Use of Nummela Standard Baseline in Present-day European Metrology Research

Jorma JOKELA, Finland

Key words: Metrology, Traceability, Geodetic Baseline, Calibration, Best Practices

SUMMARY

The Finnish Geospatial Research Institute FGI (known until 2014 as the Finnish Geodetic Institute) is a National Standards Laboratory for length in Finland. This presentation is a brief overview of FGI's recent international activities and scientific results related to metrology of long distance surveying.

The FGI re-measured its renowned Nummela Standard Baseline using the Väisälä (white-light) interference comparator in autumn 2013. New absolute calibrations for the comparator's quartz gauges in 2015 provide the traceability of scale to the SI unit metre. The remeasurement confirms the excellent stability of the 80-years-old geodetic baseline and 0.1-mm-level standard uncertainties for the baseline section lengths up to 864 m. Results and the interface to exploit them in present-day calibrations are presented.

Nummela Standard Baseline was utilized in the European Metrology Research Programme (EMRP) joint research project SIB60 (2013–2016), "Metrology for long distance surveying", jointly funded by ten EMRP participating countries within EURAMET and EU. The FGI calibrated the German geodetic baselines of UniBW in Neubiberg and PTB in Braunschweig. High-precision EDM equipment was used as transfer standard. Mutually, novel measurement instrument prototypes developed within the project were tested at Nummela.

The Nummela scale was also transferred to the control network around FGI's Metsähovi Fundamental Geodetic Station. The network connects the reference points of observation sites for global geodesy (GNSS, SLR, VLBI). Improving the network and methods for local tie measurements between the reference points was one part of the SIB60 project. For metrology of GNSS measurements the project included construction and use of a hexagonal 7-pillar test field for research and validation of GNSS antenna calibration, and optimization and estimation of uncertainty of GNSS-based distance measurements. The results include new good practice guides both for calibration of EDMs on baselines and for high accuracy GNSS based distance metrology.

FGI's bilateral metrology projects include control of national calibration baselines. Recent examples are the repeated calibrations at Kyviskes, Lithuania (1997–2014) and Innsbruck, Austria (2008–2015), and several decades co-operation with China.

Use of Nummela Standard Baseline in Present-day European Metrology Research

Jorma JOKELA, Finland

INTRODUCTION

The FGI's Nummela Standard Baseline is a national standard for length measurements in geodesy. Since year 1947 the FGI has regularly remeasured the six-pillar 864-m baseline using Väisälä interference comparator and obtaining usually smaller than 0.1 mm measurements uncertainties. The baseline has not been in its original use – determining the scale of triangulation – for a half of a century, but there are even increasingly surveying applications which need precise traceable lengths: with the best possible accuracy and known uncertainty. Overview of the unique traceability chain is presented in Fig. 1. In addition to transfer the traceable scale to other baselines and test fields the baseline is used in research, validation and testing of novel surveying instruments; international use of the world-class measurement standard has exceeded its national use.

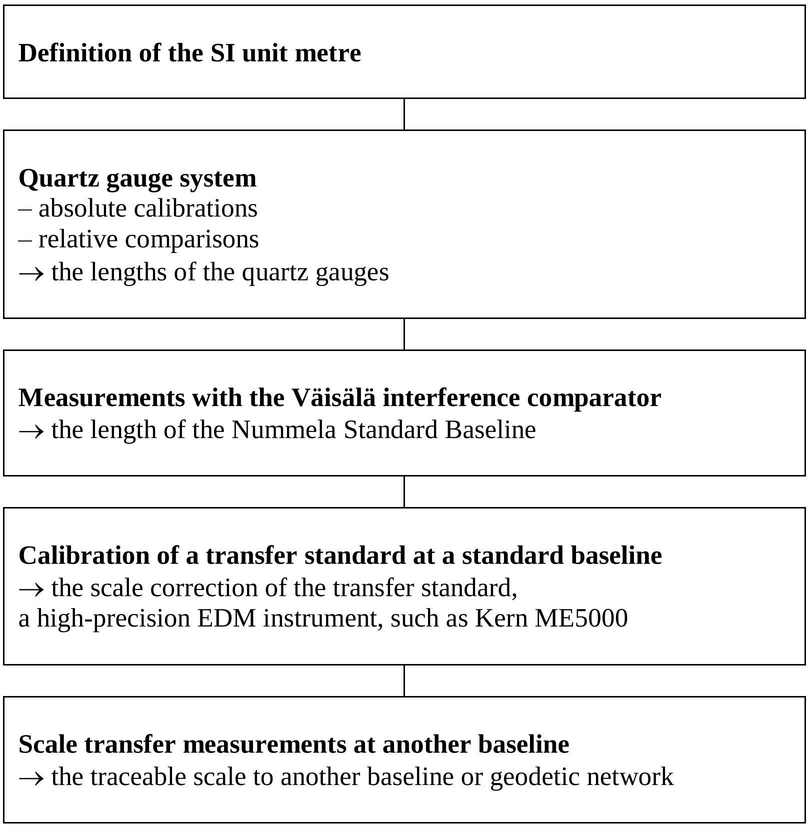

Figure 1. Overview of traceability chain of length measurements in geodesy (Jokela 2014).

