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ON TRACEABILITY OF LONG DISTANCES

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Abstract − Geodetic baselines are used to determine traceable lengths in geospatial applications. The 864-m-long Nummela Standard Baseline in Finland is a world-class length standard, which is used in calibrations of the most precise electronic distance measurement (EDM) instruments and in scale transfers around the world. At the moment new instruments based on new technology are developed to measure long distances; this is also a joint research project of the new European Metrology Research Programme (EMRP). As the state-of-the-art, the Nummela Standard Baseline is available for testing the new instruments in field conditions. The baseline was remeasured with the Väisälä interference comparator to 432 m in autumn 2005, and to 864 m in autumn 2007 with better than 0,1 mm standard uncertainty. We present here the results, which again verify the long-term stability of the baseline and excellent repeatability of measurements. We also present an example of a recent scale transfer to a calibration baseline and test field in Lithuania. In addition to national calibration activities, this Kyviškės Calibration Baseline serves in our new research project concerning the scale of precise GPS positioning. Brief introductions to another new geodetic baselines in Austria and Estonia are also given.

Keywords: geodetic baseline, Väisälä interference comparator, electronic distance measurements (EDM)

1. INTRODUCTION

A geodetic baseline consists of a set of observation pillars in line. The number of pillars is typically from a few to more than ten, and the length is from tens of metres to one kilometre or more. The distances between pillars are known with up to 0,1 mm total uncertainty, and the baseline design is usually optimized according to the unit lengths of instruments to be calibrated. The measurement instruments are installed on the observation pillars with standard fixing methods. Instrument corrections (scale correction, additive constant, periodic phenomena) are determined in calibrations by comparing the known true distances with measured distances. Proper consideration of atmospheric conditions is essential.

The Nummela Standard Baseline of the Finnish Geodetic Institute (FGI), 40 km north-west of Helsinki, is unique for its long history, stability, accuracy and traceability. It consists of observation pillars and more permanent underground benchmarks at 0, 24, 72, 216, 432 and 864 metres, and a few more pillars for the interference measurements. New working premises were built in 2004 and the observation pillars were reconditioned in 2007.

The baseline has been measured 15 times between years 1947–2007 with the Väisälä interference comparator with ±0,02 mm to ±0,09 mm standard uncertainties for the pillar intervals from 24 m to 864 m. Variation in length has been less than 0,6 mm in the longest distance during 60 years, showing the forested sandy ridge of glacial origin ideal ground for a baseline. The principle of the interference measurement method was published by Väisälä already in 1923 [1]. Detailed descriptions of baseline measurements are given e.g. by Kukkamäki [2, 3] and Jokela and Poutanen [4]. Results of the measurements in 2005 and 2007 will be published in more detail in the publication series of the FGI in 2009; this article gives only a summary.

The lengths are traceable to the definition of the metre through the quartz metre system, which is maintained in the Tuorla Observatory of University of Turku. Latest absolute calibrations of the quartz metres have been made at the PTB, Braunschweig, and MIKES, Helsinki [5]. Since its establishment in 1933 the baseline determined the traceable scale of nationwide triangulation for surveying and mapping. Now it is used in more local scientific works, where precise traceable scale is needed.

From standard baselines the scale is transferred to lower-order baselines and test fields using calibrated high precision EDM instruments as transfer standards. In practice there is nowadays only one instrument capable for this, Kern Mekometer ME5000, which is not on the market anymore. The measurement range is from 20 m to 8 000 m, and the standard deviation is ±(0,2 mm +0,2 ppm). With sufficiently accurate determination and correction for meteorological influences this is easily obtained. Still the weather conditions are often far from optimal, which remains as the main problem limiting accuracy of EDM outdoors. New methods and instruments based on new technology (femtosecond lasers, refractometers etc.) may be available in near future.

The authors of this article work in length metrology in national institutes. The Finnish Geodetic Institute is a national standards laboratory of length, and has joined the CIPM Mutual Recognition Arrangement in 2002. The

Calibration Laboratory of Institute of Geodesy of Vilnius Gediminas Technical University (VGTU) is an accredited unit for calibration of EDM instruments.

