Final Publishable JRP Summary for SIB60 Surveying
Metrology for long distance surveying

Overview

Landslides, sinkholes, and other tectonic activities may threaten populations, buildings, or industrial facilities in mining regions, mountain areas and around nuclear plants. Many of these critical sites are therefore monitored for small ground changes by surveyors, who face the challenge of measuring distances over several hundreds of metres to kilometers with uncertainties at less than a millimeter level. For example, when monitoring the stability of critical sites such as nuclear power stations or areas threatened by landslides, surveyors try to detect measurement changes smaller than a millimeter over a year. However, for distances of several hundreds of metres, environmental effects such as temperature, air pressure or local satellite obstruction limit the measurement uncertainty to the order of one millimeter for even the best state-of-the-art devices.

This project addressed the traceability of the two fundamental technologies in surveying: optical and global navigation satellite systems (GNSS) based distance measurements. Novel standards and technologies were developed by the project, leading to a better understanding of uncertainty contributions at the millimeter and sub-millimetre levels, and to a substantial reduction in the levels of uncertainty in length measurements in surveying and geodesy - the accurate study of the Earth's shape and size.

Need for the project

It is necessary to be able to measure distances up to kilometres with an accuracy of less than one millimetre in many applications. Such applications include, when constructing and monitoring current and future long-distance tunnel projects and the gigantic accelerator facilities used in high energy physics, when establishing local ties between different geodetic instruments on geodetic fundamental stations, and when monitoring deformation networks at critical sites like nuclear power plants or future carbon dioxide repositories.

Many of these critical sites are monitored for tectonic changes by surveyors. For this monitoring, distance measurements in a network of permanent reference points looking for changes over time are often used. For long-term comparability of data points, traceability to the SI definition of the metre is essential and a substantial improvement of the level of measurement uncertainty to the sub-millimetre level would help early decision making.

Due to uncontrollable environmental effects, both the optical and the GNSS approaches to distance measurement are currently unable to achieve traceability to the SI definition of the metre with the required uncertainty.

The accuracy of the optical method, using electronic distance meters (EDMs), also suffers from insufficient determination of the environmental conditions such as the effective temperature within the whole beam path over distances of hundreds of metres. As a consequence, the refractive index cannot not be determined accurately enough to derive the geometric length from the observed optical path length.

GNSS-based distance measurements are influenced by various effects. The electromagnetic properties of the receiver antennas can play an important role – the location of the reference point varies with each antenna, and can depend on the reception angle. Environmental effects such as signal transmission delays in the ionosphere and troposphere, signal reflections by the ground or the local environment, or local satellite visibility effects can also influence the achievable measurement accuracy.

Further to this, space geodetic observations are highly critical for earth science observations and for the maintenance of the global and local GNSS reference system. Space geodetic observations and their spatial correlation (so-called "local tie vectors") at geodetic fundamental stations are distributed all over the world. However, real-time 3D surveying methods and appropriately optimised measurement strategies are required to substantially improve the uncertainty of GNSS based measurements.

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Finally, in order to improve daily monitoring work in the field, it is important to offer realistic good practice guidance for state-of-the-art surveying. This includes field-capable optical standards for long-distance baseline calibrations and revised guidelines for the calibration of both EDM and GNSS-based distance meters.

This project addressed these challenges through new and improved methods and guidance. It set out to reduce the uncertainty of long-distance metrology for measurements up to 1 kilometre and to develop traceability to the SI. As part of this novel technological and methodical solutions for calibration and long-distance measurement were developed.

Scientific and technical objectives

To address the requirements outlined above, the project aimed to improve long-distance measurement methods by:

1. Improving optical measurements in air. In particular, the inline compensation of the refractive index along the whole beam path, and the impact of turbulences on the measurement, with a target relative uncertainty of 10^{-7} over a distance of 1 km.
2. Gaining a better understanding of the uncertainty of GNSS-based distance metrology. This will allow the development of a sound uncertainty model and an optimised field calibration procedure, targeting absolute uncertainties of 1 mm or better.
3. Developing concepts for the application of femtosecond laser-based many-wavelength interferometry to long-distance metrology with a targeted relative measurement uncertainty significantly better than 4×10^{-7} under controlled environments.
4. Developing solutions to improve state-of-the-art surveying practice, ranging from field-capable optical standards with relative uncertainties of 10^{-7} for long-distance baseline calibrations, over refined guidelines for the calibration of both EDM and GNSS-based distance meters, up to an extensive inter-comparison of major primary geodetic baselines in Europe.
5. Investigating different approaches to real-time monitoring of local ties at geodetic fundamental stations, both experimentally and theoretically. Thus, fundamental metrology for the Global Geodetic Observing System (GGOS) will be developed with an overall target to reduce the uncertainty of reference frames to 0.1 mm.