1. METROLOGICAL TRACEABILITY OF THE NATIONAL MEASUREMENT STANDARDS TO THE INTERNATIONAL SYSTEM OF UNITS (SI)

The metre is defined as the distance travelled by light in a vacuum in 1/299 792 458 seconds. This and the next sections shortly introduce the metrological traceability chain, first stages from the realization of the definition in laboratory conditions towards geodetic length measurements in field conditions.

1.1 Realization of the metre and absolute calibrations of quartz gauges

National metrology institutes (NMI) take care of the practical realization of the definition of the SI unit metre. Applications recommended by the International Committee for Weights and Measures (CIPM) are used (BIPM 2017). The Finnish NMI VTT-MIKES uses an optical frequency comb equipment and iodine-stabilized HeNe (633 nm and 543.5 nm) and Nd:YAG (532 nm) lasers for the realization and calibration of primary national length standards (VTT MIKES, 2016). The relative frequency uncertainty of these lasers is better than 10^{-10} (k=2).

By means of frequency comparisons the traceable scale is transferred from iodine-stabilized lasers to other stabilized lasers used in laser interferometers. Then one can construct measurement equipment with traceable scale from the lasers and capable for calibration of long gauge blocks. An application of such equipment is used at VTT-MIKES for absolute calibration of FGI’s quartz gauges (Lassila et al. 2003).

Quartz gauges are 1-metre-long measurement standards which bring the traceable scale in Väisälä (white-light) interference comparator and thereby to interferometric length measurements of Väisälä-type geodetic baselines. The latest absolute calibration for four FGI’s quartz gauges was performed in year 2015. Expanded uncertainties (k=2) of 72 nm were obtained, as reported in calibration certificates. The length of the quartz gauge no. VIII, the special one for measurements at FGI’s Nummela Standard Baseline, was 1.000 151 542 m in year 2015. It is 171 nm longer than in the previous absolute calibration in year 2000, which is compatible with the 10-nm-level annual lengthening derived from the decades-long time series. The results were utilized in the final computation of interference measurements at Nummela in autumn 2013.

1.2 Comparisons of quartz gauges

Between infrequent absolute calibrations for a limited number of quartz gauges the quartz gauge system is supported by more frequent comparisons with a principal normal, quartz gauge no. 29. They are performed in a stable underground laboratory room at the Tuorla Observatory of University of Turku. The results of every new absolute calibration are used to confirm the comparison-based system and verify traceability.

The comparisons at Tuorla are performed in a comparator box, where the quartz gauges to be compared are placed in turn between two parallel glass plates (Fig. 2). The parallelism is controlled with two side gauges. Measurements with the principal normal determine the scale and the exact distance between the glass plates, which is adjusted to be about 1 001 mm.

Quantities to be measured are the (smaller than 1 mm) air gaps between the quartz gauges and the glass plates. Two Cd (cadmium) spectral lamps are used to produce interference fringes at the glass and quartz surfaces. The fringes produced by different wavelengths are separated by optical methods, photographed using two cameras, and measured using image processing and computation programs. Subtracting the gap widths from the known distance between end surfaces give the quartz gauge length. Measurement uncertainty of the comparisons is of the order of 10 nm and thus smaller than that of the absolute calibrations. The method and results in more detail are described by Jokela (2014). A new equipment for the comparison at Tuorla is under construction and expected to be in use by year 2018.

The 1-metre quartz gauge length is multiplied to lengths between geodetic baseline pillars using Väisälä interference comparator (Fig. 3). Väisälä (1923) invented the classical ingenious method almost a century ago. Väisälä, Honkasalo (1950), Kukkamäki (1978) and others developed the method to be used to measure Nummela and other geodetic standard baselines around the world, promoted by IUGG and IAG recommendations. An new exhaustive description of the method and its present-day use is presented in Jokela (2014).

2. NUMMELA STANDARD BASELINE LENGTHS 2013–2016

The Nummela Standard Baseline section lengths are 6 m, 24 m, 72 m, 216 m, 432 m and 864 m. The FGI has measured these multiplications of quartz gauge no. VIII length using Väisälä interference comparator 16 times in years 1947–2013. The lengths are preserved by projecting them from lengths between comparator reference points on observation pillars to lengths between underground benchmarks which are buried at every observation pillar (including 0 m, excluding 6 m). After interference measurements reverse projections are regularly performed to obtain current lengths between forced-centring equipment on observation pillars from the preserved more stable lengths between underground benchmarks.

The length of the 864-m baseline has changed less than 0.7 mm since year 1947. Sub-millimetre-level annual changes may occur in lengths between observation pillars, and to monitor them the repeated projection are necessary. The projections are based of precise angle measurement using the best available theodolites and optimal measurement geometry. As a result, metrologically traceable geodetic baseline section lengths are known with about 0.3 mm expanded uncertainty (k=2, 95 %) – an accuracy which is hardly obtainable elsewhere in field conditions.