2. INTERFERENCE MEASUREMENTS AT THE NUMMELA STANDARD BASELINE IN 2005–2007

Interference measurements with the Väisälä (white light) interference comparator are performed every few years to maintain the Nummela Standard Baseline. The FGI is currently the only institute, which carries out these measurements, latest in 2005 and 2007.

The measurements are based on multiplication of length of a 1-m-long quartz metre. The method is basically simple, but extremely laborious to put into practice. The main reason is, that for long distances (> 100 m) extremely stable temperature conditions are needed: during a two-three months autumnal measurement period only a few nights are usually suitable for measurements. In stable conditions modelling the refraction is not a problem, since only the refraction difference between the divided two beams (between front-mid and front-rear mirrors) is needed. To measure this we use 31 thermometers along the baseline. In unstable conditions, i.e. when temperature differences of one to two degrees or larger occur, the light beams can not be controlled by adjusting the mirrors of the comparator, and measuring is not possible.

Two observers and two assistants are needed almost seven days and nights a week during the long measurement period. Therefore we would like to welcome new innovations for easier measurements. While waiting for them, the baseline serves as the state-of-the-art high precision geodetic length standard.

2.1. Traceability chain

The traceability chain of the Nummela Standard Baseline includes regular absolute calibrations of quartz metres with an interferometer for long gauge blocks, continuous maintenance of the quartz metre system by interferometrical comparisons with the comparator of the Tuorla Observatory, and measurements of the baseline with the Väisälä comparator, in which a quartz metre brings the scale. Measurements at Nummela include repeated projection measurements using theodolite and tape between the instrumentation on observation pillars and the underground benchmarks, between which the result with good accuracy is safely stored. From Nummela the traceability chain continues with calibrations of high precision EDM instruments, again complemented with projections, and scale transfers to lower-order calibration baselines for common use or special applications.

2.2. Comparisons of quartz metres

Lengths of quartz metres are known with 35 nm standard uncertainty from absolute calibrations. The latest calibrations were made in 2000; the next are planned close to the renovation of computer system of mutual comparisons at Tuorla. Variation in these comparisons is much smaller, altogether we obtain the absolute length with about 40 nm standard uncertainty. Latest comparisons were made in April and December 2005 and in March and December 2007, before and after the two latest interference measurement periods. New personnel was trained for this. As well as the Väisälä measurement method, the system of tens of quartz metres has been maintained for more than 70 years (Fig. 1–2).

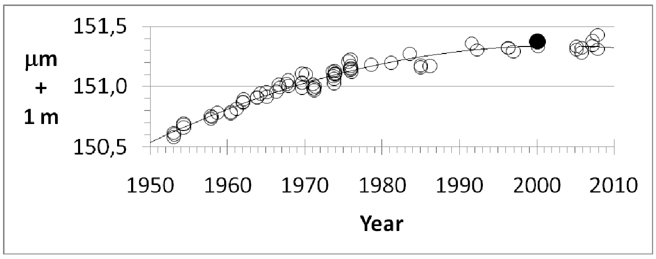

Fig. 1. Change of length of quartz metre no. VIII from comparisons at Tuorla. The filled circle is the latest absolute calibration. This quartz metre is always used in the Väisälä interference comparator at the Nummela Standard Baseline.

Fig. 2. Adjusting the quartz metre no. VIII for a comparison at Tuorla Observatory.

2.3. Interference observations

Installation of the Väisälä interference comparator takes about two weeks. It can't be set up at any baseline, but a special pillar design for multiplication of the quartz metre length is needed (e.g. at Nummela 2×2×3×3×4×6×1 m = 864 m). The main parts, mostly iron and glass, must be measured and fixed at proper locations with ±1 mm 3D-accuracy. The rest is controlled with the numerous adjusting screws around the mirrors in the comparator.

