Calibration of the BEV Geodetic Baseline

Jorma JOKELA, Pasi HÄKLI, Rupert KUGLER, Helmut SKORPIL, Michael MATUS and Markku POUTANEN, Finland and Austria

Key words: length metrology, geodetic baseline, traceability, measurement standard.

SUMMARY

Development of distance measurement instruments based on new technology is advancing. This increases interest in the best possible testing and validation services in metrology institutes and among manufacturers of surveying instruments. A recent project to improve the facilities in Europe, calibration of the new BEV geodetic baseline in Innsbruck, Austria, is presented here. The traceable scale was transferred there from the Nummela Standard Baseline of the FGI, Finland, with ±0.7 mm/km uncertainty (2-σ) in autumn 2008. The most accurate EDM instrument available at present was used as transfer standard, which was calibrated using the results of interference measurements of 2007 in Nummela. Comparison of the results of 2008 with the first results from 2006 indicate good stability of the new baseline. The method and results represent the best current practice and state-of-the-art in the world. The work is a part of the work package “Outdoor comparison” of the European Metrology Research Programme Joint Research Project “Absolute long distance measurement in air”.

ZUSAMMENFASSUNG

Die Entwicklung der Streckenmessgeräte schreitet durch die Verwendung neuer technischer Methoden voran. Das Interesse an optimalen Prüf- und Kalibriermöglichkeiten bei Metrologieinstituten und unter den Herstellern von vermessungstechnischen Messgeräten steigt. In diesem Beitrag wird ein aktuelles Projekt beschrieben, welches diese Möglichkeiten in Europa verbessert, nämlich die Kalibrierung der neuen geodätischen Eichstrecke in Innsbruck (Österreich). Der rückführbare Maßstab ist im Herbst 2008 von der Ausgangsstrecke des Finnischen Geodätischen Instituts (FGI) in Nummela (Finnland) mit einer Unsicherheit (2-σ) von ±0,7 mm/km übertragen worden. Als Transfernormal wurde das genaueste derzeit verfügbare EDM-Gerät genutzt, welches unter Verwendung der Ergebnisse der Interferenzmessungen aus dem Jahre 2007 in Nummela kalibriert worden ist. Der Vergleich der Werte aus dem Jahr 2008 mit den ersten Messergebnissen aus dem Jahr 2006 weisen auf eine gute Stabilität der neuen Eichstrecke hin. Die Methode und die Ergebnisse spiegeln die zur Zeit weltweit beste Praxis und die optimale technische Möglichkeit wider. Diese Arbeiten sind ein Teil des Teilprojekts ”Outdoor Comparison” des Europäischen Metrologischen Forschungsprogramms, und zwar des Kooperationsforschungsprojekts ”Absolute long distance measurement in air”.

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1. INTRODUCTION

New methods for long range dimensional metrology are developed in the European Metrology Research Programme joint research project T3.J3.1 “Absolute long distance measurement in air” (EMRP 2009). A part of this project, bringing together nine European metrology research institutes, is the work package for validation and reproducibility estimation of new absolute distance measurement (ADM) instruments outdoors. To improve facilities for this the 1 080 metres geodetic baseline of the Austrian metrology institute BEV (Bundesamt für Eich- und Vermessungswesen) in Innsbruck was calibrated in September 2008 by transferring the scale from the Nummela Standard Baseline of the Finnish Geodetic Institute (FGI). The extremely stable 864 metres baseline in Finland is widely known as the most accurate geodetic baseline in the world. The length is traceable to the definition of the metre with ±0.07 mm standard uncertainty (Jokela et al. 2009) through a quartz metre system and white light interference measurements with the Väisälä comparator. The scale has recently been transferred to about ten countries using high precision electronic distance measurement (EDM) instruments as transfer standards. The method – as the best current practice and state-of-the-art – and results of the scale transfer to the BEV geodetic baseline are presented here.

1.1 The BEV geodetic baseline

The BEV baseline (Fig. 1), constructed in 2006 in the western outskirts of city of Innsbruck, consists of seven observation pillars, numbered from 1 to 7, at 0, 30, 120, 270, 480, 750 and 1 080 metres. Azimuth of the baseline is 83°, southern side is open, whereas mountains rise on the northern side; the ground is grass and gravel road. The location on a strip of land between a busy motorway and fast-flowing river Inn is challenging for measurements, especially in determination of velocity corrections of EDM observations. Height difference is –1.8 m from west to east (Fig. 2). Pillars 1–4 and 6 are in line with decimetre accuracy, whereas pillars 5 and 7 are 0.4 m and 3.8 m apart from this line (Fig. 2). Based on preliminary probing and objectives set within the EMRP, measurement uncertainty of up to ±0.5 mm/km was expected in the scale transfer measurement.