The results from the interference measurements in autumn 2013 are presented in Table 1. Computation of the lengths between underground benchmarks is a multi-stage process including interference observations (compensator angles, transfer readings) and corrections to them (refraction corrections obtained from temperature data, compensator corrections), determination of projection corrections, and work using the quartz gauge when measuring the shortest interference 0–1–6 to transfer the traceable scale for the entire measurement; for details, see Jokela (2014, p. 45–111). Estimation of uncertainty of measurement is relative to the SI unit metre, including the traceability chain in its entirety.

Figure 2. Placing quartz gauges in the comparator box at Tuorla Observatory. Photo: P. Häkli.

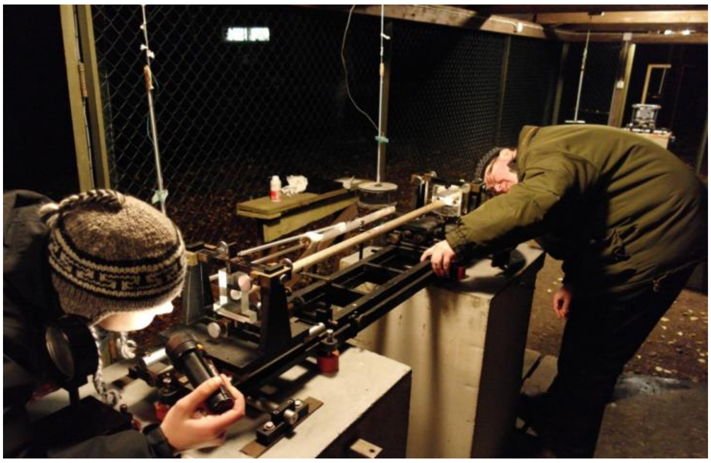

Figure 3. Working with the Väisälä interference comparator at Nummela. Photo: F. Dvořáček.

Uncertainties in the latest measurement are exceptionally large (actually worst ever), because the ground was frozen in November precluding the last projection measurements. This also causes that shorter sections may have larger uncertainties than longer sections, because uncertainties are strongly depending on success in projection measurements. The obtained accuracy is still sufficient for all present activities. Comparing the results of 2013 and 2007 all differences remain within the expanded uncertainties. When utilizing the baseline in calibrations, different combinations allow 15 different distances, ranging from 24 m to 864 m, to be measured to both directions between the six observation pillars.

Table 1. Nummela Standard Baseline section lengths (mm) from the interference measurements in autumn 2013 and change of lengths from the previous interference measurements in autumn 2007.

Baseline section	**Length (mm) between underground benchmarks**	**Expanded uncertainty (mm, k=2)**	**Change (mm) from 2007**
0–24	24 033.318	±0.159	+0.100
0–72	72 014.974	±0.111	+0.024
0–216	216 053.085	±0.106	–0.043
0–432	432 095.369	±0.135	+0.086
0–864	864 122.909	±0.235	+0.045

Table 2. Projection corrections (mm) for the six pairs of Nummela Standard Baseline underground benchmarks and observation pillars for the field work seasons in years 2014–2016.

	06/2014	**07/2014**	**08/2014**	**08/2015**	**09/2015**	**11/2015**	**04/2016**	**06/2016**	**Range, max–min**
0	–0.078	–0.014	–0.137	+0.030	–0.032	–0.081	+0.048	+0.105	0.242
24	+0.499	+0.490	+0.303	+0.531	+0.356	+0.397	+0.470	+0.373	0.228
72	+0.840	+0.830	+0.686	+0.674	+0.696	+0.682	+0.597	+0.590	0.250
216	+0.186	+0.070	+0.139	+0.113	+0.292	+0.233	+0.124	+0.152	0.222
432	+1.593	+1.585	+1.519	+1.403	+1.317	+1.318	+1.266	+1.336	0.327
864	+0.337	+0.339	+0.317	+0.022	+0.037	+0.107	+0.036	+0.056	0.317

Projection measurements create the interface to exploit the results of interference measurements in EDM calibrations. After projections the results are available for calibration of the most accurate electronic distance measurement (EDM) instruments. In 2014–2016, eight sets projection corrections were determined for the six pairs of underground benchmarks and forced-centring devices on observation pillars. These corrections in Table 2 must be used to compare EDM calibration observations with the known lengths from interference measurements. Variation in projection corrections after the interference measurements is from 0.2 mm to 0.3 mm; Table 2 shows that the excellent accuracy of interference measurements can reliably be transferred to EDM calibrations. Components for estimation of uncertainty of measurement remain small, because usually the average corrections from projections just before and just after a calibration are applied.

The metrologically traceable Nummela scale is transferred further to other geodetic baselines and test fields or to many kind of scientific or practical surveying. High precision EDM instruments are used as transfer standard. The FGI has mostly used the Kern ME5000 instrument no. 357094 with prism reflector no. 374414, property of Aalto University, which is calibrated at Nummela before and after every scale transfer measurement to a customer. According to technical specifications, the accuracy of the instrument is ±(0.2 mm +0.2 mm/km). The long calibration history shows that instrument corrections have been quite stable and small (Fig. 4). In year 2014 six calibrations were performed for the equipment and in year 2015 another three; in them scale correction varied between –0.39 mm/km and +0.22 mm/km) and additive constant between –0.01 mm and +0.04 mm. Usually annual average values are applied in scale transfer.