Results

1. Optical measurements in air with a targeted measurement uncertainty of 10^{-7} over a distance of 1 km

In surveying, optical measurements are typically performed under uncontrollable environmental conditions and therefore the accuracy of the measurement of these environmental quantities is limited. In practice, uncertainties below 1 K (kelvin) are only achievable under very stable conditions meaning that prior to the start of the project optical distance measurements were limited to a corresponding uncertainty of 1 mm (i.e. 10^{-6}) over 1 km distance.

This project developed optical methods suitable for use in the field that were capable of overcoming these limitations. One method used spectroscopy to build an optical thermometer, which was used to measure a temperature resolution below 300 mK over more than 800 m for averaging times of 120 s. The data can then be used to correct optical distance measurement data leading to uncertainties below 0.3 mm over this distance for the influence of the refractive index.

The project also developed devices for distance measurement in air that compensate for the index of refraction simultaneously with the distance measurement. The devices were based on an idea developed in the 1960s i.e. that if you measure a distance with two well-known optical frequencies and roughly determine the humidity, no further temperature or air pressure data is needed to derive the distance. The two devices were: the TeleDiode system as a cost-effective more robust transfer standard and the TeleYAG system as a prospective novel primary standard.

The TeleDiode system was realised using commercially available fibre optics in the telecom band which resulted in a compact and transportable device, with the potential for commercialisation. In the field, standard deviations of 3 µm (i.e. a relative standard deviation of 3×10^{-9}) over 800 m and 24 µm over 4.7 km were successfully demonstrated.

The TeleYAG system was based on a highly specialised optical design. Two-colour inline refractivity compensation was achieved with this system. Combined measurement uncertainties between 0.2 and

0.6 mm were successfully demonstrated for distances up to 864 m in outdoor conditions. No additional environmental monitoring systems were needed. Traceabililty to the SI definition of the metre is directly implemented in the system design and makes the TeleYAG system a suitable primary length standard for distances over several hundred metres.

As well as the index of refractivity, air turbulence also affects optical long-distance measurements. Therefore, an optical turbulence meter was developed by the project to assess this effect in typical outdoor conditions. Initial results have indicated that for moderate turbulence conditions (e.g. wind speeds up to 3 m/s) standard deviations of 10 µm for 80 m are possible, suggesting a fundamental limit for length measurements in the order of 1×10^{-7}.

In conclusion, the project reduced the achievable measurement uncertainty over 1 km from 1 mm under optimum conditions to 0.2 to 0.6 mm under reasonable conditions, i.e. for a moderate temperature window of 10 to 30°C due to limitations of the hardware used and wind speeds below approx. 3 m/s for acceptable turbulence levels. These standards have increased the reliability of the traceability chain in surveying.

2. Uncertainty of GNSS-based distance metrology, targeting absolute uncertainties of 1 mm or better

GNSS-based distance metrology is used ubiquitously. While its flexibility is an advantage of this technology, it suffers from uncertainty influences such as signal delays due to the signal traversing the troposphere and ionosphere, and satellite obstruction or signal distortions such as multiple reflections due to the vicinity of the receiver antenna. These influences are impossible to control and difficult to quantify. Therefore, to derive recommendations for optimum measurement strategies and for a sound measurement uncertainty assessment, individual uncertainty contributions were studied and isolated (as far as possible).

Fibre optics were used to synchronise the receiver clocks of two GNSS receivers and this ‘common clock’ approach eliminated the need to determine the clock as a free parameter. Thus, an unperturbed access to other parameters should have been theoretically possible but, in practice, the receiver electronics were very sensitive to the local environment and this could not be eliminated. Nevertheless, the project successfully demonstrated that the fibre optic approach enabled high resolution height measurements which is important for the monitoring of critical buildings such as bridges.

In addition to this, the optimum processing strategy for the linked parameters height, receiver clock and tropospheric delay was investigated using the standard GNSS analysis approach. With this, a correction strategy was successfully applied to co-located GNSS stations reducing height discrepancies from the centimeter-level to the millimeter-level.

The importance of symmetry in the measurement set up was underlined through outdoor studies on the effect of mounting GNSS antennas on geodetic pillars and studies of typical obstruction scenarios. In the case of symmetrical set ups (same antenna types and mounting, in a similar environment), absolute and standard deviations below 0.5 mm could be achieved, even with additional obstructions. These unexpected results indicate that satellite obstruction itself does not substantially affect measurement uncertainty.

