International Union of Geodesy and Geophysics (2019): Resolution of the XXVII IUGG General Assembly No. 2 “The International Terrestrial Reference Frame (ITRF)”. <https://iugg.org/wp-content/uploads/2022/03/2019-IUGG-GA-Resolutions.pdf> (23.09.2024).
- Moreaux, G.; Stepánek, P.; Capdeville, H.; Lemoine, F. G.; Otten, M. (2022): The DORIS contribution to ITRF2020. In: Tech. Rep., available at the ITRF2020 website. <https://itrf.ign.fr/en/solutions/ITRF2020>.
- Pavlis, E.; Luceri, V. (2022): The ILRS contribution to ITRF2020. In: Tech. Rep., available at the ITRF2020 website. <https://itrf.ign.fr/en/solutions/ITRF2020>.
- Petit, G.; Luzum, B. (Eds.) (2010): *IERS Conventions 2010*. In: *IERS Technical Note 3*. Bundesamt für Kartographie und Geodäsie, Frankfurt am Main.
- Plag, P.; Pearlman, M. (Eds.) (2009): *Global Geodetic Observing System – Meeting requirements of a global society on a changing planet in 2020*. Springer, Berlin/Heidelberg. <https://link.springer.com/book/10.1007/978-3-642-02687-4>.
- Rebischung, P. (2022): The IGS contribution to ITRF2020. In: Tech. Rep., available at the ITRF2020 website. <https://itrf.ign.fr/en/solutions/ITRF2020>.
- Seitz, M.; Bloßfeld, M.; Angermann, D.; Seitz, F. (2022): DTRF2014: DGFITUM’s ITRS realization 2014. In: *Advances in Space Research* 69(2022)6, 2391–2420. <https://doi.org/10.1016/j.asr.2021.12.037>.
- Seitz, M.; Bloßfeld, M.; Angermann, D.; Glomsda, M.; Rudenko, S.; Zeithöfler, J.; Seitz, F. (2023): DTRF2020: ITRS 2020 realization of DGFITUM (data). In: Zenodo (2023). <https://doi.org/10.5281/zenodo.8220524>.
- Smith, G. (2023): *From Jakarta to Nusantara: Land subsidence and other pressing water challenges in a sinking mega city*. Published on 29 Aug 2023, space4water PORTAL by UNOOSA (<http://www.unosa.org>) and PSIPW (<http://www.psiw.org>). <https://www.space4water.org/news/jakarta-nusantara-land-subsidence-and-other-pressing-water-challenges-sinking-mega-city> (23.09.2024).
- UN-GGCE – United Nations Global Geodetic Centre of Excellence (2023): *Strategy and Operation Plan. Version 1.0*. https://ggim.un.org/UNGGCE/documents/UN_GGCE_Strategy_%20and_Operating_Plan_v1.0.pdf (23.09.2024).
- UN-GGCE – United Nations Global Geodetic Centre of Excellence (2024): *Global Geodesy Needs Assessment – Expert Views and Perspectives. Version 1.0*. https://ggim.un.org/UNGGCE/documents/20240509-Global_Geodesy_Needs_Assessment.pdf (23.09.2024).
- United Nations – UN Resolution (2015): *A global geodetic reference frame for sustainable development, resolution 69/266 adopted by the General Assembly on 26 February 2015*. https://ggim.un.org/documents/a_res_69_266_e.pdf (23.09.2024).

AUTHORS



Dr.-Ing. Detlef Angermann

TECHNICAL UNIVERSITY OF MUNICH
DEUTSCHES GEODÄTISCHES
FORSCHUNGSINSTITUT (DGFITUM)

Arcisstr. 21 | 80333 Munich | Germany
detlef.angermann@tum.de | ORCID: 0000-0002-8852-8867



Dr.-Ing. Manuela Seitz
 TECHNICAL UNIVERSITY OF MUNICH
 DEUTSCHES GEODÄTISCHES
 FORSCHUNGSINSTITUT (DGFI-TUM)

Arcisstr. 21 | 80333 Munich | Germany
 manuela.seitz@tum.de | ORCID: 0000-0002-0316-687X



**Prof. Dr.-Ing. habil.
 Florian Seitz**
 TECHNICAL UNIVERSITY OF MUNICH
 DEUTSCHES GEODÄTISCHES
 FORSCHUNGSINSTITUT (DGFI-TUM)

Arcisstr. 21 | 80333 Munich | Germany
 florian.seitz@tum.de | ORCID: 0000-0002-0718-6069



Dr.-Ing. Mathis Bloßfeld
 TECHNICAL UNIVERSITY OF MUNICH
 DEUTSCHES GEODÄTISCHES
 FORSCHUNGSINSTITUT (DGFI-TUM)

Arcisstr. 21 | 80333 Munich | Germany
 mathis.blossfeld@tum.de | ORCID: 0000-0003-1579-0511

Manuskript eingereicht: 23.9.2024 | Im Peer-Review-Verfahren begutachtet

media2b.
 Die Medien des VDE VERLAGS.

IHR BUDGET HAT MEHR VERDIENT.

Optimale Werbeformate für Ihre Lead-Generierung – entdecken Sie unser neues B2B-Mediaportal und planen Sie den effizienten Einsatz Ihrer Mittel gemeinsam mit uns.

Tammy Rößler
 Mediaberaterin

[media2b.de](https://www.media2b.de)

NEU:
 Das Media-
 Netzwerk für Ihr
 B2B-Marketing