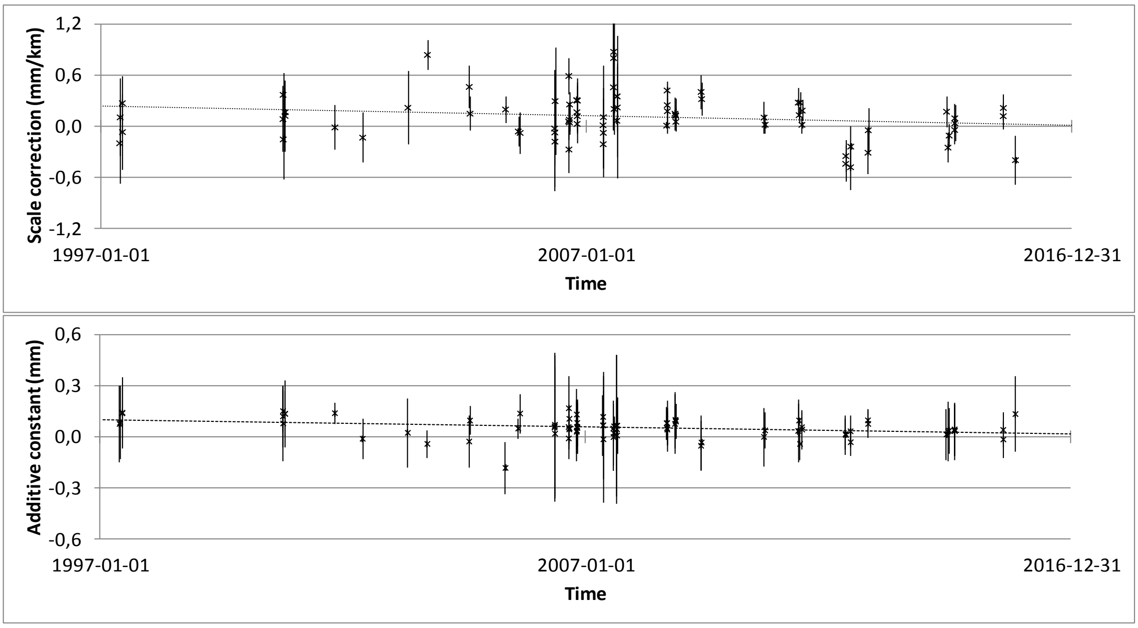

Figure 4. Calibration history of Kern ME5000 no. 357094 (EDM instrument) and 374414 (reflector). (In years 2006–2007 only a half of Nummela Standard Baseline was in use, causing large uncertainty.)

Using the calibrated high-precision EDM instrument as transfer standard, the traceable scale of the Nummela Standard Baseline is transferred to customers' use, usually by measurements similar to those at Nummela. The method is represented in Fig. 5. For weather observations the FGI uses calibrated classical instruments, psychrometers and aneroid barometers and the Ciddor & Hill computer procedure recommended by the IAG since year 2000. In measurements abroad supplementary data from local environmental sensors is welcome, if available.

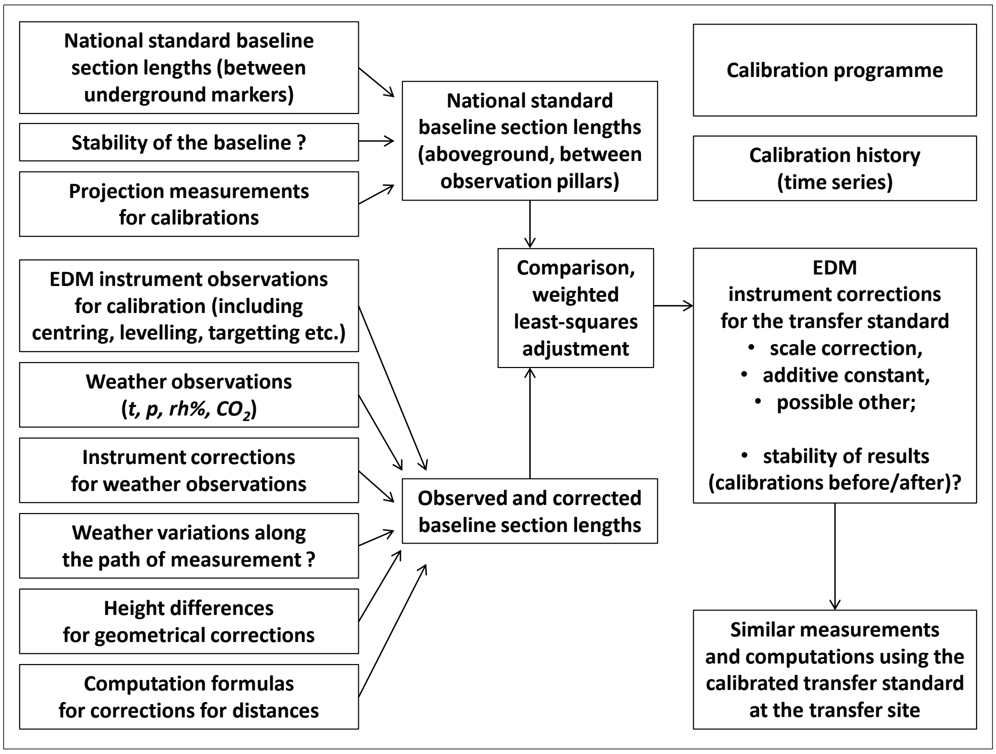

Figure 5. Overview of calibration of transfer standard for scale transfer (Jokela 2014).

