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

Overview

Geodetic reference frames form the backbone of all georeferencing services, providing the geospatial reference for global observations as sea level monitoring or Earth crustal movements. To strengthen the complex traceability chain, this project focussed on two issues: the creation of new long-distances references for the Earth-bound verification of space-geodetic methods like Satellite Laser Ranging (SLR) or Global Navigation Satellite Systems (GNSS) and on the measurement of the local tie vectors, the geometric connection of reference points of co-located space-geodetic telescopes. For this, the project developed specifically tailored instrumentation, like, e.g., new range meters capable to measure up to 5 km in air with sub-millimetric uncertainty, a metrologically-sound approach to GNSS-based distance measurement, or a 3D multilateration system for an outdoor working volume of 50 m which reduces the measurement uncertainty compared to state-of-the-art systems by a factor of 3. Using these systems and methods, novel reference standards like a new 5000 m reference network were established, and successful case studies for GNSS and SLR verification performed. In a unique effort, the local tie vector measurement was tackled from multiple angles at two European space-geodetic co-location sites. The novel measurement systems, but also novel measurement and analysis approaches showed their potential to push the accuracy limits further, below the targeted uncertainty limit of 1 mm and can now be applied to other respective sites.

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 geometric measurements and the long-term comparability of such data, but although the ITRS definitions use the SI, the absolute uncertainties were unknown, and the establishment of a metrological traceability chain is still a challenging task. The societal relevance of the ITRF has been 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 was able to address two critical issues. Systematic error sources of the space geodetic methods had to be studied, understood, and compensated for to an uncertainty level of 1 mm over several kilometres. This required suitable SI-traceable references. Furthermore, the spatial correlation of the reference points of co-located geodetic instrumentation, the so-called local tie vectors, had to be determined for the joint analysis of all data. Geodetic experts had seen the need to improve the uncertainty of these complex large-scale dimensional measurements to 1 mm. This required advances in analysis, measurement strategy, and instrumentation. Novel scientific concepts and field-capable devices were necessary for SI-traceable dimensional measurements in both one and three dimensions optimised for the specific challenges that limit uncertainties previously. These measurement capabilities also improve the surveying capabilities of critical infrastructure assets.

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Objectives

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

1. To develop and validate field-capable primary or transfer standards to disseminate the unit metre to reference baselines over distances to 5 km with the determination of the measurement uncertainty budget.
2. To develop and evaluate at least one 3D capable novel measurement device with a measurement range of 50 m for outdoor use with the determination of a targeted measurement uncertainty 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 required a coordinated effort of novel dimensional measurement systems, methodology and analysis strategies and their demonstration in pilot studies at two 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 a full measurement uncertainty budget

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. Based on the results of a previous EMRP project titled “Metrology for long distance surveying (SIB60 Surveying)”, this project explored alternative intrinsic optical refractivity compensation schemes. This led to intrinsically refractivity-compensating length measurement instruments of unprecedented range and a thorough assessment of the measurement uncertainty. These new prototype systems were also characterised by such advanced technology maturity that campaigns can be successfully conducted in the field over several weeks with the clear focus on the application rather than system maintenance. In case GNSS-based distance measurement, standard geodetic processing software did not enable a full measurement uncertainty assessment of GNSS, inhibiting sound SI-traceability to the SI-definition of the meter. In this project, a procedure was established which estimated the uncertainties in the different error sources affecting each single GNSS measurement used, rigorously propagated them through the equations by which the distance was determined, and, thus, delivered the final distance along with its corresponding measurement uncertainty.

3D-capable measurement devices with accuracy better than 50 µm over 50 m

For the targeted measurement volume, there was a lack of knowledge of the refraction and dispersive bending for the optical measurement technology. Acoustic, spectroscopic, and dispersive thermometry were investigated and compared for intrinsic refractivity compensation, making use of a novel metrology-grade 250 m baseline and enabling 1D measurement relative uncertainties better than 1 µm/m. This baseline was established in the project and is now available to metrology services. Using an acoustic sensor system developed in the project, it was shown that ventilated temperatures sensors provide measurement accuracies and dynamics sufficiently high that vertical beam bending corrections can be applied for this measurement volume. In particular, the 3D multilateration system DistriMetre was developed in this project to outdoor and long-range capability. Deployed for a 3D measurement under outdoor conditions, 3D measurement uncertainties in the order of 20 µm or better can be achieved up to 50 m, better than a factor of three compared to state-of-the-art forefront systems.

