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ORIGINAL PAPER

The European GeoMetre project: developing enhanced large-scale dimensional metrology for geodesy

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Abstract

We provide a survey on the joint European research project "GeoMetre", which explores novel technologies and their inclusion to existing surveying strategies to improve the traceability of geodetic reference frames to the SI definition of the metre. This work includes the development of novel distance meters with a range of up to 5 km, the realisation of optical multilateration systems for large structure monitoring at an operation distance of 50 m and beyond, and a novel strategy for GNSS-based distance determination. Different methods for refractivity compensation, based on classical sensors, on dispersion, on spectroscopic thermometry, and on the speed of sound to reduce the meteorological uncertainties in precise distance measurements, are developed further and characterised. These systems are validated at and applied to the novel European standard baseline EURO5000 at the Pieniny Kippen Belt, Poland, which was completely refurbished and intensely studied in this project. We use our novel instruments for a reduced uncertainty of the scale in the surveillance networks solutions for local tie measurements at space-geodetic co-location stations. We also investigate novel approaches like close-range photogrammetry to reference point determination of space-geodetic telescopes. Finally, we also investigate the inclusion of the local gravity field to consider the deviations of the vertical in the data analysis and to reduce the uncertainty of coordinate transformations in this complex problem.

Keywords N*ovel distance sensor systems* · *Multilateration systems* · *SI traceability* · *GNSS-EDM comparison* · *Local tie metrology* · *Air refractivity compensation* · *GeoMetre*

Introduction

Geodetic reference frames establish the basis of georeferenced services and observations. They are obtained by combining several space-geodetic techniques such as Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Global Navigation Satellite System (GNSS), Satellite Laser Ranging (SLR), and Very Long Baseline Interferometry (VLBI). Due to their fundamental societal and economic importance, constant improvement of their quality is considered a global task (General Assembly of the United Nations 2015). The geodetic community is constantly analysing and improving the underlying system (Plag et al. 2009). As a basis for the fusion of global observations, like the sea level rise, traceability to the SI definition of the metre is highly critical.

The GeoMetre project, funded within the European metrology research program EMPIR, works on two general aspects of the traceability chain. Firstly, systematic error sources of space-geodetic methods like VLBI, SLR, and GNSS should be studied, understood, and compensated for to an uncertainty level of 1 mm over several kilometres. For this purpose, we have developed instrumentation and methods, both optical and GNSS-based, which can serve as low-uncertainty SI-traceable ground references. The second broader aspect tackled by the GeoMetre project addresses

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the combination of the observations of the various space-geodetic techniques. The usual approach for this is to introduce local tie vectors (e.g. Altamimi et al. 2017). A local tie vector defines the relative distance and orientation between two reference points of the involved space techniques. The vector can be observed at co-location stations using classical terrestrial surveying instruments, or GNSS measurements (e.g. Kallio et al. 2016). Local ties are identified as one of the critical components during the combination because outdated or erroneous ties bias the global results (e.g. Altamimi et al. 2017). As discussed in our project outline in Pollinger et al. (2022), we have tackled these problem sets from multiple angles, working on advances in analysis, measurement strategy, and instrumentation. In this review paper, we report substantial progress in basic environmental sensing and refractivity compensation, advances towards improved 1D long range and 3D large-scale instrumentation, the establishment of a novel European reference baseline of up to 5-km length, and progress in reference point monitoring and in reference frame transformation in the local tie monitoring process.

Environmental sensing and compensation

Refractivity compensation is standard good practice in any surveying measurements (Rüeger 1996). The general approach is to measure temperature t, ambient pressure p, relative humidity e, and carbon dioxide content x_C and to apply the compensation formulas for the index of refraction. For most geodetic instrumentation, the group index of refraction n_g is the relevant quantity. Since 1999, the International Association of Geodesy (IAG) officially recommends the algorithm published by Ciddor and Hill in 1999 for use in geodetic measurements. We discovered a subtle, but highly unfavourable sign error in their published algorithm which impacts the group index of refraction by several parts-per-million (ppm), depending on the carrier wavelength (Fig. 1; Pollinger 2020).