By adjusting the quartz metre between mirrors at 0 m and 1 m (Fig. 3) and directing one part the light beam to reflect between mirrors 0 and 1 six times, and the other part once between mirrors 0 and 6, the exact place of mirror 6 (six times multiplication of quartz metre length) is found. Here mirror 0 is front mirror, mirror 1 mid mirror and mirror 6 rear mirror. Point-like source of white light is used. Interference fringes are visible in the telescope only if the mirrors are in correct positions with about 0,001 mm accuracy. This can't be obtained by adjusting the mirrors only, but delaying one of the two light beams with the compensator glasses of the telescope. The positions of mirrors are registered with a special transferring device relative to permanent transferring bars on every pillar and projected later on between underground benchmarks for further use. The 6-m-interference is then multiplied to longer lengths. Actually the measurement procedure starts with 864 m, proceeds to shorter distances and several measurements of 6 m with the quartz metre, and proceeds again to longer distances, ending in 864 m.

Because of weather conditions, in 2005 we could measure only to 432 m seven times, whereas the new record of 2007 is eight measurements to 864 m and three more to 432 m. For one successful measurement, small ($\leq 1°$) temperature differences are needed not only along the baseline but also during the (at least) seven hours observation period; this always requires a cloudy night. Since only a few such nights are available during one autumn, making the entire measurement period last two to three months, projection measurements are needed not only before and after the period, but every few weeks. This repetition reduces the total uncertainty, in which the projection measurements are a major factor, together with the uncertainty of the quartz metre length.

Projections caused 0,034 mm to 0,043 mm uncertainty in 2005, but in 2007 only 0,016 mm to 0,033 mm, due to the strengthened pillar structures; these values are independent of length. Random errors in interference observations and transfer readings caused 0,009 mm to 0,022 mm in 2005 and 0,010 mm to 0,054 mm in 2007. These "Type A" values are evaluated by statistical analysis of series of observations [6, 7]. Uncertainty of the length of a quartz metre causes 0,001 mm to 0,030 mm uncertainty in baseline lengths of 24 m to 864 m. This data is provided in calibration certificates and results of comparisons. Other small sources of uncertainty, "Type B", are e.g. temperature of the quartz metre, variation in thicknesses of mirror coatings in the comparator, and levellings of the instrumentation. They are evaluated on the basis of previous measurements during 60 years.

2.4. Results

Lengths with total standard uncertainties are listed in Table 1. They are lengths between underground benchmarks, reduced to the height level of underground marker at 0 m. Reverse projections are needed annually, when the results are utilized in EDM calibration. The results of both recent comparisons of quartz metres and interference measurements are congruent with previous results. Repeatability of measurements is good, and possible pillar movements at Nummela are at 0,1 mm level or smaller. Stability, repeatability and small uncertainties comparable to Nummela are not self-evident, but arduous to attain, and regular remeasurements with the Väisälä interference method are essential also at Nummela.

Table 1. Latest results of interference measurements at the Nummela Standard Baseline. The full time series includes 15 measurements in years 1947–2007, 13 of them up to 864 m. The uncertainties here are standard uncertainties.

Epoch	**0 – 24** **mm + 24 m**	**0 – 72** **mm + 72 m**	**0 – 216** **mm + 216 m**
1996,9	33,41 ±0,03	14,87 ±0,04	53,21 ±0,04
2005,8	33,23 ±0,04	14,98 ±0,04	53,20 ±0,04
2007,8	33,22 ±0,03	14,95 ±0,02	53,13 ±0,03

Epoch	**0 – 432** **mm + 432 m**	**0 – 864** **mm + 864 m**
1947,7	95,46 ±0,04	122,78 ±0,07
...	…	…
1996,9	95,23 ±0,04	122,75 ±0,07
2005,8	95,36 ±0,05	–
2007,8	95,28 ±0,04	122,86 ±0,07