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. A new European reference network called 'EURO5000' was established in Poland during the project with baselines up to more than 5 km. SI-traceable reference lengths were derived from joint measurement campaigns using the novel SI-traceable long-range standards developed in the project has been 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, served as benchmarks to demonstrate the capabilities of the novel methods to the surveying and geodesy communities. These studies verified the new uncertainty model developed for GNSS-based distance measurement and offered a tool for the Earth-bound study of SLR uncertainty contributions at low uncertainty.

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

In a world-wide unique effort, the project systematically combined innovative length and environmental metrology with forefront local tie monitoring. The complex problem was tackled from three major different angles: (1) High-accuracy distance determination for scale definition, (2) reference point monitoring, (3) the combination of terrestrial and GNSS observations for a joint network solution. Instrumentation developed by the project was deployed to reduce the uncertainty of the inter-pillar distances of the local tie network solutions and thus the scale, as well as for the reference point monitoring. New methods, like close-range photogrammetry were successfully demonstrated for the latter application as well. Instrumental and methodical approaches to improve the orientation of the network solution were explored. In summary, the uncertainties of the local tie vector solutions at the GGOS-CS Metsähovi, Finland, and Wettzell, Germany, where the case studies were performed in the project were successfully reduced to below 1 mm. Parts of the results already contributed to the ITRF 2020 solution.

Results

Field-capable standards of 5 km range with a full measurement uncertainty budget

The project aimed 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 was generated by an amplitude modulated distributed feedback (DFB) laser at 1550 nm. The complimentary 780 nm beam necessary for dispersive refractive index compensation was produced by second harmonic generation using a PPLN waveguide. Working with telecom wavelengths (1550 nm) enabled a stringent use of optical fibre components, leading to a compact and field-capable source [35]. This so-called Arpent system was carefully studied, characterized and optimized at the Nummela Standard Baseline in Finland, for example. A full and detailed measurement uncertainty budget was derived, including contributions from the optical absolute distance measurement, the mechanical setup of head and targets, and the two-colour operation mode. In single-colour operation, a standard measurement uncertainty (coverage factor k=1) of 55 µm can be achieved for a measurement range of up to 1 km, neglecting the influence of the air index of refraction. If the two-colour method had been used for the compensation of the air index of refraction, the standard uncertainty of the refractivity-compensated distance meter could have been better than 0.65 mm at k=1 for a range of 1 km. More generally, the standard uncertainty (k=1) was better than 0.95 mm up to 5 km. For measurements over 5.4 km, a measurement resolution of approx. 5 µm can be demonstrated [38].

As an alternative approach, optical multi-wavelength interferometry was used to realize an optical standard for a range of up to 5 km. The interferometric measurement principle required an optical source of high stability. For this, a robust stabilization scheme was developed. It acted as a flexible multi-wavelength generator, providing non-ambiguity ranges between 6 mm and 2.4 m. Furthermore, multiple laser beams of different colours had to be perfectly superposed for the multi-wavelength scheme. Thereby, critical delicate beam properties like polarisation or wave front had to 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 was mounted on the pillar, was very carefully designed in mechanics as well in optics [18, 36]. The system was investigated and optimized on an indoor 50 m interference comparator, as well as outdoor verification measurements up to 864 m on the Nummela Standard Baseline and the 600 m standard baseline at Braunschweig. During the project, the system was constantly revised for optimization. A full, GUM-conformal assessment of the absolute distance measurement is yet to be achieved in future work.

In normal geodetic and surveying measurements, temperature, ambient pressure, and humidity are usually measured by auxiliary sensors 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 was considerable, this finding was 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, 20, 31, 32].