1.2 The Nummela Standard Baseline

The Nummela baseline (Fig. 1), founded in 1933, consists of six observation pillars and more permanent underground markers at 0, 24, 72, 216, 432 and 864 metres. Since the advent of interference measurements with the Väisälä comparator in 1947, the baseline has been called Nummela Standard Baseline. The interference measurement method was invented by Yrjö Väisälä already in 1923 (Väisälä 1923), and even today it is the most accurate method for traceable distance measurements in field conditions. Since 1951 similar measurements standards for geodetic measurements have been recommended by the International Association of Geodesy (IAG) and since 1954 by the International Union of Geodesy and Geophysics (IUGG).

The baseline is located close to the town centre of Nummela, 45 km NW of Helsinki, on a frost-resistant ridge of moraine and sand with glacial origin, covered with pine forest. Large renovation works of working premises and observation pillars were carried out in 2004–2007. All observation pillars are on the same line in space, since this is a requirement for interference measurements; the height difference from 0 m to 864 m is –4.1 m. The result of interference measurement is preserved in lengths between the underground markers, which can be accessed and utilized through regular theodolite-based projection measurements. The use of underground markers and excellent environment together with methods with superb accuracy guarantee the high quality of the baseline. It serves customers worldwide in calibration of high precision EDM instruments and in scale transfers to other baselines (Jokela and Häkli 2006).

Figure 1. Geodetic baselines of the FGI in Nummela (left) and of the BEV in Innsbruck.

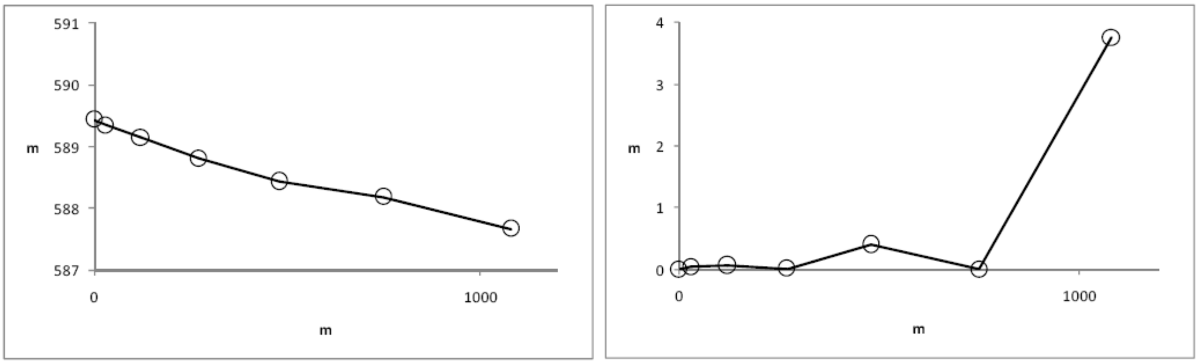

Figure 2. Altitudes (left) and horizontal nonparallelism (right) of the BEV baseline pillars. Azimuth of baseline direction is about 83°.

In autumn 2007 the Nummela Standard Baseline was measured for the 15th time with the Väisälä comparator. The successful measurements and excellent compatibility with previous results prove the reliability of the baseline again. Standard uncertainties of baseline lengths from 24 m to 864 m range from ±0.022 mm to ±0.074 mm. Maximum variation in the 864 metres length has been only 0.6 mm during the 60 years time series.

2. TRACEABILITY CHAIN

The traceability chain from the definition of the metre to lengths at a standard baseline are described in numerous publications (one of the latest is by Jokela and Poutanen 1998), and only the main points are listed here. Information on Väisälä baselines and interference comparator is given also e.g. in Kukkamäki (1969 and 1978) and on quartz gauges in Väisälä and Oterma (1967).

