JRP SIB60 “Metrology for Long Distance Surveying”- a concise survey on major project results –

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Abstract. Long-term comparability and independence of measurement devices in general require tight traceability to the SI definition of the underlying unit. This requirement is difficult to fulfill in the metrology of distances at the kilometre level. Even state-of-the-art methods are unable to secure traceability at an uncertainty level below 1 ppm. Therefore, in 2013, the European Metrology Research Programme (EMRP) decided to fund a joint research project (JRP) to develop novel technologies and explore methods to strengthen the traceability chain in surveying.

The scientific work covers the two major technologies in distance metrology: Electro-optical and GNSS-based distance measurements (DM). In case of EDM, the main goal was to develop novel primary and transfer standards for the calibration of geodetic baselines with uncertainties well below 1 ppm. For this purpose, two approaches to inline refractivity-compensation were realized and verified against each other and state-of-the art standards on primary baselines. Additional optical methods were developed to rigorously quantify temperature gradients and the impact of turbulence on the optical measurement. Beyond, the potential of novel optical sources like fibre-based frequency combs for high precision length measurement was explored. In case of GNSS-based DM, several sources of uncertainty, like the influence of troposphere, or near-field and obstruction effects were investigated thoroughly, making use of facilities like common-clock fibre baselines, antenna calibration facilities, or novel test field designs. All measurement campaigns were jointly analyzed in search of a proposal of state-of-the-art good practice standards for high-accuracy DM and uncertainty considerations. The consortium also studied approaches to real-time 3D monitoring of the IGS/VLBI local tie vector at the geodetic fundamental stations of Onsala, Sweden and Metsähovi, Finland.

The contribution is intended to provide an overview of major project results and to serve as basis for a discussion of length metrology challenges in surveying.

Keywords. Length metrology, EDM, GNSS, traceability, EMRP JRP SIB60 Surveying

1 Introduction

The one dimensional determination of distances is without doubt a fundamental measurement method in surveying, and apparently a routine operation. Two measurement principles based on fundamentally different physical effects are used for this measurement today: the electro-optical distance measurement (EDM), and the distance measurement based on the Global Navigation Satellite System (GNSS-DM). The former is based on the propagation of an electromagnetic radiation between start and end point of the distance. GNSS-DM, on the other side, is derived from 3D coordinates obtained in the International Terrestrial Reference Frame (ITRF) using satellite signal reception and processing, often building on products and services provided by the International GNSS Service (IGS).
Typical distances in monitoring networks are in the order of several meters up to a few hundred meters. When talking about changes in the sub-millimetre regime for these distances measured under typical uncontrolled conditions, both measurement technologies have their limitations. The EDM measurement uncertainty is dominated in this case by the limited knowledge of the index of refraction (Rüeger (1996), Pollinger et al. (2012)), while GNSS-DM accuracy is limited by multiple, in part uncontrollable contributions that are difficult to quantify, from ionosphere and troposphere influences on the signal propagation, over signal deterioration in the local vicinity of the antenna (e.g. by obstruction or multi-path), down to the electromagnetic properties of the antenna, like phase centre offset (PCO) and variation (PCV) (Seeber (2003), Görres (2010)).

In addition to the pure measurement technology, stability and traceability of global and local reference frames are also related to this complex of challenges in length metrology. One particularly critical issue is the determination of the local tie vector at geodetic fundamental stations. This special monitoring problem is of high importance to link the reference points of the various space geodetic methods co-located there. For GGOS 2020, uncertainty requirements for these local tie vectors between 0.1 mm (Rothacher et al. (2009)) and 1 mm (Ray and Altamimi (2005)) have been stated.

Independently from the measurement technology used, long-term comparability of the often very critical monitoring data requires strict traceability to a realization of the SI definition of the metre:

> The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second. (Giacomo (1984)).

The uncontrollable environment in which surveying measurements are typically performed limits the uncertainty of these important measurements when aiming at ultimate accuracy. In 2013, the European metrology community initiated the joint research project (JRP) SIB60 on “metrology for long distance surveying” within its European Metrology Research Programme (EMRP), tackling technological and methodical challenges in the field (Pollinger et al. (2015)).

Meanwhile, 30 months of the project time have passed. This contribution intends to provide a survey on the progress of the project. The reader is referred to specialised publications for details. It should also be noted that, although the experimental work on the objectives is largely completed by now, not all data has been analyzed and not all joint conclusions have been worked out yet.

2 Optical distance metrology

2.1 Optical distance measurement in air

The SI definition of the metre refers to the propagation velocity of light in vacuum. Unfortunately, vacuum is rarely the medium to work in surveying practice. In practice, most optical distance measurements in air over a larger volume are limited in uncertainty by the influence of the medium air on the propagation velocity of electromagnetic waves due to the inevitable imperfect monitoring of environmental conditions

Fig. 1 TeleYAG measurement head mounted at the baseline.

and, to second order, to the fact, that the used models do not perfectly describe nature.