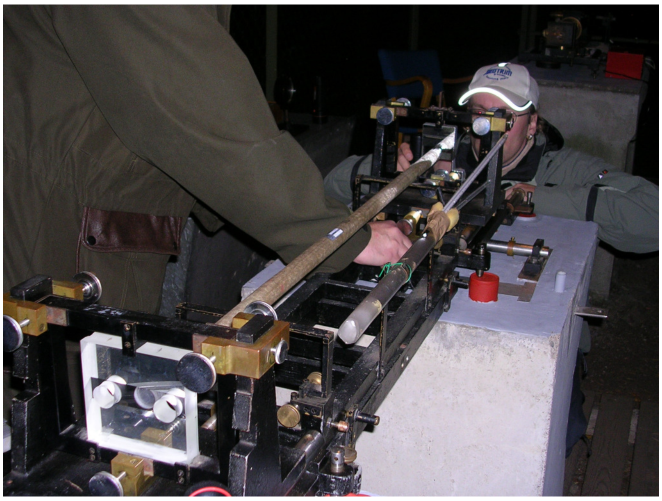

Fig. 3. The quartz metre no. VIII installed in the Väisälä interference comparator.

3. SCALE TRANSFER MEASUREMENTS TO CALIBRATION BASELINES

During the last 15 years the scale of the Nummela Standard Baseline has been transferred to nearly 20 baselines and test fields in more than 10 countries. One of the most interesting is in Lithuania, as described here. The recently remeasured baselines in Innsbruck, Austria, and Vääna, Estonia, are also promising. Instead of establishing more new national measurement standards for long distances, metrological and other scientific activities are now more directed to collaborative use of limited number of well-maintained stable baselines.

3.1. Kyviškės Calibration Baseline in Lithuania

The Kyviškės Calibration Baseline, 15 km east of Vilnius, is proving to be a new high-grade multi-purpose calibration site. The VGTU established it in 1996 in a treeless airfield area. The 1 320-m-long baseline consists of six observation pillars at intervals of 100, 260, 760, 180 and 20 metres. In 2000 it was expanded to a triangle-shaped test field with a seventh pillar at 644–949 metres distance from the other pillars. The scale is traceable through the Nummela Standard Baseline. The FGI and the VGTU have performed scale transfer measurements three times, in June 1997, in October 2001 and in August 2007. The results are summarized in Table 2, and reported in detail in three publications [8, 9, 10]. A Kern ME5000 EDM instrument is used as a transfer standard (Fig. 4).

Fig. 4. Calibration of Kern ME5000 EDM instrument at the Väisälä-type Nummela Standard Baseline.

Table 2. Baseline lengths (m + mm) with extended uncertainties at the Kyviškės Calibration Baseline.

	m	June 1997 mm	Oct. 2001 mm	Aug. 2007 mm
1–2	100	163,8 ±0,4	163,6 ±0,2	163,8 ±0,3
1–3	360	177,3 ±0,6	177,4 ±0,4	177,4 ±0,3
1–4	1 120	387,3 ±1,0	386,6 ±0,6	387,3 ±0,7
1–5	1 300	484,7 ±1,2	483,7 ±0,7	484,6 ±0,8
1–6	1 320	495,9 ±1,2	494,9 ±0,7	496,1 ±0,8
1–7	841		814,1 ±0,7	814,4 ±0,6
2–3	260	13,6 ±0,6	13,9 ±0,3	13,7 ±0,3
2–4	1 020	223,6 ±1,0	223,1 ±0,6	223,6 ±0,7
2–5	1 200	321,1 ±1,1	320,3 ±0,7	3201,0 ±0,7
2–6	1 220	332,3 ±1,1	331,5 ±0,7	332,5 ±0,7
2–7	775		244,1 ±0,7	244,2 ±0,5
3–4	760	210,0 ±0,8	209,2 ±0,5	209,9 ±0,5
3–5	940	307,5 ±0,9	306,4 ±0,6	307,4 ±0,6
3–6	960	318,8 ±0,9	317,7 ±0,6	318,8 ±0,6
3–7	644		380,7 ±0,7	380,8 ±0,5
4–5	180	98,4 ±0,4	98,1 ±0,3	98,3 ±0,3
4–6	200	110,3 ±0,5	109,9 ±0,3	110,4 ±0,3
4–7	804		746,6 ±0,7	747,5 ±0,6
5–6	20	12,4 ±0,4	12,4 ±0,3	12,7 ±0,3
5–7	933		821,6 ±0,7	822,4 ±0,6
6–7	949		189,5 ±0,7	190,5 ±0,6

Projections and calibrations were made at Nummela before and after every scale transfer. Compared with the true values from interference measurements, the determined fairly insignificant scale correction of the transfer standard was +0,03 ppm (1997), –0,01 ppm (2001) and +0,32 ppm (2007). The additive constant was +0,11 mm, +0,14 mm and +0,05 mm, respectively. The recent values of 2008 for the same instrument are +0,15 ppm and +0,08 mm (Fig. 5).