The central practical question for the application of such a compensation strategy, however, is how the effective ambient pressure and temperature can be determined along the whole beam path. The pressure can be considered relatively homogeneous for equal heights within the visible range; height differences can be taken into account by the barometric height formula. The local air temperature can strongly vary along an optical path in the field, depending on shadowing, cloud coverage and ground material, for example. In practice, the key to low uncertainty in length measurement in the field hence has always been the temperature measurement. It seems straightforward to use (ideally ventilated) calibrated temperature sensors distributed along the beam path. We have investigated the performance of several quadrature

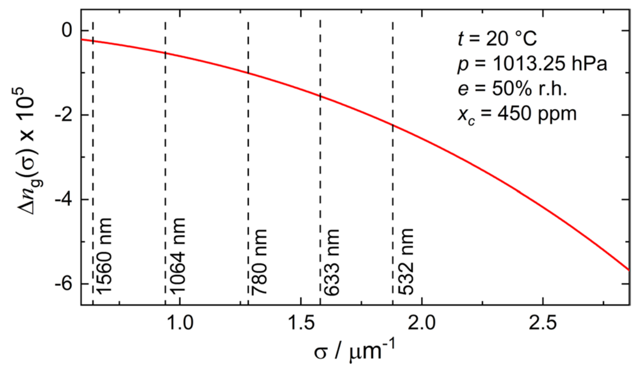

Fig. 1 Difference Δn_g between the group index of refraction derived from the numerical evaluation of the determining equation from the phase index and of the prior erroneous solution (Pollinger 2020, reprinted under the OSA Open Access Agreement)

methods to approximate the exact integral $\overline{n} = 1/\mathrm{L}\int_0^L \mathrm{n}(s)\mathrm{d}s$ by distributed sensors providing point-wise information on the local environment and gradients (Neyezhmakov et al. 2020a). For the linear geodetic polygon of the National Scientific Centre "Institute of Metrology" (Kharkiv, Ukraine), a relative uncertainty of 10^{-7} can be achieved which will provide a level of uncertainty of 1 mm for baseline 5 km (Neyezhmakov et al. 2020b).

But sampling the environment with point sensors implies a high measurement effort, especially for larger distances in arbitrary terrain. We explore alternative methods with which the influence of the air refractive index can be compensated by parallel measurements to the distance measurement in situ over the entire distance. A first approach is based on a measurement of the speed of sound. Demonstrated first indoors by Korpelainen and Lassila 2004, realizations for fast humidity measurements (Underwood et al. 2015) and over longer distances (Pisani et al. 2018) have recently been reported. To reduce the uncertainty of the method, we investigated the uncertainty of the underlying Cramer equations in the laboratory, using two different approaches (see Fig. 2). For distance measurements up to about 200 m, a bidirectional acoustic temperature sensor has been developed as well as a sensor to determine vertical gradients for beam bending corrections. Both systems will be deployed in the remainder of the project for outdoor measurement campaigns. An alternative approach is the deduction of the thermodynamic temperature from the population of molecular levels of oxygen. Hieta et al. demonstrated such a thermometer to achieve 10 mK uncertainty indoors in 2011, Tomberg et al. applied in 2017 a simplified setup to outdoor measurements over several hundred metres. In the GeoMetre project, we have further developed this system. A greater compactness of electronical and laser source unit strongly improves the field capability. The spectroscopic beam can be superposed, e.g. to measurement beams of the Arpent system.

Fig. 2 Simultaneous measurement of the speed of sound by differential distance change (foreground) and by the cavity resonance method in an anechoic chamber (sphere in the background) for verification and reduction of uncertainty of the Cramer equations

Finally, we also pursue dispersive (or "two-colour") compensation. In the refractive index models, the dependencies on environmental parameters and on optical frequency separate. Therefore, if a distance is measured by at least two optical wavelengths, the geometric length can be derived from these observations without the need of environmental observations. This concept was originally proposed in the 1960s (Earnshaw and Owens 1967) and refined by Meiners-Hagen and Abou-Zeid in 2008. In 1975, Hugget and Slater presented a first out-door capable electronic distance meter based on this principle, a predecessor of the renowned Terrameter (Huggest and Slater 1975; Huggett 1981). Critical for this measurement concept is a very accurate measurement of the optical path lengths.

