Publishable Summary for 18SIB01 GeoMetre
Large-scale dimensional measurements for geodesy

Overview

Geodetic reference frames form the backbone of all georeferencing services. In order to compare global measurement data for observations such as sea level monitoring an uncertainty of 1 mm or better is required, significantly below the current capability of 4 mm. This project focuses on two critical points within what is a complex traceability chain. Firstly, references of unprecedented accuracy for the Earth-bound verification of space-geodetic methods like Satellite Laser Ranging (SLR) or Global Navigation Satellite Systems (GNSS) are established. Secondly, the surveying capabilities for the geometric tie of co-located space-geodetic observations are systematically improved. Innovative field instrumentation and novel analysis strategies will thus be developed.

Need

Monitoring changes in sea level, retreating ice sheets, and long-term tectonic motion is critical. Many Earth science measurements are referenced to the International Terrestrial Reference Frame (ITRF), the realisation of the International Terrestrial Reference System (ITRS). The ITRF is a smart combination of several services of the International Association of Geodesy (IAG), using global networks of observatories. The Global Geodetic Observing System (GGOS) of the IAG aims at aggregating all this information with other information, like gravimetrical data. A network of well-instrumented sites constituting the GGOS core sites (GGOS-CS) has been set up where space-geodetic methods like Very Long Baseline Interferometry (VLBI), SLR, Doppler Orbitography and Radiopositioning Integrated by Satellites (DORIS) and GNSS receivers are co-located. In practice, the ITRF defines the scale of global measurements, ensures traceability to the SI definition of the metre and, thus, the long-term comparability of the data. The societal relevance of the ITRF is demonstrated by a resolution of the UN General Assembly (GA). Many high-end applications, like sea-level or volcano stability monitoring, however, require the accuracy of the ITRF to be substantially improved in order to extract meaningful observations from global data comparisons.

Dimensional metrology can address two critical issues. Systematic error sources of SLR and GNSS must be studied, understood, and compensated for to an uncertainty level of 1 mm over several kilometres. This requires suitable SI-traceable references. Furthermore, the spatial correlation of the reference points of co-located geodetic instrumentation, the so-called local tie vectors, must be determined for the joint analysis of all data. Geodetic experts see the need to improve the uncertainty of these complex large-scale dimensional measurements to 1 mm. This requires advances in analysis, measurement strategy, and instrumentation. Novel scientific concepts and field-capable devices are necessary for SI-traceable dimensional measurements in both one and three dimensions optimised for the specific challenges that limit uncertainties today. These measurement capabilities will also improve the surveying capabilities of critical infrastructure assets.

Objectives

The overall objective of this project is to improve the complex traceability chain in geodetic length metrology. The specific objectives of the project are:

1. To develop and validate field-capable primary or transfer standards to disseminate the unit metre over reference baselines over distances of at least 5 km with a measurement uncertainty below 1 mm (k = 2).

2. To develop and validate 3D capable novel measurement devices with a measurement range of operation of 200 m and accuracies of better than 200 µm outdoors, capable of compensating fast variations of the index of refraction at a relative uncertainty level better than 1 µm/m.
3. To develop technologies, methods, and uncertainty assessment for the Earth-bound SI-traceable verification of space-geodetic measurement technologies like GNSS or SLR over distances of at least 5 km with uncertainties of 1 mm or better and their implementation in a European reference standard.
4. To reduce uncertainty of the so-called local tie between co-located space-geodetic techniques at GGOS-CS (and all other eligible sites) by one order of magnitude to 1 mm over 200 m in real time continuous tracking. This requires a coordinated effort of novel dimensional measurement systems, methodology and analysis strategies and their demonstration in pilot studies at 2 European GGOS-CS.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the European geodetic measurement infrastructure by provision of European-wide access to the developed high-level references, collaboration with the established existing measurement supply chain (accredited laboratories, instrumentation manufacturers), and dissemination to standards developing organisations (ISO, IAG working groups) and end users (geodesy, surveying, high energy physics, and Earth sciences).