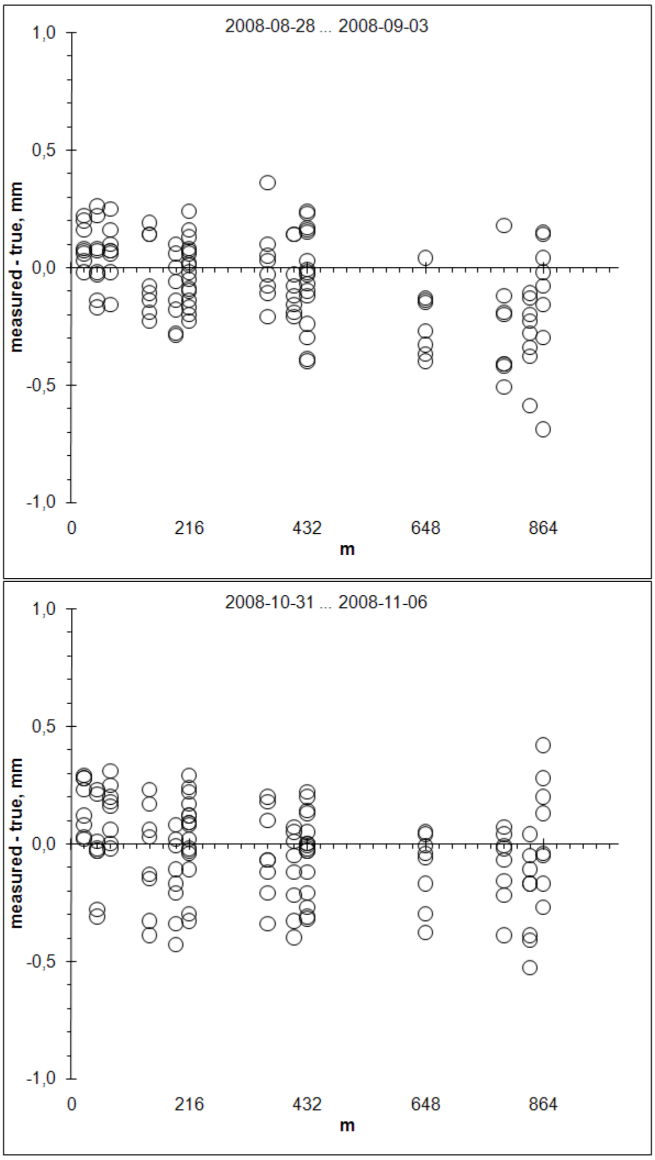

Fig. 5. Scale correction and additive constant of an EDM equipment are determined in calibrations before and after a scale transfer by comparing the measured values (after geometrical and velocity corrections) with true values from interference measurements. Here is an example of the calibrations at the Nummela Standard Baseline for scale transfers in autumn 2008.

All three measurements at Kyviškės include four measurements of the baseline double-in-all-combinations. They have been performed in very varying weather conditions with more than 30 degrees difference in temperatures. This is challenging in modelling the refraction with present instruments, and probably explains the small systematic variation in results. Nevertheless, the repeated measurements are quite consistent and show the baseline stable.

Uncertainty components (1-σ) e.g. in 2007 include the “Type B” uncertainty of the Nummela Standard Baseline (interference measurements up to 432 m) ±0,04 mm, with extension (up to 1,32 km) ±0,09 mm/km, and “Type A” uncertainty of projections between underground markers and forced-centring plates on observation pillars ±0,07 mm, uncertainty of the Mekometer between calibrations ±0,17 mm/km, weather observations ±0,20 mm/km and random errors, from the adjustments, ±0,11 to ±0,15 mm; total uncertainty (2-σ) for the pillar intervals 20 m to 1 320 m is ±0,3 to ±0,8 mm. The measurements in 1997 were made in worse weather conditions, causing larger uncertainty.