Dimensional measurement instrumentation

Multi-wavelength interferometry

One way to realise an optical high-resolution measurement is the use of absolute interferometry. For such a measurement, the optical phase shift of beams of multiple colours after propagating the complete optical path is analysed. This measurement approach can be highly accurate and is therefore the method of choice for the most accurate dimensional measurements over distances longer than 10 m. For an application to geodetic measurements, however, this measurement concept is highly challenging. It is, e.g. very sensitive to structural stability of the instrument, to surface quality and turbulence effects. Meiners-Hagen et al. demonstrated in 2015 and 2017 that a sub-millimetric uncertainty over

Fig. 3 Multi-wavelength interferometer TeleYAG-II mounted on a pillar in the Metsähovi network. The trailer in the background hosts the optical source and the detection electronics. Trailer and optical head are connected by optical fibres

several hundred metres can be feasible for dispersive refractivity compensation using the heterodyne interferometer system "TeleYAG". In the GeoMetre project, this system has been developed further. Critical aspects were tackled. One prerequisite, the perfect beam superposition of the multiple beams, is now being assured using photonic crystal fibres as broadband wavelength division multiplexers (Liu et al. 2020). The optical system has been optimised and custom-built for a range of up to several kilometres. The mechanical base has been carefully designed for structural and thermal stability and was manufactured with single-digit micrometre tolerances (Pilarski et al. 2021). The system works with Nd:YAG lasers which emit laser light at 532 nm and 1064 nm. The measurement is simultaneously performed with three interlaced scales. The finest scales are generated by offset-locking of the laser sources against each other. Thus, the frequency difference can be externally controlled and provides the direct link to the SI definition of the metre. In the novel TeleYAG-II, the frequency difference can now be almost arbitrarily chosen within the bandwidth of the Nd:YAG lasers, allowing to construct scales from several tens of metres down to millimetre range. Thus, the ambiguity of the optical ranging solution can be resolved with little prior knowledge at the cost of extra measurement time of about 20 min. The system was completed in July 2021 and then characterised in the laboratory. It was then deployed to the reference baseline in Nummela, Finland, and measured parts of the surveillance network at the Metsähovi geodetic co-location station (see Fig. 3).

The heterodyne interferometer design comes along with a phase resolving capability of 10 pm but requires a cumbersome interferometer design. With the so-called Absolute3D system, we also work on a demonstration of a multi-wavelength interferometer which uses sinusoidally modulated laser light and a 2f/3f demodulation scheme (Sasaki and Okazaki 1986 and Meiners-Hagen et al. 2004) to enable multi-wavelength interferometry and phase detection. This technology requires a sophisticated electronic signal modulation but allows a very compact optics design (Röse et al. 2020). Besides intrinsic first velocity compensation for 3D measurements, such a system can also be used for 3D gradient measurements to compensate for beam bending. But the accuracy requirements on the optical measurement are extremely challenging (Röse et al. 2021). Both systems, TeleYAG-II and Absolute 3D, are discussed in more depth by (Sauthoff et al. 2022).

RF frequency modulation

An alternative, well-established successful concept to measure distances optically is the modulation of the laser beam intensity by a RF carrier. It is then possible to measure the phase accumulated by the modulating light during its propagation in air and thus to deduce the distance as follows:

$$D = \frac{1}{2}\left(\frac{\phi}{2\pi} + k\right) \times \frac{c}{n_g \times f_{RF}} \quad (1)$$

with D the mechanical distance, φ the measured phase, k the number of times that the phase has rotated by 2π, c the speed of light, n_g the air group refractive index, and f_{RF} the modulation frequency. This technique has been adopted for the development of two prototypes of scientific instrument: the first one, called "Arpent", is dedicated to long distance measurements up to 5 km, while the second one, called "Distrimetre", is dedicated to the measurement of three-dimensional positions by multilateration up to 200 m.

Like the TeleYAG-II system, Arpent is intended as a two-colour instrument which intrinsically compensates the refractive index changes due to temperature or pressure. To this end, two optical beams, at 780 nm and 1560 nm, have been modulated by a RF carrier around 5 GHz. However, to achieve a millimetre accuracy, the optical distances at each wavelength must be determined with an accuracy better than 20 µm. This instrument is still under development, but previous results obtained for a wavelength at 1.5 µm had shown encouraging outcome: an accuracy around 2 µm (coverage factor $k = 1$) for displacement measurements up to 100 m and a resolution around 25 µm for 5.4 km distance measured in an urban environment (Guillory et al. 2019) were demonstrated. More recent measurements made in October 2022 and depicted in Fig. 4 have even shown a resolution around 5 µm, still for a distance of 5.4 km. For this purpose, the distant corner cube was moved by a translation stage with steps of 1 mm per minute. This was done in cloudy weather, without sunlight.