Progress beyond the state of the art

Field-capable standards of 5 km range with 1 mm uncertainty

Optical measurements must compensate the index of refraction for the correct measurement interpretation. Inevitable local inhomogeneity in ambient environmental conditions for example limits the achievable accuracy of classical sensor systems. GNSS-based distance measurement struggles with a set of complex effects limiting its uncertainty today to several millimetres. Based on the results of a previous JRP SIB60 Surveying for shorter distances up to several hundred metres, this project will explore alternative intrinsic optical refractivity compensation schemes. This will lead to intrinsically refractivity-compensating length measurement devices of unprecedented range and uncertainty. This effort is complemented by studies of error sources having an impact on the determination of the distance by GNSS, especially multipath effects and residual tropospheric delay, potentially improving achievable uncertainties to a one-millimetre level for this technology.

Refractivity-compensating 3D-capable measurement devices, accuracy better than 200 µm over 200 m

For the targeted measurement volume, optical measurement technology suffers from an imperfect knowledge of refraction and dispersive bending. Acoustic, spectroscopic, and dispersive thermometry are investigated and compared for intrinsic refractivity compensation. Two high accuracy ranging systems will be developed, making use of intrinsic refractivity compensation. 3D capability will be achieved by multilateration. To deal with beam bending, volumetric information on the refractive index distribution is necessary. Two complementary devices, sensitive to the effective air temperature, will be developed. These unique measurement systems will be specifically designed for implementation in local tie surveillance networks. In addition, a novel metrology-grade 200 m baseline will be established by device verification and made available to metrology services in the future.

Earth-bound verification over distances of at least 5 km with uncertainties of 1 mm or better

SLR and GNSS verification requires baselines over several kilometres with uncertainties below 1 mm. The novel SI-traceable long-range standards developed in the project will be deployed to establish the first European reference network in Poland with baselines up to 5 km in length and traceability to the SI definition of the metre with uncertainty of better than 1 mm. Case studies at the renowned CERN reference network and at the GGOS-CS in Grasse, France, will serve as benchmarks to demonstrate the capabilities of the novel methods to the surveying and geodesy communities. These studies will also further improve the understanding of systematic GNSS and SLR uncertainty contributions.

Local tie vectors over 200 m to 1 mm uncertainty in real time continuous tracking

In a world-wide unique effort, the project will systematically combine innovative length and environmental metrology with fore front local tie monitoring. Acoustic, dispersive, and spectroscopic thermometry will enable an unprecedented absolute and spatial resolution of the environmental parameter field. The novel 1D standards will foster the uncertainty of the scale in the network solution. Real-time tracking of telescope reference points will be realised. Furthermore, the observational data will be adjusted by a novel approach, reducing the impact of the local geoid. All these individual measures will be implemented in a coordinated effort as case studies at two European GGOS-CS. The optimum local tie vectors derived in these studies will contribute to the next ITRF realisation.

Results

Field-capable standards of 5 km range with 1 mm uncertainty

The project aims to achieve a low-uncertainty long range measurement in a first approach by using phase-shift modulation in a high frequency regime. The fundamental laser beam at 1550 nm is generated by an amplitude modulated distributed feedback (DFB) laser at 1550 nm. The complimentary 780 nm beam necessary for dispersive refractive index compensation is produced by second harmonic generation using a PPLN waveguide. Working with telecom wavelengths (1550 nm) enables a stringent use of optical fibre components, leading to a compact and field-capable source. The system has been preliminarily characterized on a non-permanent baseline over 5.4 km in Paris. That distance was measured during a whole day. The observed raw optical distances, i.e., without any air index compensation distance variation, varied over 15 mm on that day. The two-colour compensated measurement value remained stable within 1 mm, without the need for auxiliary measurements of temperature or air pressure variations.