The project partners also investigated possible enhancements of GNSS based distance measurement techniques [25]. The resulting enhanced GNSS-based distance meter (GBDM+) was investigated in campaigns at the geodetic reference network CERN and the EURO5000 baseline. The results were consistent within 1 millimetre with reference lengths [27, 28]. Furthermore, the GBDM+ formalism enabled a rigorous quantitative estimate of the uncertainties on the different GNSS error sources. These uncertainties can be analytically propagated through the equations by which the distance was determined in the GBDM+, thus delivering a measurement result with a measurement uncertainty according to the "Guide to the expression of measurement Uncertainty" (GUM). This procedure providing a sound metrological treatment of the GNSS-based distance measurement was described in a good practice guide written in the project.

Therefore, the highly challenging objective 1 has been achieved as the Arpent system has successfully demonstrated a high-accuracy measurement over 5 km and a full measurement uncertainty budget could be provided.

3D-capable measurement devices with accuracy better than 50 µm over 50 m

The multilateration measurement system 'DistriMetre' has been developed and realized based on radio frequency modulation technology. It consisted of four measurement heads and a smart reflector as target. The measurement heads measured consecutively, one after the other. The target oriented itself towards the active measurement head. A complete cycle took 20 seconds. A thorough analysis showed that the achievable measurement uncertainty (k=1) in a well-controlled environment was 4 µm up to 100 m due to the ranging technology, and the mechanical design of the measurement head and the target added only 4 µm and 9 µm, respectively [5, 15,19]. The 3D coordinates of the target were derived by a multilateration measurement. For this, a GUM-conformal full uncertainty model was derived [26]. Refractivity-compensation was based on a classic sensor approach for this system. For reasonably stable measurement conditions, like cloudy sky or night-time, measurement uncertainties were between 10 and 22 µm during outdoor campaigns in the project, achieving the 1 µm/m target.

Furthermore, an interferometric multilateration system was developed as an alternative approach. It was designed to measure both geometric distance and temperature in a measurement volume of 50 m using the two-colour method. The deployed 2f/3f modulation scheme enabled 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 was 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.

The imperfect knowledge of the air index of refraction remained a challenge also for dimensional measurements in 3D. This led to uncertainties in the scale and the beam propagation via beam bending. Two different technologies were pursued to deal with this issue. In a first approach, a spectroscopic temperature measurement instrument was developed. It exploited the fact that temperature determined the excitation distribution of molecular states in oxygen in air. The control and analysis electronics were successfully implemented to a compact electronic board. In comparison measurement, the temperature probe beam could use the same target as the respective optical distance meters, enabling a temperature measurement very close to the actual distance measurement path. During these campaigns, deviations from reference sensor systems maintained below 0.3 K. In a second approach, the dependence of the speed of sound on the air temperature was 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 for the relevant environmental conditions in the range of 10 to 30 °C. This was required to achieve 0.1 K accuracy for a speed-of-sound-based temperature measurement. In a quiet indoor environment, a measurement uncertainty of 0.1 K for distances up to 60 m was demonstrated, while outdoors, for distances up to 200 m, measurement uncertainties below 0.2 K were achieved under favourable, i.e., windless conditions.

The project developed and evaluated with the DistriMetre at least one fully field-capable 3D capable novel measurement device with a measurement range of 50 m and a demonstrated measurement uncertainty better than 1 µm / m. Beyond, the consortium delivered an interesting tool set of measurement approaches and instrumentation that could also be combined with classical instrumentation to achieve the targeted measurement uncertainty in other ways. The Objective 2 was hence successfully achieved.

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 built and monitored over three years by GNSS and electronic distance measurement (EDM) methods. Furthermore, measurement campaigns with the GBDM+ method and the Arpent distance meter were performed. All these results were used to establish reference distances. This analysis also confirmed the assumed uncertainty budgets for the novel methods. For future calibration measurements on the EURO5000 baseline, a GUM-conformal measurement uncertainty has been derived for GNSS-based and optical distance meters. The tectonic stability of the area leads to changes of millimetre level between years. Shortly after a fresh calibration of the baseline, however, a measurement uncertainty of better than 1 mm can be achieved for verification measurements up to 5 km. Thus, there is now a high-accuracy standard baseline for mid-range distance meters available in Europe.