2.1 Quartz gauge system and Väisälä interference comparator

Lengths of 1-m-long quartz gauges bring the scale in the Väisälä (white light) interference comparator. The quartz metre system is maintained with regularly repeated comparisons in the laboratory of Tuorla Observatory of University of Turku. The standard uncertainty of comparisons with the principal normal, quartz gauge no. 29, is a few nm. The scale of the system is validated through absolute calibrations of a transfer standard, quartz gauge no. 30 and some other quartz gauges. The latest absolute calibrations were performed at the PTB (Physikalisch-Technische Bundesanstalt) Braunschweig, in 1995 and at the MIKES (Centre for Metrology and Accreditation) Helsinki, in 2000 (Lassila et al. 2003), both of them with congruent results with about ±35 nm standard uncertainty. Next calibrations are planned in connection with the renewal of the computer system at Tuorla.

2.2 Projection measurements

For calibrations at the Nummela Standard Baseline the lengths preserved between the underground markers are restored to lengths between forced-centring plates on observation pillars with repeated projection measurements.

The projection measurements are based on precise angle measurements. A theodolite is adjusted on an observation pillar, and pointings are made and angles read to distant targets on one or two other observation pillars in the baseline direction, and to a plumbing rod that is adjusted above the underground marker at the projection site, perpendicular to the baseline direction. For one projection, four sets of horizontal angles are measured in two theodolite face positions. The distance between the observation pillar and underground marker is measured with a calibrated steel tape; due to optimal geometry one millimetre uncertainty is easily obtained and sufficient here. The projection corrections are calculated with simple trigonometric formulas.

For the scale transfers in autumn 2008 four calibrations of the transfer standard were scheduled between the first and second projections, and four more between the third and fourth projections. One Leica TC2003 theodolite was used in August and November, and another in September and October; depending on the instrument there is 0.2 mm systematic difference in projection corrections. This difference was not corrected, since the correction would not be generally valid for the other instruments used at the baseline. The average values were used instead. To obtain known distances s_{cal} between observation pillars 0 and v to be used in calibration the average values of all projection corrections P are added to the true values s_{int} from interference measurements,

$$s_{cal}^{0-v} = s_{int}^{0-v} + P_0 - P_v .$$

Congruent results from projection measurements before and after scale transfer (Table 1, from –0.05 mm to +0.13 mm in average values) prove both that the baseline is stable and that the distances from interference measurements could be accurately transferred to distances between observation pillars. Empirically, based on long experience, the standard uncertainty of projection corrections was estimated to be ±0.07 mm.

Table 1. Projection corrections (mm) between underground markers and observation pillars before and after the scale transfer. One theodolite was used in August and November and another in September and October.

Pillar v	August 25–28	September 4–11	**Average "before"**
0	+1.292	+1.365	**+1.33**
24	–0.364	–0.577	**–0.47**
72	+1.589	+1.360	**+1.48**
216	–0.161	–0.331	**–0.25**
432	+1.716	+1.461	**+1.59**
864	+0.929	+0.705	**+0.82**
	October 28–30	November 7–11	**Average "after"**
0	+1.331	+1.295	**+1.31**
24	–0.473	–0.199	**–0.34**
72	+1.440	+1.618	**+1.53**
216	–0.383	–0.177	**–0.28**
432	+1.467	+1.608	**+1.54**
864	+0.787	+0.902	**+0.84**

2.3 Calibration of transfer standard

The Kern Mekometer ME5000 EDM instrument and prism reflector of the Laboratory of Geoinformation and Positioning Technology of Helsinki University of Technology (TKK) have been used as transfer standard between the two baselines. Four calibrations of the transfer standard were performed in Nummela both before and after the calibration of the BEV baseline in Innsbruck. The EDM calibrations also served three other scale transfer measurements during autumn 2008, to high precision calibration baselines in Lithuania and Estonia and to a baseline for geodynamical research in Finland.

The first calibrations were performed in Nummela on August 29 – September 3 in mostly cloudy and rainy weather. During the second calibrations on October 31 – November 6 the weather was varying from cloudy to clear; in general the autumn weather is mostly favourable at the northern latitudes. All calibrations included observations from every 6 pillars to all other 5 pillars, altogether 2 × 4 × 6 × 5 = 240 distances ranging from 24 m to 864 m. Every observation included at least two pointings and measurements to the prism reflector, and temperatures were measured at least twice at both ends of every pillar interval. Dry temperature varied during the measurements between 6.5 °C and 15.9 °C, air pressure between 98.24 kPa and 100.52 kPa, and relative humidity between 74 % and 100 %; extreme value of the velocity correction was –15.5 mm.