Distrimetre is a "single-colour" instrument where the air refractive index is calculated from data recorded by local weather stations. It is composed of a fibre-optic absolute distance meter shared by means of an optical switch and a network of optical fibres between four measuring heads (Fig. 5). By this way, the positions in space of optical retroreflectors, i.e. targets, can be determined from the knowledge of the multiple distances measured between several targets and the four heads. This is the multilateration technique with self-calibration, which determines the coordinates of both, the positions of the targets and those of the heads. Distrimetre uses hollow corner cubes as targets for distances up to 200 m. However, for shorter distances up to 20 m, retroreflective glass spheres of 14-mm diameter and of glass index $n = 2$ can also be adopted. The advantage of

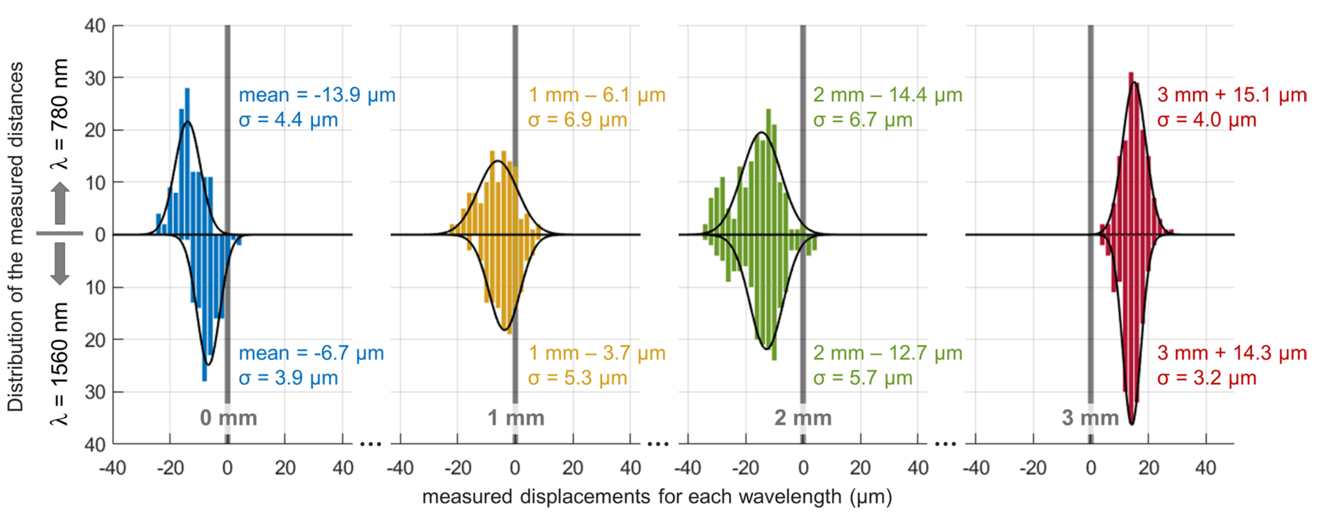

Fig. 4 Distribution of recorded distances when a distant corner cube is moved by step of 1 mm, 5.4 km away from Arpent. This demonstrates a resolution around 5 µm

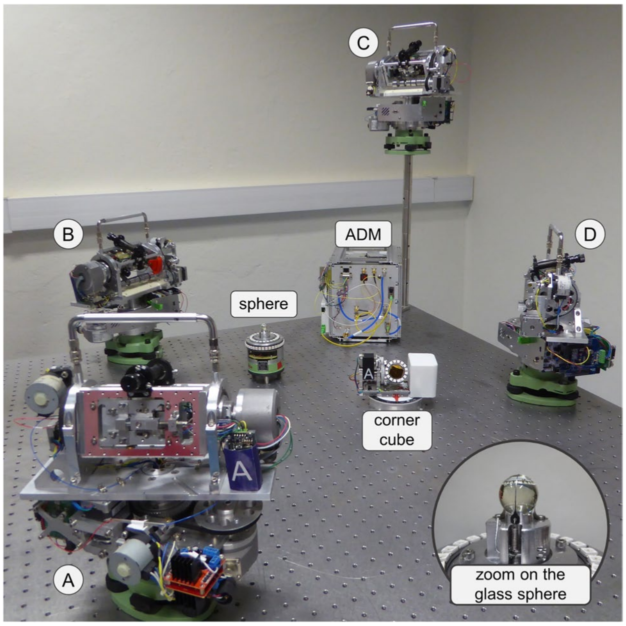

Fig. 5 Multilateration system composed of a shared absolute distance meter (ADM), four measurement heads (from A to D) and targets

such targets is a visibility from any angle, while their main drawback is significant optical losses due to a low reflectivity and a beam deflection at its output, which explain the limited range of operation.