In the SIB60 JRP, we developed four different measurement devices targeting to study environmental influences on the distance measurement, and to push the relative uncertainty of long distance measurements to the 10^{-7} limit. The classical approach for index compensation is to distribute environmental sensors for pressure, temperature, relative humidity and CO_2 contents along the measurement path and use semi-empirical compensation formulae by Ciddor (1996), Bönsch and Potulski (1998), or Ciddor and Hill (1998) to derive the index of refraction and to correct the optical path measurement. For extended measurements, it appears tempting to use optical methods to compensate for the index of refraction *in-situ.*

One approach is to measure the inhomogeneous environmental parameters *in-situ* by optical spectroscopy. This has been demonstrated on laboratory level for temperatures with 0.1 K uncertainties (Hieta et al. (2011)). In the course of the SIB60 project, the measurement setup was refined to enable measurements over longer distances. Laboratory tests of this revised setup are promising that a similar level of uncertainty and resolution is feasible. In September 2015, an outdoor measurement campaign on the 864 m baseline of the Finnish Geospatial Research Institute (FGI) at Nummela was performed. The approach is discussed in detail also in Tomberg et al. (2016) in these proceedings.

Alternatively, the optical path can be determined with two well defined vacuum wavelengths λ_1 and λ_2. The refractivity-compensated length can then be derived if the dispersion between both wavelengths

can be appropriately applied. Already in 1967, Earnshaw and Owens introduced this “dual wavelength” method. In 1981, the “Terrameter” was introduced as a first commercial device working with this principle (Hugget (1981)). Meiners-Hagen and Abou-Zeid succeeded in 2008 in extending the measurement principle to wet, i.e. “real” air. Making use of latest advances in laser technology and high frequency electronics, the JRP SIB60 consortium developed two measurement systems which are based on this principle.
The TeleYAG system is based on heterodyne multi-wavelength interferometry and on two YAG lasers stabilized onto each other. The system is still relatively complex, in particular the source, but the consortium was successful in setting up a relatively robust and field-capable measurement head (Bosnjakovic et al (2015), cf. also Fig. 1). Under laboratory conditions, the refractivity-compensated measurement deviated less than 100 µm from the reference distance (Meiners-Hagen et al. (2015)). Outdoor measurements in 2015 revealed several sources of instability. Refractivity-compensation, however, could successfully be demonstrated for distances up to 864 m, the observed deviations being of the order of the uncertainty of the reference length. The system is intended to serve as future primary standard for the calibration of geodetic baselines.
In a second technology route, a more cost-efficient and compact telemeter design was targeted in the project. The so-called TeleDiode EDM is based on diode lasers as optical sources and RF modulation for the distance measurement, cf. Fig. 1. In fact, a fully embedded system design was realized successfully. On single wavelength level, standard deviations below 25 µm were demonstrated for outdoor measurements so far (Guillory et al. (2015)). Indoors, a 2-σ deviation of 5 µm was demonstrated. Meanwhile, the second wavelength has been implemented into the system, and outdoor measurements for the performance characterization are scheduled for spring 2016. Results so far indicate this approach to have the potential to serve as a prototype for future transfer standards or high accuracy EDMs.
Besides its influence on the propagation speed of light, the medium air also deteriorates the length measurement by changing the beam path. Temperature gradients and turbulence lead to beam wandering and fluctuations of amplitude, intensity, phase and angle-of-arrival (Brunner et al. (1979), Weiss et al. (2001)). In order to study the impact of this effect on the measurement uncertainty of an EDM measurement, two optical sensors were developed: one to investigate beam deflection, a second one to study the magnitude phase and amplitude fluctuations. First indoor and outdoor measurement campaigns show results which agree with expectations from literature (Zucco et al. (2015)).

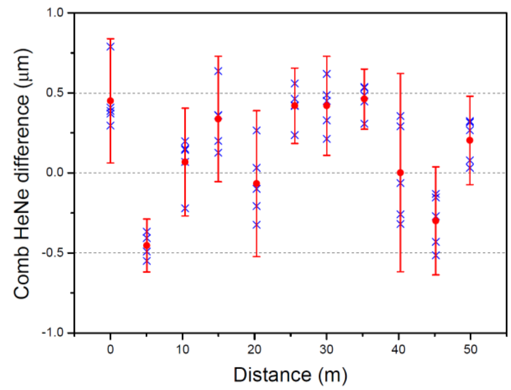

Fig. 2 Deviation of the length determined by the mode-resolved frequency comb interferometer from the reference length determined by a traceable incremental HeNe interferometer. The error bars indicate twice the standard deviation over the 5 measurements (Figure from van den Berg (2015)).