3. CONTROL OF NATIONAL GEODETIC BASELINES

The FGI participates in international baseline measurement projects almost every year. Most of them nowadays receive external funding. Scale transfer to national surveying and mapping authorities or to universities or research institutes is the most wanted service.

The FGI has calibrated the 7-pillar 1 080-m geodetic baseline of Austrian Land Survey BEV (Bundesamt für Eich- und Vermessungswesen) in Innsbruck twice, first as a part of the EMRP joint research project “Absolute long distance measurement in air” in year 2008, and later as ordered by the BEV in year 2014. The baseline is located in a challenging environment between a busy motorway and sunny mountainside next to an ice-cold river (Fig. 6). Results of the two measurements show quite good stability and no different scale: differences of the six pillar intervals range from –0.43 mm to +0.37 mm, four of them being smaller than 0.10 mm and the average difference being 0.00 mm. Expanded uncertainties (k=2, 95 %, in the traceability chain) varied from 0.14 mm to 1.09 mm for distances from 30 m to 1 080 m. The results are also compatible with a minor measurement in year 2006. This easy-to-access baseline is in frequent use as a national metrological resource.

Figure 6. Geodetic baselines of BEV Innsbruck and VGTU Kyviskes.

Vilnius Gediminas Technical University (VGTU) established a six-pillar 1 320-m geodetic baseline at Kyviskes in year 1996. Four years later a seventh pillar expanded it to a test field. The FGI has calibrated the baseline and test field in years 1997, 2001, 2007 and 2014, and also used it in a GPS research project in 2008 (Fig. 6). Results of repeated measurements in an excellent environment, but in very different weather conditions, prove the baseline stable. They also reveal some interesting variation in scale, dependent on temperature, though within the estimated uncertainties of measurement (Buga et al. 2014). In the latest measurement expanded uncertainties (k=2, 95 %, in the traceability chain) varied from 0.31 mm to 0.89 mm for distances from 20 m to 1 320 m. Also this baseline is in frequent use as a national metrological resource.

FGI's recent projects also include the calibration of the 330-m baseline and GNSS test field at UPV in Valencia, Spain, in year 2012. An expedition from the Chinese Academy of Surveying and Mapping visited the Nummela Standard Baseline in August 2015, calibrating a set of tacheometers. Measurements in China in 2018 are under discussion.

Scale transfer projects and international comparisons are expected to continue. – The height component is not forgotten: FGI's laboratory premises serve in calibration of precise levelling instruments and systems worldwide.

4. "METROLOGY FOR LONG DISTANCE SURVEYING" – PARTICIPATION IN EMRP JRP SIB60

4.1 Tracing the kilometre to the SI metre

"Metrology for long distance surveying" was a joint research project of the European Metrology Research Programme (EMRP). In years 2013–2016 it was jointly funded by ten EMRP participating countries within EURAMET (the European Association of National Metrology Institutes) and EU. The partners were metrology institutes PTB (Germany, coordinator), CNAM (France), FGI (Finland), INRIM (Italy), IPQ (Portugal), MIKES (Finland), SP (Sweden), VSL (Netherlands) and NSC-IM (Ukraine) and other participants German universities LUH, TUBS and UBO. The purpose of the project was to improve metrological traceability of long distance surveying (up to one kilometre) to the SI unit metre by improving two fundamental technologies in surveying, namely optical and GNSS based distance measurements. Novel technologies and standards were developed, including constructing and testing of new instruments, improving methods for dimensional metrology (local ties), comparisons, models and simulations, good practise guides etc. An introduction to the project is presented, for example, in Pollinger et al. (2015). A summary of the work done and results is soon available in the final report (EMRP SIB60 2017).

The seven workpackages of the project were (1) optical distance measurement in air, (2) GNSS-based distance measurement, (3) femto-second laser-based long distance metrology, (4) improving surveying practise, (5) local tie metrology at geodetic fundamental stations, (6) creating impact and (7) JRP management and coordination. They included about 30 tasks and about 150 deliverables; just a few of them concerning the Nummela Standard Baseline are shortly discussed here.

Comparisons of different baselines, measurements instruments and methods and other results of the project will probably advance establishing new official internationally acknowledged calibration services, calibration measurement capabilities as listed in BIPM CMC. As one of the major geodetic baselines in Europe, such a listed status should now be possible also for the Nummela Standard Baseline.

4.2 Measurements on-site at Nummela

Two novel refractivity-compensated absolute distance meters (ADM), German PTB's TeleYAG and French CNAM's TeleDiode, were successfully tested at Nummela in September–October 2015 and April–May 2016, respectively (Fig. 7). The work is a continuation of a previous EMRP project "Absolute long distance measurement in air", carried out in 2008–2011, including testing at Nummela already then.

A set of related publications with results achieved can be accessed through the project's internet page (EMRP SIB60 2017). The final publishable report and summary and some more publications were in finalization process in February 2017 and expected to be available soon.