Due to the extreme accuracy requirements for the component alignment in high energy physics, CERN maintains one of the best-known geodetic reference networks in the world which has always served as high-level benchmark in the surveying community before. Four baselines of between 2.2 and 6.5 km of this network were measured by the GBDM+ method. Comparison with data obtained by a Kern Mekometer ME5000 distance meter in the same epoch as well as with other data available from previous campaigns showed an overall satisfactory agreement [28]. The distances observed by the Arpent system in separate campaign also agreed within their expanded measurement uncertainty with the GNSS-based value.

In a case study at the end of the project, a baseline measurement comparison between the Arpent system and a two-colour SLR under development in Calern, France was performed. A joint baseline over 2.6 km was determined using both techniques. For the comparison result, an expanded measurement (k=2) of 0.83 mm could be achieved.

The Objective 3 was successfully achieved as multiple joint long-range comparisons up to 5 km for terrestrial distance and GNSS-based as well as SLR based distance measurements were successfully conducted. Based on the experience gathered in the various campaigns, the consortium wrote a good practice guide on high accuracy GNSS-based distance metrology. The EURO5000 is a new, metrology reference baseline for geodetic methods where verification up to 5 km distance with an uncertainty better than 1 mm is possible.

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 were supposed to meet the capabilities of the novel high-accuracy long-distance range meters developed in the project. 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 were derived. The goal of these measures was to reduce the uncertainty of the scale of the local tie vectors as well of the orientation of the network in a global frame.

Selected baselines of the reference networks at Metsähovi and Wettzell were measured by the two long-range distance meters developed in the project. The spectroscopic and the acoustic thermometer were also used for the measurement of baselines at these sites. The observation data of the various campaigns were preliminarily included to the network adjustments. Their impact on the adjustment result, however, remained limited by the end of project. Due to their limited number, the observations by the new instruments had a small weight for the final adjustment result. To achieve a larger impact on the network solution, the prototype instruments must be developed to shorter measurement times and to faster installation times so that more observations can be performed within reasonable time frames. This work will be continued in future collaboration.

A second critical issue was 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 could 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 Ålesund 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 was 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 allowed 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 were also 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, 34].

Furthermore, a measurement campaign was performed with the DistriMetre multilateration system developed in the project to determine the reference point of the TTW1 VLBI telescope at Wettzell. 101 target positions were measured with distances ranging from 12 m to 73 m. The data was combined with complimentary observations by polar measurements with a commercial instrument. All data was analyzed together in a new model developed during the project. The results showed that the accuracy achieved by the GeoMetre multilateration measurement system was at least three times better than the accuracy of a conventional total station. The uncertainty of the derived position of the reference points was considerably better than the targeted GGOS spatial uncertainty of 1 mm. In Metsähovi, reference point monitoring by GNSS of the new VGOS antenna was validated [33].

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 combined inter-antenna differentials and laser tracker measurements. A huge advantage for GGOS core sites was the fact that it could be applied to determine the phase centre of as-installed individual receiver antennas at system critical sites without compromising the permanent installations [10].

The GNSS coordinates from permanently and temporarily measured pillars were introduced as datum points in the adjustment procedure, and all measured angles which referred to the local plumb line were used after correction of the local deflection of the vertical (DoV). To reduce the uncertainty of this transformation, the local gravity field at Metsähovi and Wettzell were thoroughly investigated with a high spatial resolution. This information was included into several adjustment software tools used for the local tie vector analysis. Several approaches were studied [24]. At both sites the poorly constrained vertical orientation from GNSS observations was significantly improved by the introduction of DoV data in the adjustment of terrestrial observations. This approach could easily be adopted by other geodetic observatories.