A detailed analysis of this multilateration system has demonstrated, indoors with an air refractive index well assessed, an uncertainty around 5 μm ($k=1$) on the distance measurements for a range of operation of 20 m when the targets are glass spheres (Guillory et al. 2022) and of at least 100 m when the targets are corner cubes (Guillory et al. 2020). At the end, the propagation of the uncertainties into the coordinates of the measured positions leads to uncertainties up to 25 μm ($k=1$) with optimised locations of the heads relative to the targets.

High-accuracy GNSS network measurements

The standard geodetic processing of GNSS measurements (e.g. by Bernese software, Dach et al. 2015) does not permit to assess the individual contribution of the different error sources to the final uncertainty in the baseline length, which seems to lead to the general conclusion that GNSS measurements are not traceable in the metrological sense. Direct comparison between the final distances obtained by GNSS and calibrated EDM, as proposed in the good practice guide by Bauch et al. (2016) can shed light on the achievable accuracy but the result may be not transferable to other sites and observation campaigns. In the GeoMetre project, the GNSS-Based Distance-Meter methodology is being developed further (GBDM +), first, to rigorously estimate the uncertainties in the different error sources affecting each single GNSS measurement used; second, to analyse their propagation though the equations by which the distance is determined; and, finally, to deliver the final distance along with its corresponding uncertainty, as required for metrological purposes. Of the leading error sources which persist after double-differencing observations—namely, tropospheric and ionospheric delays, multi-path effect and mismodelling of antenna phase centres—we have already shown that multi-path can not only be mitigated but also the uncertainty of its remaining part be estimated by using sidereal filtering (García-Asenjo et al. 2021). We have also shown that tropospheric delays are still substantial after double-differencing. They may cause a significant bias of several millimetres in the final distance in the test field of Cortes de Pallás for lengths of some 2 km and significant height differences, 400 m (García-Asenjo et al. 2022). This effect can also be observed in our first computations for the EURO5000 baseline (Wezka et al. 2022), which show a first account of the uncertainty evaluation for each of the contributing sources and their corresponding uncertainty transferred to the final distance considering the baseline and the observations in use.

European reference baselines

Primary baselines in Europe used for verification

The project can use well-established European reference baselines for the verification of the techniques introduced in the previous sections. The 600 m reference baseline at the Physikalisch-Technische Bundesanstalt (PTB), Germany (Pollinger et al. 2012) and the reference baseline of the Universitat Politècnica de València (García-Asenjo et al. 2017) serve to study and verify the instrumentation, the Ukrainian Geodetic Polygon for the verification of the gradient sensor data interpolation method. A novel baseline over 250 m was established at the Warsaw University of Technology during the project for the verification in the medium range regime, as benchmark for their performance, however, serve comparisons at the Nummela Standard Baseline in Finland. Established originally in 1933 for calibration and comparison of invar wires, it is the only baseline in the world that has continuously been investigated using the Väisälä method (Väisälä 1923 and 1930). Since 1947, the baseline has been measured sixteen times, in most cases obtaining the 864 m total length with 0.06 mm to 0.09 mm standard uncertainty. Variation of this length has been smaller than 0.7 mm in 70 years, which indicates good repeatability and reproducibility of the measurement and good stability of the baseline

(Jokela 2014). It is therefore perfectly qualified for the purpose of verification of the instrumentation.

EURO5000: a new reference baseline

Most of the established European reference baselines have a range of several hundred metres up to 1 km. Baselines over several kilometres with uncertainties below 1 mm, however, would allow for GNSS verification in a specifically non-trivial application case. For this purpose, the GeoMetre project developed the EURO5000 reference baseline in the Pieniny Mountains in Poland (Fig. 6). Since 2004, horizontal movements in the area have been determined using a network of 15 GNSS stations (Walo et al. 2016). Geodynamic examinations indicate that the region exhibits minor neotectonics activity, which manifests itself mainly by clearly noticeable changes in elevation. The horizontal point movements are minor and do not exhibit clear tendencies in their magnitude and direction. Over 17 years, the observed relative position stability qualifies the region for a long-term reference baseline. Line of sight visibility is necessary for terrestrial measurements. Therefore, five new points have been established EURO5000 baseline near to the existing long-term monitoring points. They have been intensely studied by classical EDM and GNSS-based methods (Wezka et al. 2022). In the remaining months of the GeoMetre project, the novel SI-traceable long-range standards developed in the project as well as dedicated GBDM + measurement campaigns 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 a targeted uncertainty of better than 1 mm.