The TeleYAG system is based on heterodyne multi-wavelength interferometry, both for the distance measurement itself and the dispersion-based in-situ refractivity compensation. The TeleDiode system is based on optical fibre technology and operates simultaneously at two wavelengths. Simultaneously with PTB's Nummela measurements VTT-MIKES tested a spectroscopic thermometer for geodetic measurements (Tomberg et al. 2017). The FGI delivered "true" baseline distances including fresh projection corrections for the works.

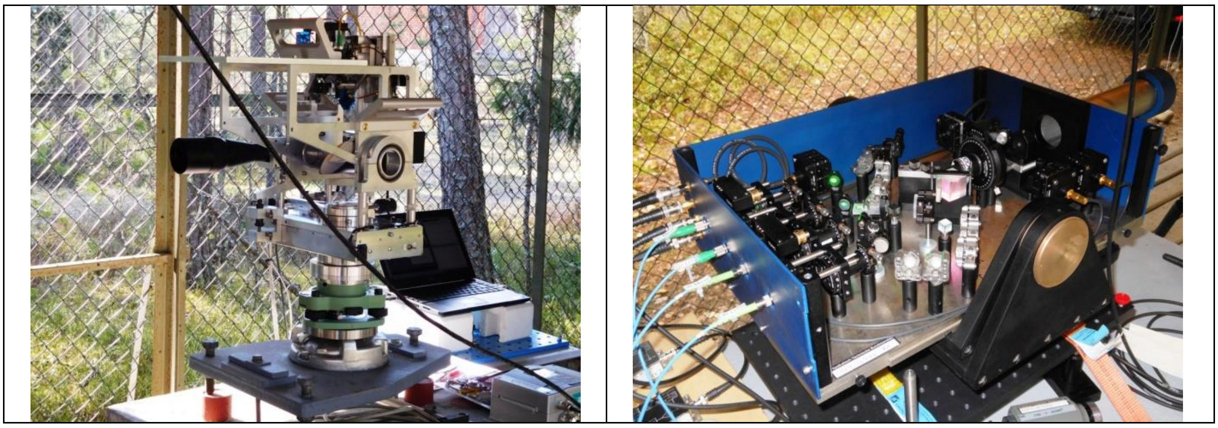

Figure 7. Testing CNAM's and PTB's new ADM equipment, TeleDiode and TeleYAG, at Nummela.

4.3 Scale transfer measurements in Germany

In July 2014 the FGI calibrated the geodetic baseline of the German national metrology institute PTB (Physikalisch-Technische Bundesanstalt) in Braunschweig (Fig. 8). The FGI measured 126 distances at the baseline, where the observation pillars are at 0, 50, 100, 150, 250, 350, 500 and 600 metres, thus allowing to measure every distance from 0 m to 600 m at 50 m intervals. The specialty of the baseline is the automated environmental sensor system: 60 thermometers at 10 m intervals, six humidity sensors and two pressure gauges (Pollinger et al. 2012). This system was used beside FGI's classical instruments.

The calibration of the PTB baseline was a repetition of FGI's calibration in June 2011. Both calibrations, 2011 and 2014, produced expanded uncertainties (k=2, 95 %) from 0.2 mm to 0.5 mm for the distances from 50 m to 600 m, compatible within uncertainties, but also a significant scale difference was discerned, without any clear reason so far.

In October 2014 the FGI calibrated the geodetic baseline at the University of the Federal Armed Forces Munich UniBW (Universität der Bundeswehr München) in Neubiberg, Germany (Fig. 8). Before this the German Society for Calibration of Geodetic Devices had organized an international comparison in 2009–2011, in which an inclusive set of precision instruments had been utilized: Kern ME5000 instruments, Leica total stations and new laser trackers, even GNSS equipment. The FGI's calibration supplemented the comparison by a scale transfer exploiting a distinct traceability chain.

The FGI measured 122 distances at the UniBW baseline, where the observation pillars are at 0, 18, 101, 247, 425, 540, 590 and 1 100 metres. When comparing the 2011 and 2014 data sets a 0.2 mm/km scale difference is apparent and the average deviation in distances between pillars is smaller than 0.1 mm, confirming good accuracy and uniformity (Heunecke 2015). PTB measured the UniBW baseline using TeleYAG in July 2015.

Figure 8. Geodetic baselines of PTB Braunschweig and UniBW Neubiberg.

Technische Universität Braunschweig (TUBS) collated the data from all the measurement campaigns in the project and analysed the data with support from the participants. A report on the comparative analysis of all baseline datasets and comparisons is a deliverable of the project (for now confidential).

4.4 Metsähovi

The control network around FGI's Metsähovi Fundamental Geodetic Station connects the reference points of observation sites for global geodesy (GNSS, SLR, VLBI). Repeated measurements aim at sub-millimetre accuracy in this monitoring known as "local ties", ultimately needed in maintenance and development of geodetic reference frames. The network now consists of two GNSS mast points, 15 observation pillars, 12 points inside the VLBI radome, two points inside the SLR radome and five points for SAR (Fig. 9, Jokela et al. 2016). On the rotating part of the VLBI telescope nearly 1 000 points are observed during VLBI sessions. Observation methods include tacheometry, EDM and GNSS measurements; the metrologically traceable scale is transferred from the Nummela Standard Baseline using high precision EDM equipment as transfer standard. How to improve the local ties is a major research topic at fundamental geodetic stations worldwide and thus internationally interesting.