2.2 Frequency-comb based EDM

A second contemporary challenge in optical length metrology is the efficient exploitation of the spectral properties of novel optical sources, namely optical frequency combs. Frequency combs are characterized by a broad optical spectrum. The optical frequency of each comb mode is completely determined by two frequencies only, the offset frequency and the repetition rate, which are typically in the radio frequency (RF) band. The long coherence lengths, stability of the spectrum, and, in particular, the direct traceability to the SI definition of the metre make optical combs conceptually highly attractive for length metrology (Udem et al. (2002), Kim (2009)).
The JRP followed two technology routes to access the rich phase information of optical combs. In a first effort, the JRP explored the macroscopic applicability of spectral interferometry, a concept

that has drawn considerable attention recently (van den Berg et al. (2012)). Indeed, the consortium successfully demonstrated a comb-based absolute distance measurement of 50 m under laboratory conditions. The deviation of the measurement result from the reference value derived by a counting HeNe interferometer remained below 1 µm over the complete 50 m (Fig. 2, cf. also van den Berg et al. (2015)) .

Dual comb heterodyne interferometry is a second promising absolute distance measurement technology that might have potential to go beyond the conceptual stage. The JRP developed such a measurement based on cost-effective electro-optic frequency comb sources (Yang et al. (2014)). Up to 20 metres, the relative measurement uncertainty remained below 6×10^{-7} (Yang et al. (2015)). In the latter case, the uncertainty was basically limited by the bandwidth of the used comb generator. To gain access to larger bandwidths with reasonable costs for these measurement technologies, the JRP also explored optical filtering or repetition rate multiplication. Thus, commercially available fibre comb sources can potentially be used (Lesundak et al. (2015), Mildner et al. (2016), under review). Beyond these fundamental interferometry methods, the JRP is also investigating a scheme that implements inline refractivity compensation by comb-based spectroscopy. First results thereof are expected within the next months.

3 GNSS-based distance metrology

GNSS-DM is the measurement technology of choice if long-term monitoring is required. But the traceability chain to the SI definition is non-trivial. In particular when targeting millimetric or even sub-millimetric uncertainties, uncertainty contributions like multi-path effects, influence of troposphere and ionosphere and the uncertainty of antenna parameters need consideration. The JRP designed a number of experiments to study these effects as isolated as possible.

Recently, low noise metrological fibre links between selected sites allowed frequency distribution and comparison with unprecedented accuracy (Predehl et al. (2012), Droste et al. (2015)). Such links, but also links intended for optical time transfer (Rost et al. (2012), Śliwczyński et al (2013)) offer the chance to connect two GNSS receivers at different locations to the same clock, enabling potentially signal analysis on single difference level. The JRP studied configurations like this on multiple scales, on zero, very short (approx. 5 m) and short baseline distances (approx. 250 m), but also to a very long distances of 450 km. The intention was to study the impact of multipath and short periodic tropospheric refraction without additional noise introduced by double differences. But already short distance measurements on the campus of the Physikalisch-Technische Bundesanstalt in Braunschweig, Germany, showed that for single difference measurements other sources of uncertainty that usually cancel in the analysis based on double differences now dominate the uncertainty. Even in the case of most modern equipment, two receivers of the same type in the same rack may show different sensitivity to ambient temperature or humidity variations, exceeding the low picosecond range in noise level over time. Thus, common-clock experiments unfortunately proved of little benefit for the investigation of second order uncertainty contributions for the setup used. However, this interesting set up is well suited to study the impact of various receiver-antenna-cable related error sources thoroughly (Leute et al. (2016)). In addition, it was shown that common-clock set-ups can be beneficial for kinematic analyses of distances changes between the GPS stations linked to a common clock, cf. Schön et al. (2016b). They showed, e.g., that the noise of the kinematic height component can be reduced by up to 70%.

For many applications, the treatment of the troposphere seems to be under control in the well defined cases of strictly local measurements and of coordinates determined in local networks. In the former case, signals are assumed to experience the same signal delays. Therefore, troposphere correction is inherent when analyzing difference signals for the distance measurement (L1 solution). Additional corrections can even lead to misinterpretation. In the latter case, the ionosphere-free linear combination with an estimated tropospheric zenith path delay (L3T solution) is used. In the SIB60 project, a correction procedure based on a height correction term was developed for the height component in case of a short baseline analysis (Krawinkel et al. (2014)). The application to co-located stations of the EUREF permanent network (EPN) supported the benefit of this measurement strategy, Schön et al. (2016a, under review).