As an alternative approach, optical multi-wavelength interferometry is used to realize an optical standard of such a long range. The interferometric measurement principle requires an optical source of high stability. For this, a robust stabilization scheme was developed. It acts as a flexible multi-wavelength generator, providing non-ambiguity ranges between 6 mm and 2.4 m. Furthermore, multiple laser beams of different colours must be perfectly superposed for the multi-wavelength scheme. Thereby, critical delicate beam properties like polarisation or wave front must be preserved. In a dedicated study, polarization-maintaining photonic crystal fibres (PM-PCFs) were identified as a suitable means for this purpose [6]. Finally, the interferometer head, i. e. the part of the instrument that is mounted on the pillar, was very carefully designed in mechanics as well in optics [18]. All components have been assembled and first verification measurements on an indoor 50 m interference have been performed, as well as outdoor verification measurements up 864 m on the standard baselines at Nummela and Braunschweig.

In standard measurements, temperature, ambient pressure, and humidity are usually measured to compensate for the index of refraction. During their work on the intrinsic refractivity compensation theory, the consortium discovered an error in the standard formula for the air group index by Ciddor and Hill [11]. Since this had been the standard algorithm in the field for almost twenty years and the magnitude is considerable, this finding is of high relevance for the whole field of high accuracy long distance metrology. Beyond, the classic approach was further refined for the application to extended sensor networks along the beam. An improved interpolation scheme was developed that reduces the uncertainty of the derived effective mean value considerably [9, 13].

The project partners also investigated possible enhancements of GNSS based distance measurement techniques, in comparison to the performance of the optical approaches over the 5 km range. Moreover, a measurement campaign was performed at Cortes de Pallás, Spain, in order to verify methods to reduce influences by multipath and troposphere.

Refractivity-compensating 3D-capable measurement devices, accuracy better than 200 µm over 200 m

A multilateration measurement system has been developed and realized based on the radio frequency modulation technology. It consists of four measurement heads and a smart reflector as target. The measurement heads measure consecutively, one after the other. The target orients itself towards the active measurement head. A complete cycle takes 20 seconds. A thorough analysis shows that the achievable measurement uncertainty (k=1) in a well-controlled environment is 4 µm up to 100 m due to the ranging technology, and the mechanical design of the measurement head and the target adds only 4 µm and 9 µm, respectively [5, 15,19]. The limiting factor for this highly promising measurement system remains the imperfect knowledge of the index of refraction. This leads to uncertainties in the scale and the beam propagation via beam bending. Two different technologies are being pursued to deal with this issue. In a first approach, the dependence of the speed of sound on the air temperature is exploited. Using a spherical resonator originally developed to determine the Boltzmann constant, the uncertainty of the relationship between air temperature and the speed could be reduced to the 100 ppm level. This is required to achieve 0.1 K accuracy for a speed-of-sound-based temperature measurement. For outdoor distances up to 200 m, a long-range acoustic thermometer has been developed and will be verified in the remaining project. The acoustic measurement principle will also be applied to measure temperature gradients in the vicinity of the optical ranging or levelling instruments. This system, a grid of affordable microphones and sound detectors, was able to measure temperature gradients with a resolution better than 10 mK in the laboratory. The system is now developed further towards field capability. In conjunction with this, a spectroscopic temperature measurement instrument is being developed. It exploits the fact that temperature determines the excitation distribution of molecular states in oxygen in air. The control and analysis electronics were successfully implemented to a compact electronic board. First outdoor measurements over several hundred meters showed the desired field capability.

Furthermore, an interferometric multilateration system is developed as an alternative approach. It will measure both geometric distance and temperature in a measurement volume of 50 m using the two-colour method. The 2f/3f modulation scheme enables absolute distance interference measurements with a high-resolving capability, while limiting the complexity, cost and volume of the actual measurement head [7, 17]. A versatile FPGA-based stabilization method was developed. It is able to both stabilize the frequency difference of two Nd:YAG lasers and to modulate the sources up to 20 MHz (peak-to-peak). A laboratory prototype of this compact, field robust method has been built. Under laboratory conditions, standard deviations of 40 µm were achieved for the single colour measurement for a 26 m distance and an integration time of 1 s.