Finally, the project investigated a practical approach for the assessment of uncertainties in GNSS-based distance metrology. The results showed that deviations from reference coordinates taking into account the uncertainty of these reference coordinates and the observed standard deviation were a good indication of the achievable measurement uncertainty for specific configurations and measurement times.

In conclusion, although, a general method for millimetre uncertainties in GNSS could not be produced, the project improved the quantification of relevant uncertainty contributions, and suggested improvements for reducing measurement uncertainties in GNSS-based distance metrology.

3. Femtosecond laser-based many-wavelength interferometry for long-distance metrology

Since their invention in the last decade, optical frequency fibre combs have been advocated as ideal sources for high accuracy length measurements. They provide multiple laser modes with frequencies that can be directly locked to reference clocks in the radio frequency regime, and thus directly to the SI definition of the metre. However, prior to this project, commercially available fibre combs were characterised by low repetition frequencies which complicated their use for length metrology applications. Therefore, the project studied several approaches to address this, such as mode filtering by air-spaced or fibre based Fabry-Perot cavities. From the results a design for a novel broad band dual-comb generator was produced which can be used as a potential source for length metrology applications, as well as being applied to spectroscopic applications.

Heterodyne multi-wavelength interferometry as a fast detection technology was also investigated by the project. It was successfully used to demonstrate a relative measurement uncertainty of 5.3 x 10^{-7} (0.53 mm) for a measurement distance of 20 m, for cavity-enhanced electro-optic frequency combs.

In conclusion, in terms of length measurement, spectral interferometry proved to be the most successful method with deviations from a counting interferometer below 1 µm up to 50 m, corresponding to a relative measurement uncertainty of 2 x 10^{-8}. This is the first time that spectral interferometry has been successfully applied over such distances.

4. Improvement of state-of-the-art surveying practice with respect to length metrology

One of the major outcomes of the project was the linking of three European primary geodetic baselines in Finland and Germany via an extensive field study using different transfer standards such as the TeleYAG and TeleDiode systems developed in objective 1, as well as commercial state-of-the-art devices. Following their comparison, these primary geodetic baselines can now provide European surveyors with SI traceable calibration of their devices with low uncertainty.

The project also developed the sophisticated "Revolver" field test for the validity of GNSS antenna calibration parameters. This test is based on measurement campaigns with multiple antennas. By suitable antenna swapping and rotating, and using high-level analysis, the test procedure is sensitive to 0.1 mm level for the absolute residual offsets of each antenna for the North and East component and relative residual offsets for the 'Up' component. Therefore, a verified tool to test GNSS equipment in the field with reduced instrumentation is now available for European surveyors.

Finally, two good practice guides were produced by the project with the aim of reducing uncertainty contributions in GNSS-based distance metrology and in electronic distance meters baseline calibrations. These good practice guides are available for end-users on the project's website http://www.emrp-surveying.eu/emrp/2984.html.

In conclusion, the project was able to improve the metrological core of European surveying and to provide measurement and verification strategies for daily work in surveying. These combined outputs contribute to improving the state of the art of surveying practice.

5. Local tie metrology for the Global Geodetic Observing System (GGOS)

Local tie vectors connect the reference points of different space-earth measurement observing systems. Their monitoring networks are highly complex, but are crucial for the generation of a global reference system which forms the basis for GPS-based navigation or global observations of climate-induced changes, for example. This project theoretically investigated existing networks and derived complex models for uncertainty propagation. Different approaches were used to estimate the overall achievable measurement uncertainty of contemporary local tie vector monitoring in the order of 1 – 2 mm. The project also installed GNSS-based and terrestrial real-time 3D observation systems at the geodetic fundamental stations of Onsala, Sweden and Metsähovi, Finland. The observation systems are capable of monitoring reference points during system operation in real-time. They can therefore directly measure unexpected position changes induced, for example, by temperature expansion. This is expected to reduce the uncertainty of local tie vectors, in the longer term and provides a promising 'new' approach.

In conclusion, the project established analysis tools to assess the measurement uncertainty of local tie measurements. This is necessary to make quantifiable advances in the measurement technology. The 3D observation systems installed in the project will be studied in the community in the next few years. The goal of 0.1 mm, as inspired by geodetic roadmap papers needs further work and will require a much larger effort from the surveying community in forthcoming years.

Actual and potential impact

Traceability of long distance measurements in surveying remains a highly challenging field. This project developed scientific and technological solutions for high-accuracy long distance metrology. Lower uncertainty levels were successfully met by the project, including reducing the measurement uncertainty of optical distance measurements in air well below 1 mm over a distance of 1 km. Many of these outputs are already available to end users to improve traceability in surveying, geodesy and earth sciences.