The magnitude of the impact of near-field and obstruction on the measurement was studied in a combined experimental and simulation study. For a double-difference based measurement configuration

Fig. 3 Revolver test field for the verification of antenna calibration parameters at the geodetic fundamental station of Metsähovi, Finland.

a similar combination of the antenna and spacer types was shown to minimize near-field effects. At the reference baseline at the University of the armed forces in Neubiberg, Germany, providing optimum satellite visibility (Heister (2012)), accuracies better than 0.5 mm for the distance and height components were achieved for integration times below 4 hours using this configuration. More surprising might be the fact that mere satellite obstruction does not seem to affect the accuracy substantially according to this study. As conclusion, the significance of the DOP (dilution of precision) value for the prediction of the measurement uncertainty should be questioned. Instead, the impact of far-field multipath effects on the measurement accuracy has to be reconsidered (Zimmermann and Kuhlmann (2016)).

It is well established that individual antenna calibration of PCO and PCV is absolutely necessary for high accuracy GNSS applications in surveying (Görres (2010)). When managing a pool of antennae in monitoring networks, a procedure is needed that validates the quality of the antenna calibration in the surrounding on site and after a certain period of time. For this important task, the consortium developed a test scenario based on antenna circulation and rotation. From simulations, a hexagonal symmetry was identified as optimum geometry. Such a “revolver” test field was set up at the geodetic fundamental station in Metsähovi, Finland, including traceable reference distances and levelled height differences (Figure 3). The full procedure is considerably time-consuming (in case of eight antennas, e.g., a minimum of sixteen twenty-four hours sessions is necessary), but enables identification of absolute residual offsets of 0.1 mm level. (Jokela et al. (2016), in these proceedings).

4 Local Tie Metrology

It is obvious that traceability to the SI definition of the metre depends on the traceability of the measurement device and method used. But in addition in surveying, it also comprises traceability of local and global reference frames. Reference frames like the ITRF are based on the joint analysis of different space geodetic observations like GNSS, Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), or Doppler Orbitography and Radiopositioning Integrated by Satellites (DORIS). Of course, traceability and a sound estimate of the measurement uncertainty of the individual observation methods are inevitable prerequisites for a traceable reference frame. The determination of the vectors connecting the reference points of these methods for the Helmert transformation into a joint reference system, the so-called local tie vectors, is thus also a very critical step in the traceability chain. On the example of the local ties connecting VLBI and GNSS baselines, the JRP SIB60 performed a systematic experimental and analytical study on measurement uncertainty and real time 3D monitoring to explore metrological paths to achieve the targeted measurement uncertainties of 1 mm or better for this monitoring task.

The surveying network for local ties is relatively complex. Proper application of the “guide to the expression of uncertainty in measurement” ‘(GUM) (JCGM (2008)) is non-trivial. As a tool to model the propagation of uncertainties in these complex measurement networks, Monte-Carlo simulations were performed. Using state-of-the-art technology, measurement uncertainties between 1 mm and 2 mm appear realistic (Tengen et al., to be published).

A practical question is the benefit of real-time monitoring of the local tie vectors instead of the use of fixed values. To study this approach, two real-time 3D monitoring systems along the lines of Kallio et al. (2013) and Lösler et al. (2013) were implemented at the geodetic fundamental stations at Onsala, Sweden and Metsähovi, Finland. In summer 2015, a joint VLBI and GNSS measurement campaign was performed, determining the VLBI and IGS baseline distances between these two stations. The results of this campaign are currently being analysed and will be presented in the near future.

5 Conclusions

The target of the JRP to tighten the traceability chain and to reduce the uncertainty of technologies for high accuracy surveying and monitoring was without doubt ambitious. Today, about six months before the end of the project, major conclusions of the joint analysis of the individual sub projects are still to be worked out and drawn. Nevertheless, the results presented above allow some conclusions already at this point. In case of EDM, the consortium successfully revived and implemented *in-situ* refractivity compensation. The consortium members are open to industrial partners willing to take this technology beyond prototype level. Even with few prototypes only, the technological solutions developed in this project enable improved traceability of geodetic baselines, and thus tighten traceability of EDM measurements in general. In addition, comb-based metrology has proven its potential for future application in the field. Recommendations on optimum procedures for EDM baseline calibrations are currently worked on as well. The complex measurement and analysis process labelled “GNSS-DM” makes it impossible to suggest general solutions or universal recipes for high-accuracy applications. Nevertheless, based on the various measurement campaigns and the insight gained in the project, the consortium is currently trying to work out conclusions on optimum measurement strategies and recommendations for work at the uncertainty limit of GNSS based length metrology. Finally, we admit that the study on local tie metrology is more of pilot character. But this work is already triggering consecutive investigations and will possibly contribute to metrological progress of this important measurement. Besides, the analysis methods developed for the local tie problem are of interest for GUM conformal uncertainty determination in any complex monitoring network in surveying.

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