Local tie metrology

Network solution

Local survey networks on co-location stations tie the different space-geodetic techniques together. As the solutions of the space techniques are given in geocentric coordinates, the local ties, which are usually measured in a local horizontal system, must be converted into the geocentric frame, e.g. by a transformation using GNSS pass points. Due to the significant orientation error of GNSS-based solutions on short baselines, the high accuracy of terrestrial measurements is substantially degraded during the transformation. The introduction of GNSS coordinates as datum points providing the translation and horizontal orientation of the network and the use of deviations of the vertical (DoV) to account for the vertical orientation is a promising approach to overcome the transformation error. In the analysis, the inner constraints of the GNSS solutions are formed for rotations and translations only, while the scale results from the refraction-compensated distance observations provide SI-traceability. In the framework of this project, different techniques for DoV measurements were investigated and were applied (Lösler et al. 2022b). High resolution local geoid models, strictly speaking quasi-geoid models based on gravimetric data have been developed in the surrounding of the GGOS

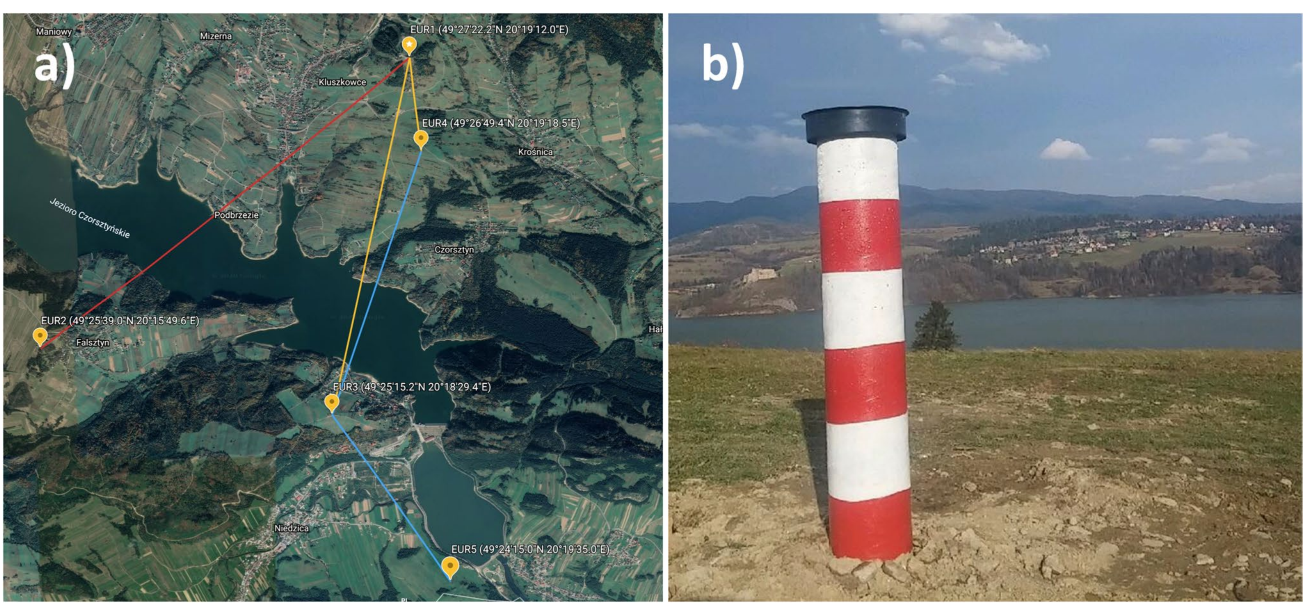

Fig. 6 **a** Survey on the five Euro 5000 baselines. **b** Newly erected pillar EUR1

core stations Metsähovi, Finland, and Wettzell, Germany. The difference to the national geoid solutions FIN_EIGEN-6C4 and GCG2016 are small, 2 µrad in Metsähovi and less than 1 µrad in Wettzell. The local DoV is represented by the normal of the quasi-geoid surface. In Wettzell, additional astrogeodetic observations using the QDaedalus system were performed (Albayrak et al. 2021). Both techniques provide the DoV angle with an accuracy of less than 1 µrad (0.2 arcsec). The transformation-free approach has successfully been tested using classic tachymeter data from a previous campaign (Kallio et al. 2022). The solutions were submitted to the ITRF2020. In a next step, new data from multilateration measurements to VLBI telescopes and fully refraction compensated network measurements taking advantage of the newly developed instrumentation will be processed to obtain the final local tie data set for the core sites Metsähovi and Wettzell.