In summary, the GeoMetre project provided a unique opportunity to investigate novel instrumentation, experimental methods and approaches as well as novel analysis strategies for the local tie metrology problem. Different perspectives and professional backgrounds led to considerable progress despite delays and problems for the multiple measurement campaigns due to the Covid 19 pandemic situation during the project. While some methods need to be developed further before generating considerable impact on the final ITRF product, several measures led to an immediate reduction of the uncertainty of the local tie vectors and have already been taken up for standard work or even contributed to the ITRF2020 solution. A full automated real-time tracking of the local tie was not established. Yet, novel procedures reduced the telescope downtime for these significantly. Thus, the results of the project offer multiple tools for GGOS-CS operators to improve the uncertainty of their local tie vector measurement considerably. For the local tie vectors at Wettzell and Metsähovi, vector sets with uncertainties below 1 mm connecting the respective reference points were successfully derived as a product of the various measures, combined with the already sophisticated measurement strategies applied there before. Hence, objective 4 was successfully achieved for these two case studies.

Impact

The potential uptake of the project results by end users was promoted by a range of dissemination activities such as presentations at conferences and workshops, and input to metrology committees. The project website presents an overview of the project, together with new updates and announcements, and also provides access to papers, reports and open data produced during the project. The consortium produced and published 38 publications of different types (papers, proceedings, thesis, contributions to books). The major project results were presented in six presentations at two dedicated sessions of the 5th Joint International Symposium on Deformation Monitoring (JISDM) June 8-10, 2022, held in Valencia, Spain.

Impact on industrial and other user communities

This project's primary impact target was 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 developed novel measurement technologies for distance metrology and thermometry in general. These are interesting for the surveying community, as well as automotive, aerospace and wind power industries. Surveying instrument manufacturers, top level surveyors, and European legal metrology 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. The project has also 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 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 consortium organized its kick-off meeting as an open workshop. The results relevant for space geodesy in the field of SLR verification and local tie metrology were presented and discussed at key stakeholder events like the 22nd International Workshop on Laser Ranging, the Reference Frames for Applications in Geosciences (REFAG 2022), or the GGOS Unified Analysis Workshop in autumn 2022.

Impact on the metrology and scientific communities

This project substantially strengthened 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 uncertainty level below 1 mm. Moreover, the project has developed 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 has already being provided by RISE as a direct outcome of their project work. Improved surveying instrument calibration and verification are possible at Europe's first metrology-grade baseline over 5 km, as well as at the novel 250 m baseline for shorter distances. Furthermore, the primary standards developed in the project for long range 1D measurements and 3D capable measurement devices enable the calibration of respective national standards, like large-scale coordinate measurement machines or geodetic baselines. Project results have already been presented at thirty-nine contributions to international conferences, leading to fifteen peer-reviewed conference proceedings papers. Twenty-two manuscripts have been accepted and published by high-ranking peer-reviewed international journals.

Impact on relevant standards

The project was represented in twelve standardisation bodies in the field of space geodesy and surveying. These included 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. Members of the IERS Working Group on Site Survey and Co-location were addressed by contributions to the REFAG 2022 and the GGOS Unified Analysis Workshop 2022. The ISO working groups ISO TC211 "Geographic information/Geomatics, the IERS Working Group on Site Survey and Co-location, and the ISO TC172 SC06 "Optics and photonics – geodetic and surveying instruments" were addressed by representation at their meetings as well as presentations at respective national mirror bodies. As a major impact on standardization, EURAMET TC-L has launched Euramet project 1572 with the target to adopt the GNSS best practice guide as EURAMET Technical Guide.

Longer-term economic, social and environmental impact

The UN GA has acknowledged the great importance of geodetic reference frames. Considerable advance was generated in the field of local tie metrology. Many of the outcomes can easily applied by the 15 GGOS-CS and other eligible co-location sites world-wide. This can help 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 project hence made a small, but significant contribution to a better understanding of these globally important environmental changes.

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<table>
<tr><td colspan="2">Project start date and duration:</td><td>June 1, 2019, 42 Months</td></tr>
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<tr><td>Internal Funded Partners:
1. PTB, Germany
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