Earth-bound verification over distances of at least 5 km with uncertainties of 1 mm or better

In Poland, at the Pieniny Kippen Belt, five baselines of distances between 1 and 5 kilometres were established, forming the novel ‘EURO5000 reference baseline’. Novel pillars have been constructed and first measurements are being performed. These baselines will be studied during the project via different methods, involving both optical and GNSS-based distance measurements, in order to establish a European long-distance reference. Further comparisons over 5 km between the primary standards developed in this project and GNSS and SLR are in preparation, e.g., at the surveillance network of CERN or at the GGOS-CS of Grasse, France.

Local tie vectors over 200 m to 1 mm uncertainty in real time continuous tracking

The GGOS core site operators in Metsähovi and Wettzell have updated their local tie surveillance networks. Several novel pillars were constructed, and lines of sight over several hundred metres up to 5 km established. These longer baselines are supposed to meet the capabilities of the novel high-accuracy long-distance range meters developed in the project. The long-range multi-wavelength interferometer has already measured a sub-net of the Metsähovi reference network. Furthermore, adapters for a ‘seamless network’ of GNSS and terrestrial observations were implemented to the Metsähovi network and the uncertainty contributions of auxiliary equipment to local tie network surveying have been thoroughly reviewed. An experimental study on the systematic errors of retroreflectors depending on the angle of incidence was performed. Consequences for an optimized use are currently derived. The goal of these measures is to reduce the uncertainty of the scale of the local tie vectors as well of the orientation of the network in a global frame.

A second critical issue is the observation of the reference point of the large antenna systems used in SLR and VLBI under movement. Deformations of the large dishes of the VLBI antenna thereby can be determined using laser scanning. A measurement setup and analysis procedure were developed for this purpose and deployed to the VLBI antenna at the GGOS-CS Ny Aalesund in Norway. As an alternative approach, close range photogrammetry was used for this measurement at the GGOS-CS Onsala, Sweden [2,3]. The accurate synchronization of the measurement systems with the antenna movements is a critical challenge. An improved procedure for SLR and VLBI reference point monitoring was developed in the project with a new algorithm [14]. The new approach allows for an in-process metrological determination of the reference point with a reduced synchronisation need. It has been successfully implemented and validated at the Geodetic Observatory at Wettzell [1]. Furthermore, the application of unconventional measurement technologies is being investigated. Several approaches to dynamic reference point monitoring have been proposed [2-4, 8, 12]. Close range photogrammetry was successfully demonstrated for the SLR reference point determination at Wettzell [16]. A measurement campaign was performed with the multilateration system developed in the project to determine the reference point of the TTW1 VLBI telescope at Wettzell. The data is currently being analyzed.

As a further contribution to the enhanced SI traceability and long-term stability of the ITRF, the consortium developed a new assessment procedure for GNSS absolute antenna calibrations and for its impact on accurate positioning that combines inter-antenna differentials and laser tracker measurements. A huge advantage for GGOS core sites is the fact that it can be applied to determine the phase centre of as-installed individual receiver antennas at system critical sites without compromising the permanent installations [10].

Finally, the local gravity field at Metsähovi and Wettzell were thoroughly investigated with a high spatial resolution. This information is now included into several adjustment software tools used for the local tie vector analysis. It is expected that this will significantly reduce uncertainties in the height coordinates caused by transformations between GNSS and terrestrial observations.

Impact

Impact on industrial and other user communities

This project's primary impact target is a substantial contribution to an improved ITRF solution. First results have already been taken up: a procedure for dynamic reference point determination at SLR and VLBI telescope has been implemented by the Wettzell GGOS core site, and the local gravity field is now considered at Metsähovi and Wettzell for the network adjustment. This capability was also included into a software package used by IGN, a main service provider for these measurements worldwide. Both European core sites also upgraded their surveillance networks. Finally, a new antenna calibration verification procedure that can be performed without removing the antennas can help maintaining continuity in the GNSS network IGS. Beyond, this project will develop novel measurement technologies for distance metrology and thermometry in general. These will be interesting for the surveying community, as well as automotive, aerospace and wind power industries. Surveying instrument manufacturers, top level surveyors, and European legal metrology will also benefit from the good practice guide on high-accuracy GNSS-based distance metrology and the novel verification opportunities provided by the new European primary standard network EURO5000. To accelerate uptake, the project has successfully established close connections with key stakeholders. Two major European GGOS core site operators, the Spanish core site Yebes and the Italian core site Matera, and a representative from GGOS have joined the project's stakeholder committee, as well as three major European manufacturers in the field, together with representatives from high energy physics, and measurement science. The project web site has been set up and the consortium organized its kick-off meeting as an open workshop.