After first velocity corrections (based on weather observations), geometrical corrections onto the reference height level (top surface of the underground marker 0), and projection corrections, the observed distances were compared with the true distances from interference measurements (Fig. 3). Scale correction and additive constant were determined with linear regression separately for all eight calibrations. Average values “before” (August–September) and “after” (October–November) were determined from the results of four single calibrations, weighted inversely proportional to variances. Results are shown in Table 2. The standard uncertainty of the four calibrations was larger before than after, but for the scale transfers both calibration periods were regarded equally important, allowing e.g. for possible changes in the instrument. Therefore equally weighted average of weighted averages of “before” and “after” is used in the final computations (average of two independent calibration sets). The final values with standard uncertainties used in the scale transfer are +0.079 mm ±0.014 mm for the additive constant and +0.151 mm/km ±0.049 mm/km for the scale correction.

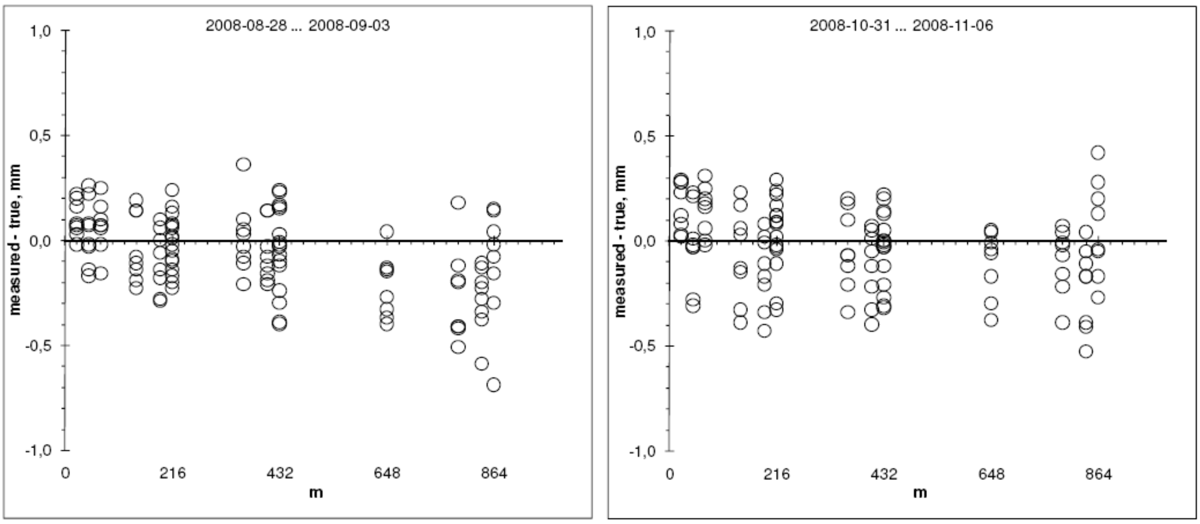

Figure 3. Corrected EDM observations compared with the true values from interference measurements in the calibrations before (left) and after (right) the scale transfer in autumn 2008.

Table 2. Additive constant (mm) and scale correction (mm/km) from eight calibrations, with standard uncertainties.

	Additive constant	Scale correction
August 28–29	+0.081 ±0.048	+0.011 ±0.048
September 1	+0.052 ±0.051	+0.423 ±0.054
September 2	+0.082 ±0.066	+0.251 ±0.075
September 3	+0.044 ±0.063	+0.180 ±0.075
average "before", equal weights	+0.065 ±0.010	+0.216 ±0.085
average "before", weighted	+0.065 ±0.010	+0.200 ±0.099
October 31	+0.077 ±0.086	+0.151 ±0.096
November 3	+0.101 ±0.083	+0.134 ±0.094
November 5	+0.096 ±0.045	+0.125 ±0.048
November 6	+0.091 ±0.052	+0.056 ±0.049
average "after", equal weights	+0.091 ±0.005	+0.117 ±0.021
average "after", weighted	+0.093 ±0.004	+0.102 ±0.022

3. MEASUREMENTS AT THE BEV BASELINE

Four calibrations were performed in Innsbruck during four days, September 16, 17, 18 and 22, at mostly unfavourable weather conditions, because of a lot of sunshine. Every calibration included observations from every 7 pillars to other 6 pillars, altogether 4 × 7 × 6 = 168 distances. Every observation included at least two pointings and measurements to the prism reflector, and temperatures were measured at least twice at both ends of every pillar interval. Dry temperature varied during measurements between 6.6 °C and 16.2 °C, air pressure between 94.62 kPa and 95.32 kPa, and relative humidity between 42 % and 92 %; extreme value of velocity correction was +20.3 mm. The temperature range was thus about the same both in Nummela and in Innsbruck.