For research and validation of GNSS antenna calibration results the original network was expanded by constructing a hexagonal 7-pillar test field, in which the antennas can be circulated and their residual offsets analyzed. A set of baselines at Metsähovi was selected to research a metrologically optimal processing strategy of GNSS measurements; different models, simulations and measurements set-ups were tested.

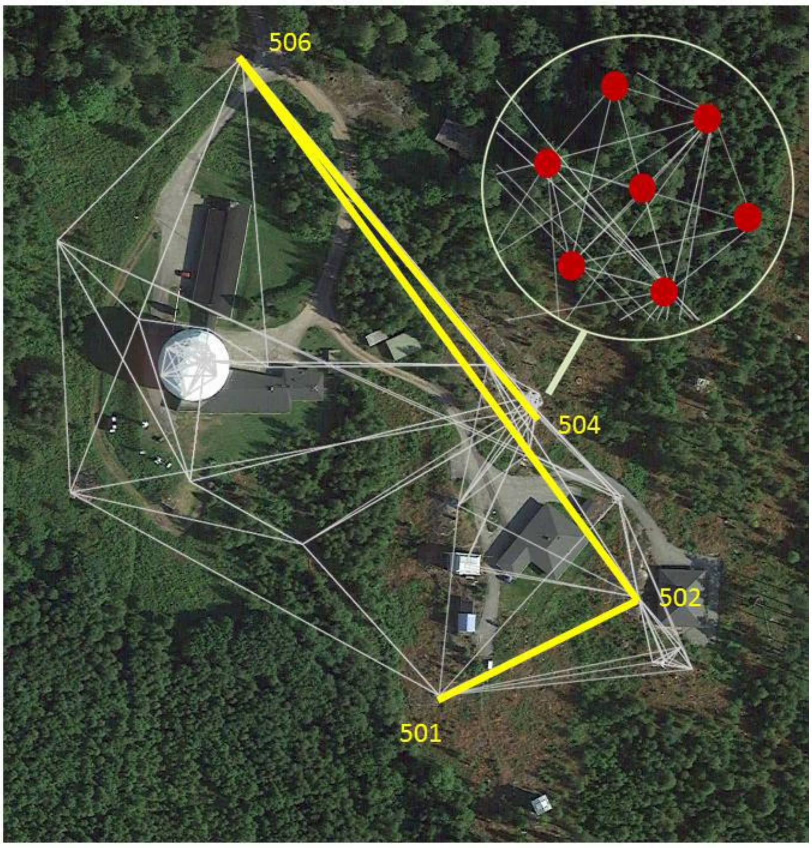

Figure 9. Metsähovi control network, measured with tacheometers (shape), EDM (scale) and GNSS (orientation), ties the VLBI, SLR and GNSS reference points of the fundamental geodetic station together. The hexagonal “Revolver” pillar set (red) is used for GNSS antenna testing. Three distances of 191 m, 131 m and 63 m (yellow) determine the traceable scale transferred from Nummela, another three reference distances shorter than 20 m were computed. Google Earth photo edited by U. Kallio.

4.5 Good practice guides

The results of EMRP SIB60 include good practice guides both for calibration of electro-optic distance meters on baselines and for high accuracy GNSS based distance metrology. They are available at the project’s internet pages (EMRP SIB60 2017). The guidance for EDM includes requirements for reference baselines, recommendations for calibration measurements, general considerations on the processing strategy, components of a suitable 3D adjustment model and estimation of measurement uncertainty (Astrua et al. 2016). The guidance for GNSS metrology includes preparatory measures for antenna calibration and station set-up, recommendation on the actual measurement with a focus on the tropospheric correction strategy, and assessment of uncertainties of GPS-distances (Bauch et al. 2016).

5. CONCLUSION

The FGI's Nummela Standard Baseline has remained and is maintained and developed as a world-class measurement standard in length measurements in geodesy. For lengths of tens of metres to one kilometre it still transfers the traceable scale with smaller uncertainty of measurement than other methods. During its honourable history the baseline has always helped us surveying the world of tomorrow. Innovations and new instruments and methods are yet welcome and hopefully in use at Nummela some day.