Fig. 6. The 7-pillar 1 320-m geodetic baseline and test field of the Vilnius Gediminas Technical University at Kyviškės in Lithuania are an optimal place also for testing of GPS equipment.

3.2. An application in geodetic satellite positioning

One topical application of precise EDM is to control the scale of GPS network with traceable EDM. In Olkiluoto nuclear power plant and disposal site of nuclear waste in Finland EDM is used parallel with GPS measurements in geodynamical studies. GPS is used for determining the possible deformations in the monitoring network, and one 511-m EDM baseline gives the traceable scale in it. GPS measurements have been carried out since 1995 and EDM since 2002.

However, some contradictions in results have been seen from the parallel measurements. The scales from GPS and EDM seem to differ an average of 0,64 mm (over 1 ppm) and the difference is systematic of nature, i.e. GPS gives always longer distances [11]. Since EDM results are very accurate, uncertainties well-defined, and the difference is detectable regarding to uncertainty of EDM, this leads to a conclusion that the GPS solution is biased. Systematic GPS errors may be of site specific origin or related to uncertainty in e.g. antenna calibration values, modelling of atmosphere or satellite orbits.

The difference is unsolved yet, but EDM and GPS measurements were carried out at Kyviškės in 2008 to study the problem more thoroughly. We were able to do the comparison for more and longer distances than at Olkiluoto, and in ideal conditions (open sky, stable monumentation, etc., Fig. 6). A three-days GPS measurement was carried out in between of two double-in-all-combinations EDMs. Also absolute antenna calibrations and other antenna tests have been performed. The results are anticipated to enable more accurate GPS computation and better traceable GPS measurements for our deformation studies. Results will be available during autumn 2009.

3.3. BEV Baseline in Austria

The scale transfer method is also used in the current EMRP joint research project “Absolute long distance measurement in air” between nine European metrology institutes [12, 13]. The scale is transferred from Nummela to the 7-pillar 1 080-m-long baseline of BEV (Bundesamt für Eich- und Vermessungswesen) in Innsbruck, Austria, to improve European facilities in testing new measurement methods and instruments outdoors. Measurements were performed in September 2008 in problematical weather conditions and in urban environment. Preliminary results show, that 0,7 mm/km extended uncertainty was reached.

3.4. Maa-amet Baseline in Estonia

The Estonian Land Survey Maa-amet has recently reconditioned a 13-pillar 1 344-m-long geodetic baseline in Vääna, 20 km west of Tallinn (Fig. 6). All the pillars are in the same line in space, both horizontally and vertically. Screws for centring the instruments are embedded in the observation pillars, making centring simple and accurate. Scale transfer measurements were performed in October 2008 in ideal weather conditions. Preliminary results show, that 0,4 mm/km extended uncertainty was reached. To compare this to the best possible, based on our experience, 0,2 mm/km extended uncertainty can be utilized in calibrations at the Väisälä-type standard baselines.

Fig. 7. The modern 13-pillar 1 344-m geodetic baseline of the Estonian Land Survey at Vääna.

4. CONCLUSIONS

We have shortly presented here some remarkable geodetic length standards that are used for traceable long distances. Geodetic baselines have long been essential in terrestrial surveying and mapping, but new measurement methods and instruments are bringing new users at them. The Nummela Standard Baseline in Finland and the Kyviškės Calibration Baseline and test field in Lithuania are excellent places for testing and validation of innovations in outdoor conditions. The same can be expected at the newer geodetic baselines in Austria and Estonia. The uncertainties are probably the smallest that can be achieved with the present methods. Geodetic baselines may also benefit estimation of uncertainty of satellite positioning, though there we are still far from traceable lengths.

ACKNOWLEDGEMENTS

In the scale transfer to Lithuania we have used the Kern Mekometer ME5000 of the Laboratory of Geoinformation and Positioning Technology of Helsinki University of Technology (HUT) as a transfer standard. We thank Prof. Martin Vermeer and other staff there for good cooperation.

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