3.1 Estimation of uncertainty of velocity correction due to weather conditions

Observations of ambient temperature, air pressure and relative humidity are an essential part of EDM observations. Using the weather data the influence of medium in propagation of measurement signal is taken into account, for our transfer standard e.g. with formulas given in Kern (1986). Weather conditions anyhow usually remain as the main source of uncertainty, the extent of which is estimated here in some detail.

An outdoor baseline is seldom equipped with an extensive system of weather sensors, and weather data is usually registered at end points of the distances to be measured only or at a few intermediate points in addition. Appropriate instruments are available, but modelling the true temperature along the measurement beam with them is problematic especially in field conditions. This is often a major factor in estimation of total uncertainty, since 1 °C error in temperature causes 1 mm/km error in measured distance. The same applies to 0.3 kPa error in pressure; influence of humidity is less significant.

Two Assmann-type psychrometers were used for observing dry and wet temperature. Instrument corrections of +0.02°C to +0.15°C have been determined in calibrations in Germany with ±0.08° uncertainty. Since the same instruments are used at all stages of scale transfer, possible small systematic errors are eliminated, and uncertainty due to instruments remains small in temperature measurements. During every distance observation dry and wet thermometers were read at both ends of the interval to be measured, and the average value of four readings was used for velocity correction. Reading accuracy was 0.1°C.

The uncertainty of temperature measurements can be estimated from temperature differences between the ends. In favourable conditions on cloudy days differences are typically within a few tenths of degrees, whereas during varying cloudiness larger than one degree differences are common. On sunny days instruments are protected against direct sunlight, but the temperature under parasols may still be different from the temperature at the path of the measurement beam. Rain will bring in another problems. Unfavourable weather conditions result in about three times larger variation in observed distances, compared with optimal field conditions. In Innsbruck the standard deviations of temperature observations (at EDM instrument minus at prism reflector) were 0.30°C (dry) and 0.22°C (wet), and maximum differences were 2.00°C (dry) and 1.65°C (wet), see Fig. 4. Determination of dry temperatures is estimated to cause ±0.30 mm/km standard uncertainty and determination of relative humidity (with about ±2% standard uncertainty) about ±0.02 mm/km. This estimation is based on analysis of temperature differences. Variation in Fig. 4 does not depict uncertainty in temperature observations, but most of the differences are caused by real temperature differences between the end points. How well the average value represents the temperature along the measurement beam, depends on measurement conditions. Turbulences caused by the heavy traffic on the passing motorway or by the chilly river Inn on the other side could not be modelled, and they certainly explain a part of the large temperature variations. Since the measurement conditions are equal (though varying) at the points of weather observations and between them, the two observations are regarded as an acceptable estimate of conditions along the measurement beam. If this estimation is insufficient, the deficiencies appear in the estimation of total uncertainty as larger variation in results of single calibrations. With a less abundant data set or with few single calibrations the estimate of uncertainty should be considerably increased. Also the uncertainty due to the computation method could be considered.

Air pressure was measured with two Thommen aneroid barometers at one point. Pressure variation along the baseline due to the height differences or weather changes was neglected, since for every calibration every pillar interval is measured from both ends. The aneroids were compared with the mercury barometer of the FGI before and after the scale transfer. Standard uncertainty of air pressure observations with two barometers was ±20 Pa. This is estimated to cause ±0.06 mm/km standard uncertainty, and ±0.03 mm/km is estimated due to calibrations of barometers. This value is congruent with the long time series for controlling the drift of our mechanical barometers.