Impact on the metrology and scientific communities

This project will substantially strengthen traceability of the ubiquitous global mapping systems to the SI definition of the metre by reducing the uncertainty of local tie vectors and enabling the SI-traceable verification of SLR measurements at an unprecedented uncertainty level. Moreover, the project will develop a draft EURAMET guide on metrologically-sound GNSS-based distance measurements and their realisation with low uncertainty. Furthermore, European NMIs will be able to offer novel services. Laser scanning assisted VLBI antenna deformation monitoring is already being provided by RISE as a direct outcome of their project work. Improved surveying instrument calibration and verification will be possible at Europe's first metrology-grade baseline over 5 km, as well as at the novel 200 m baseline for shorter distances. Furthermore, the primary standards developed in the project for long range 1D measurements and 3D capable measurement devices will enable the calibration of respective national standards, like large-scale coordinate measurement machines or geodetic baselines. Project results have already been presented at twenty-two international conferences, leading to ten conference proceedings papers. Twelve manuscripts have been accepted and published by high-ranking peer-reviewed international journals. The consortium will also present their results in two dedicated sessions at the 5th Joint International Symposium on Deformation Monitoring held 2022 in Valencia, Spain.

Impact on relevant standards

The project is represented in eleven standardisation bodies in the field of space geodesy and surveying. These include ISO and national standardisation bodies, but also IAG and IERS working groups or national surveying organizations. IAG e.g., has been informed about the project's discovery of the error in the original Ciddor and Hill algorithm for group refractive index compensation.

Longer-term economic, social and environmental impact

The UN GA has acknowledged the great importance of geodetic reference frames. The proposed work can substantially improve this field by technological solutions to two core challenges: Earth-bound verification of space-geodetic devices and substantially improved local tie metrology. The outcomes primarily need to be applied by the 15 GGOS-CS and other eligible co-location sites world-wide to improve future ITRF solutions. Improved quality of the reference networks (as well as of optical measurement equipment) will enhance the capability to monitor critical sites, e.g., future nuclear waste repositories or carbon sequestration repositories, and construction engineering projects such as bridges, dams, tunnels, and roads in mountainous regions. Most importantly, lower uncertainties in geodetic surveillance data will empower Earth science to draw reliable conclusions faster, e.g., on the real velocity of glacier retreat in Greenland, or on the rise of global sea levels.

The proposed research will hence contribute to a better understanding of these globally important environmental changes. Conclusions on climate change have triggered and will continue to influence political decisions with economic and social impacts on a multi-billion Euro level. The proposed research will strengthen the underlying data basis, and thus help politicians to draw conclusions responsibly.

List of publications

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td>June 1, 2019, 42 Months</td></tr>
<tr><td colspan="3">Coordinator: Name, Organisation Tel: +49 531 592 5420 E-mail: florian.pollinger@ptb.de
Project website address: www.ptb.de/empir2019/geometre</td></tr>
<tr><td>Internal Funded Partners:
1. PTB, Germany
2. CNAM, France
3. GUM, Poland
4. INRIM, Italy
5. NLS, Finland
6. NPL, United Kingdom
7. RISE, Sweden
8. VTT, Finland</td><td>External Funded Partners:
9. BKG, Germany
10. CNRS, France
11. Frankfurt UAS, Germany
12. IGN, France
13. NSC-IM, Ukraine
14. UPV, Spain
15. WUT, Poland</td><td>Unfunded Partners:</td></tr>
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