Reference point monitoring

As mentioned, local ties provide the geometric relation between the space techniques. Changes in local tie vector components are a direct consequence of changes at the corresponding reference points. The VLBI and SLR reference points are defined as the orthogonal projection of the secondary axis onto the primary axis. By definition, this position is invariant and independent of the telescope orientation, but also not materialised or accessible for direct optical or tactile measurements. Within the GeoMetre project, a novel analysis strategy has been developed to obtain telescope reference points by indirect measurements (Lösler 2021). The reference point is derived by modelling trajectories of mounted markers at the rotatable part of the telescope. Beside the reference point, additional important parameters are estimated, for instance, orientation parameters that are used to reduce the pointing error of telescopes (Zhang et al. 2021), or the axis-offset which, if unconsidered, biases the global position (Combrinck and Merry 1997).

At the Geodetic Observatory Wettzell, the new approach has been evaluated using close-range photogrammetry for the first time (Lösler et al. 2021; 2022a). The reference point of the two-colour laser telescope, the Satellite Observing System Wettzell, was derived several times in a local frame using various configurations. Figure 7 depicts the photogrammetric reference frame as well as the prepared SLR telescope. The repeatability of the reference point is about ±0.1 mm. The uncertainties of the parameters to be estimated strongly depend on the stochastic model. Due to the high dependencies between the photogrammetrically derived points, correlations should not be neglected. If the fully populated dispersion matrix is reduced to a diagonal variance matrix or a uniformed scaled identity matrix—as usually used in industrial applications—the obtained uncertainties are up to three-time overestimated with respect to the fully populated dispersion matrix. A detailed description of the measurement campaign and the data analysis can be found in (Lösler et al. 2021; Eschelbach et al. 2022).

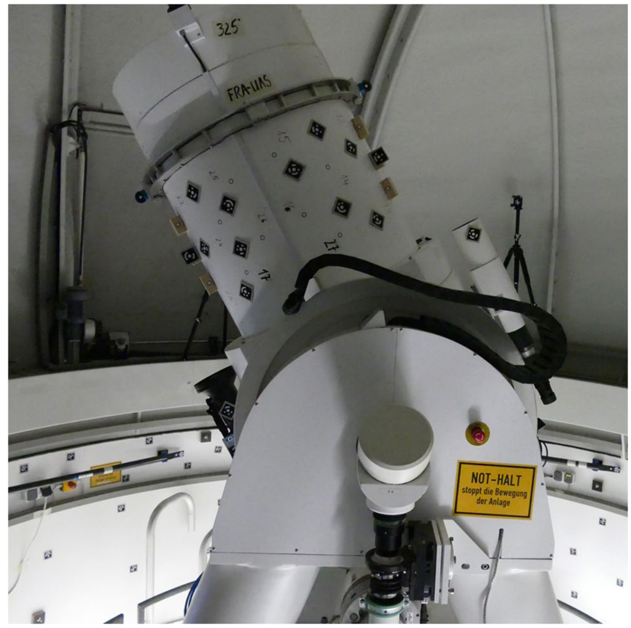

Fig. 7 Local reference frame with certificated scale-bars and photogrammetric targets as well as the prepared Satellite Observing System Wettzell