Dissemination activities and stakeholder engagement

35 publications were published, predominantly in high impact journals such as Scientific Reports, Optics Letters, Journal of Applied Geodesy, Review of Scientific Instruments and Measurement Science and Technology. The publications as well as many presentations are available for end-users on the project website www.emrp-surveying.eu.

A stakeholder advisory board with representatives from surveying, device manufacturers, space geodesy and high energy physics regularly monitored the project and provided feedback.

Presentations were given at more than 40 conferences, such as at the International Association of Geodesy Scientific Assembly, the International Earth Rotation and Reference Systems Service Workshops and MacroScale. Furthermore, the project was invited to present its work on local tie metrology at the International Very Long Baseline Interferometry Service General Meeting in South Africa, and the project coordinator was invited to present the outcomes of the project to the association of professional surveyors in Germany, the “Deutscher Verein für Vermessungswesen (DVW)”.

25 presentations were given by the consortium and external researchers at the “1st Workshop on Metrology for Long Distance Surveying”, attended by 50 worldwide experts and end-users. The 3rd Joint International Symposium on Deformation Monitoring jointly organised by the International Federation of Surveyors and the international association of geodesy also hosted 2 dedicated sessions for the presentation of the project’s results.

Contribution to standards

The consortium discussed its outcomes with several major standardisation bodies, including the ISO/TC 172/SC6 "Optics and photonics - geodetic and surveying instruments" and DIN NA 005-03-04 AA "Geodätische Instrumente und Geräte (SpA zu ISO/TC 172/SC6)" (the German standardisation equivalent committee to ISO/TC 172/SC6). The project’s GNSS work (objective 2) was presented to both committees.

Two Good Practice Guides (objective 4) were published:

1. Good practice guide for the calibration of EDMs on baselines
2. Good practice guide for the calibration of GNSS-based distance meters under different conditions

The project, developed close collaborations with standardisation bodies in local tie metrology. A member of the consortium was elected head of the International Earth Rotation and Reference Systems Service (IERS) Working Group on Site Survey and Co-location and the conclusions from the project’s local tie studies (objective 5) were fed into the development of a best practice guide for core sites (geodetic fundamental stations) in the GGOS http://cddis.gsfc.nasa.gov/docs/2015/SiteRecDoc_Rev2_D3.4.pdf

Early impact on traceability in surveying and geodesy

Project outcomes are being taken up by several organisations:

- Discussions are underway with a French SME about the commercialisation of the one wavelength TeleDiode system (from objective 1) for high-end long distance measurements.
- The use of optical cavities combined with mode-locked femtosecond lasers (objective 3) for the length characterisation of piezoelectric actuators is being discussed with the Czech company MESING who specialise in the design and manufacture of length measuring devices for the engineering industry.
- A specialised software tool developed in the project for the analysis of the data from the comparison of the three European primary geodetic baselines (objective 4) will be made available to the surveying community.
- PTB will use the data from the comparison from objective 4, to establish a Calibration and Measurement Capability (CMC) service for the long-distance calibration of EDMs.

- CNAM will make the TeleDiode prototype (from objective 1) available to the French national geodesy and cartography institute IGN for use in a practical survey in order to demonstrate the TeleDiode prototype's accuracy and productivity. Joint studies between CNAM and IGN are currently on-going.
- CNAM has developed an all-fibred EDM with surprisingly high performance at low cost. This is expected to be available within the next year.
- The 3D real time local tie monitoring system (from objective 5) will be permanently installed and used at the geodetic fundamental stations of Onsala, Sweden, and Metsähovi, Finland. It will contribute to the International Terrestrial Reference Frame (ITRF), a set of coordinates located on the Earth's surface.
- At Metsähovi, the project's sophisticated "Revolver" test field (objective 4) was integrated into the local tie network and is now routinely used there to check antennae deployed for local tie monitoring of the ITRF.

Potential impact

The project's outcomes will help surveyors and researchers in geosciences face the challenge of measuring distances over several hundred metres up to kilometres with lower uncertainties. The potential fields of application are landslide monitoring, the monitoring of critical sites like future carbon dioxide or nuclear waste repositories, and for ensuring the accurate positioning of agricultural machinery such as combine harvesters and thus helping to control European agricultural subsidies.

The results of the GNSS studies have triggered further studies at PTB regarding the optimum set up of the GNSS system for time transfer. These studies may lead to a refurbishment and optimisation of this important installation in the future.

PTB intends to improve transportability of TeleYAG technology further to offer calibration service of primary baselines for legal metrology purposes in legal metrology.

Scientific conclusions on local tie metrology will influence local tie monitoring at geodetic fundamental stations of the GGOS in future.

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