REFERENCES

Astrua, M., T. Fordell, C. Homann, J. Jokela, W. Niemeier, F. Pollinger, D. Tengen, J.-P. Wallerand, M. Zucco (2016). Good practice guide for the calibration of electro-optic distance meters on baselines. EMRP JRP SIB60 Surveying. Retrieved February 17, 2017, from http://www.emrp-surveying.eu/emrp/fileadmin/documents/surveying/Good_practice_guide_for_the_calibration_of_EDMs_on_baselines_public_v1_01.pdf

Bauch, A, L. Eusébio, U. Kallio, H. Koivula, H. Kuhlmann, S. Lahtinen, F. Marques, O. Pellegrino, C. Pires, F. Pollinger, M. Poutanen, F. Saraiva, S. Schön, F. Zimmermann (2016). Good practice guide for high accuracy global navigation satellite system based distance metrology. EMRP JRP SIB60 Surveying. Retrieved February 17, 2017, from http://www.emrp-surveying.eu/emrp/fileadmin/documents/surveying/Good_practice_guide_for_high_accuracy_GNSS_based_distance_metrology_public_v1.pdf

Buga, A., R. Putrimas, D. Slikas and J. Jokela (2014). Kyviskes Calibration Baseline: measurements and improvements analysis. The 9th International Conference "Environmental Engineering", 22–23 May, Vilnius, Lithuania. http://leidykla.vgtu.lt/conferences/ENVIRO_2014/Articles/5/195_Buga.pdf

BIPM (2017). Practical realizations of the definitions of some important units. Retrieved February 17, 2017, from http://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies.html

EMRP SIB60 (2017). "Metrology for long distance surveying" project homepage. European Metrology Research Programme. Retrieved February 17, 2017, from http://www.emrp-surveying.eu/emrp/sib60-project.html

Heunecke, O. (2015). Die neue Neubiberger Pfeilerstrecke. *ZfV* **140:6**, 357–364.

Honkasalo, T. (1950). Measuring of the 864 m-long Nummela standard base line with the Väisälä light interference comparator and some investigations into invar wires. *Publ. Finn. Geod. Inst.* **37**. 88 p.

Jokela, J. (2014). Length in Geodesy – On Metrological Traceability of a Geospatial Measurand. *Publ. Finn. Geod. Inst.* **154**. 240 p. ISBN (printed) 978-951-711-309-0, ISBN (pdf) 978-951-711-310-6, ISSN 0085-6932. http://urn.fi/URN:ISBN:978-951-711-310-6

Jokela, J., U. Kallio, H. Koivula, S. Lahtinen and M. Poutanen (2016). FGI's contribution in the JRP SIB60 "Metrology for Long Distance Surveying". *Proc. of the 3rd Joint International Symposium on Deformation Monitoring (JISDM)*, 30 March – 1 April, Vienna, Austria. 8 p. https://www.fig.net/resources/proceedings/2016/2016_03_JISDM_programme.asp

Kukkamäki, T. J. (1978). Väisälä interference comparator. *Publ. Finn. Geod. Inst.* **87**. 49 p.

Lassila, A., J. Jokela, M. Poutanen and J. Xu (2003). Absolute calibration of quartz bars of Väisälä interferometer by white light gauge block interferometer. *Proc. XVII IMEKO World Congress*, June 22–27, 2003, Dubrovnik, Croatia, p. 1886–1890.
http://www.imeko.org/publications/wc-2003/PWC-2003-TC14-026.pdf

Pollinger, F., M. Astrua, A. Bauch, S. Bergstrand, B. Görres, J. Jokela, U. Kallio, H. Koivula, H. Kuhlmann, V. Kupko, K. Meiners-Hagen, M. Merimaa, W. Niemeier, P. Neyezhmakov, M. Poutanen, F. Saraiva, S. Schön, S. A. van den Berg, J.-P. Wallerand and M. Zucco (2015). Metrology for Long Distance Surveying: A Joint Attempt to Improve Traceability of Long Distance Measurements. In Rizos, C. and P. Willis (Eds.), IAG 150 Years, *International Association of Geodesy Symposia* **43**, 651–656. DOI: 10.1007/1345_2015_154

Pollinger, F., T. Meyer, J. Beyer, N. R. Doloca, W. Schellin, W. Niemeier, J. Jokela, P. Häkli, A. Abou-Zeid and K. Meiners-Hagen (2012). The upgraded PTB 600 m baseline: a high-accuracy reference for the calibration and the development of long distance measurement devices. *Meas. Sci. Tech.* **23:9**, 094018, 11 p. DOI:10.1088/0957-0233/23/9/094018. http://iopscience.iop.org/article/10.1088/0957-0233/23/9/094018/pdf

Tomberg, T., T. Fordell, J. Jokela, M. Merimaa and T. Hieta. 2017. Spectroscopic Thermometry for Long Distance Surveying. *Appl. Opt.* **56:2**, 239–246.

Väisälä, Y. (1923). Die Anwendung der Lichtinterferenz zu Längenmessungen auf grösseren Distanzen. *Publ. Finn. Geod. Inst.* **2**. 47 p.

VTT MIKES (2016). MIKES Metrology Calibration Service. International competitiveness and reliability. 82 p. Retrieved February 17, 2017, from http://www.mikes.fi/mikes/Esitteet/kalibrointiesitteet_eng_www.pdf

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

BIOGRAPHICAL NOTES

Jorma Jokela is a research manager in FGI’s Department of Geodesy and Geodynamics. His specialty is geodetic metrology. He published his doctoral thesis “Length in Geodesy – On Metrological Traceability of a Geospatial Measurand” in 2014.

CONTACTS

D.Sc.(Tech.) Jorma Jokela
National Land Survey of Finland
Finnish Geospatial Research Institute (FGI)
Geodeetinrinne 2, FI-02430 Masala, FINLAND
Tel. +358503437482
Email: jorma.jokela@nls.fi
Web site: www.fgi.fi