Discussion

This paper reports on the progress of the GeoMetre project after about two-thirds of its lifetime. So far, the work was focussed on instrumental and methodical development. Trying to improve the SI-traceability chain of space-geodetic techniques, the length measurement is the fundamental tool. Optical distance measurement allows a direct link to the SI definition of the metre. State-of-the-art commercial technology is of course well-advanced, but not really designed for the extreme dimensions relevant for space geodesy, and more importantly, limited in practice by the imperfect measurement of air refractivity. Therefore, there has been a strong focus in developing dedicated instrumentation for low-uncertainty terrestrial measurement in 1D and 3D. Based on a decade in instrumental development in the field, the metrology institutes could develop several solutions to field capability in the GeoMetre project. Spectroscopic and acoustic thermometry are sensitive to the effective temperature along the whole measurement path and have a very low latency time. Acoustic thermometry has been demonstrated over up to 200 m in this project, spectroscopic thermometry over up to 1 km. They can be relatively easily combined with any optical distance measurement and reduce the uncertainty of the environmental compensation considerably. Turbulence and wind, however, limit their applicability in practice in the field. Nevertheless, they are also excellent probes to characterize and study the performance of classical sensors with respect, e.g. to their latency times and self-heating effects. Respective work is currently being done. The two-colour distance measurement promises intrinsic compensation of the index of refraction. But it requires a highly accurate measurement of the optical path lengths—i.e. distance uncompensated for the index of refraction—at two colours. We pursued two different technology routes. Interferometry as potentially most accurate length measurement technique seems the obvious technology choice at least from a metrologist's point of view. The realization of a stable, field-capable interferometric measurement over the distances in question is a real challenge to instrumental design and scientific analysis. Considerable progress has been achieved, and a working instrument was developed. However, although the operability of this instrument is considerably easier compared to previous approaches, it still requires three experts and a laboratory trailer within 20 m range for the measurement. The modulation-based systems Arpent and DistriMetre developed in the project show a comparable and sometimes even better performance in the field. As shown in Fig. 4, the Arpent system, for instance, can achieve standard deviations well below 10 μm over 5 km under favourable conditions. Their design and operability strongly resemble commercial instruments. Two-colour compensation has been realized, but in its current implementation, it still has its limits. It can deal with spatial inhomogeneity of the environmental conditions. But visibility, of course, will always limit the applicability of optical techniques in the field. Longer integration times and power filtering can help to a certain degree, and we are currently investigating different filtering approaches. GNSS-based distance measurement (GBDM) suffers much less from the environmental conditions and does not require a clear line-of-sight. Nevertheless, GBDM has always been a difficult tool to establish SI-traceable distance measurements since an assessment of the uncertainty conformal to the "Guide the expression of uncertainty" (GUM) (BIPM 2008) requires a sophisticated Monte-Carlo simulation. The procedure developed in part in this project enables a rigorous uncertainty assessment using standard forward-propagation of uncertainties. We consider this an important milestone for the acceptance of GBDM as metrology-grade length measurement tool.

The target of the GeoMetre project, however, is not only to develop fore-front dimensional measurement tools, but to combine them with advanced measurement strategies to improve the SI-traceability of space-geodetic instrumentation and products. Comparison to reference baselines is the standard surveying approach to establish traceability. In the project, two new high-quality baselines were established in Europe, the 250 m baseline established at the Warsaw University of Technology for the verification in the medium range regime as well as the EURO5000 with its extended baselines over up to 5 km enabling the verification of GBDM over these medium distances. Established baselines like the Nummela Standard Baseline were used to verify the novel instrumentation which could then be used to characterize the novel baselines. Baselines of kilometres are also important to study space-geodetic techniques like SLR or VLBI. The Arpent system can serve as reference and establish respective baselines on site, accessible to these telescopes. Respective pilot experiments are foreseen in the near future. Finally, beyond pure baseline comparison, the local tie measurement is a second key challenge that the GeoMetre project is addressing. The determination of the local tie vectors at space-geodetic co-location sites requires multiple measurements with different techniques. Reducing the uncertainty further is non-trivial but given the importance of space-geodetic products like geodetic reference frames of high importance. We tackle this problem from multiple angles. Transformation from terrestrial to geocentric reference systems of the observation has been investigated using different approaches. A high-resolution map of the local gravity field must be acquired for this. Using the novel long-distance instrumentation, we will also investigate the impact of longer baselines at local tie network on the determination of the network orientation. Dynamic reference point monitoring is another critical aspect for the local tie measurement problem. As shown, photogrammetric techniques can provide high-accuracy data if analysed properly. Experiments to determine the reference point of a VLBI telescope at Wettzell by the DistriMetre system have been recently performed. First results are promising and will be reported soon.

Conclusions

In summary, the GeoMetre project has set out to contribute substantially to a significant improvement in the traceability of space-geodetic reference frames. It tackles this huge challenge from different angles and can already now, about a year left of project duration, report on substantial progress in instrumentation, measurement methods and analysis approaches. In the remainder of the project time, case studies at the renowned CERN reference network and at the space-geodetic station in Grasse, France, will serve as benchmarks to demonstrate the capabilities of the novel methods. These studies will also further improve the understanding of systematic GNSS and SLR uncertainty contributions. Reference baselines, instrumentation, and progress in refractivity compensation will remain beyond the lifetime of the project and can be used to tackle further monitoring challenges in future.

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Data Availability The data of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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