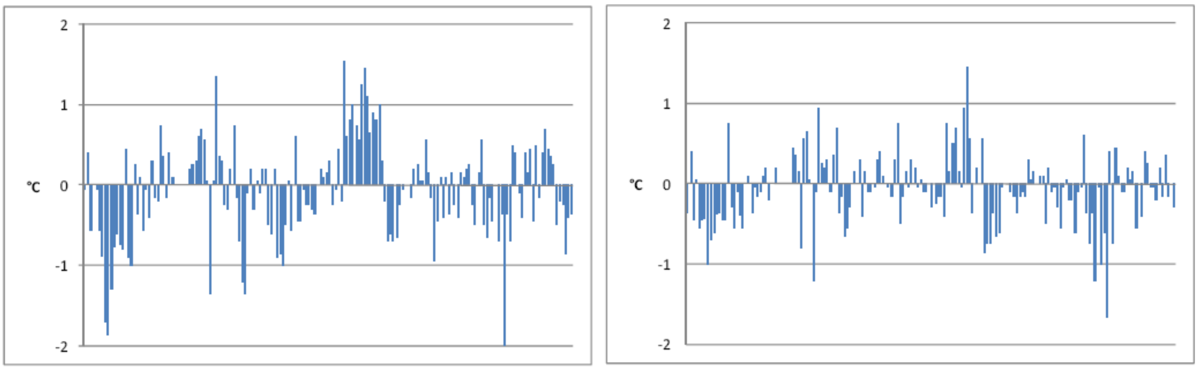

Figure 4. Dry (left) and wet (right) temperature differences (at EDM instrument minus at prism reflector) during 168 observations at rather unfavourable conditions.

3.2 Estimation of uncertainty due to centring method

Fixing surveying instruments on the top plate of observation pillar with a 5/8 inch screw through the plate is a widely used simple standard method, using which instruments are attached also on most types of surveying tripods. This is not an optimal centring method for geodetic baselines, but usually sufficiently accurate. At the BEV baseline fixing screws were rather tight, and the uncertainty in centrings is difficult to be treated separately. The small uncertainty due to centrings is included in the observations.

At the Nummela Standard Baseline instruments are attached on observation pillars using another standard method, permanently fixed Kern forced-centring plates. Results of projection measurements there show, that a few tenths of millimetres repeatability in the centring is obtainable with this method.

One more recommended centring method is to install fixing screws permanently on the observation pillars, and to screw instruments directly in them. This method has shown very good repeatability in centrings e.g. at the recently rebuilt Vääna geodetic control baseline of Maa-amet, the Estonian Land Board. This baseline was calibrated by the FGI in October 2008.

At the Lithuanian Kyviskes calibration baseline of the Institute of Geodesy of Vilnius Gediminas Technical University, which has been calibrated by the FGI four times in 1997–2008 (Jokela et al. 2009), the centring method is about the same as at the BEV baseline. At Kyviskes and BEV baselines standard deviations are of the same order and somewhat larger than at Nummela and Vääna baselines.

4. COMPUTATION OF BASELINE LENGTHS

In the computation, distances between pillar top surfaces are unknown. The instrument-dependent additive constant may be unknown, too, though it has been determined in the calibrations in Nummela. This allows to control the stability of the constant, but the value should remain close to zero.

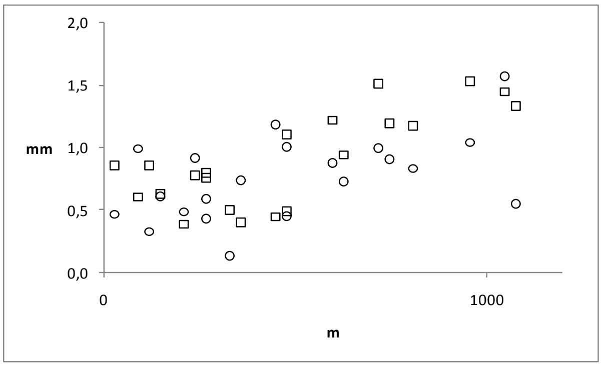

Figure 5. Variation of observations (max–min) in four calibrations. Circles stand for 21 distances downhill from west to east and squares for 21 distances uphill from east to west.

4.1 Weighting of observations

Preliminary analysis of observations after velocity corrections showed clearly that differences of maximum and minimum values are larger for longer than shorter distances (Fig. 5). This is common in EDM, and caused by weather conditions, but seldom found in Kern ME5000 measurements at shorter than 1 km distances. No significant difference between "downhill" (from west to east) and "uphill" (from east to west) observations was found. Weights of observations were set reversely proportional to distances, based on a priori accuracy information of the instrument, ±(0.2 mm + 0.2 mm/km), which seemed to work well. No observations were rejected.

4.2 Geometrical corrections

In addition to velocity corrections, based on weather observations, geometrical corrections for vertical and horizontal nonparallelism may be applied before adjustments. Height differences are usually determined by precise levelling and reduced onto the reference height level. At the BEV baseline the altitude of the pillar no. 1 top level, 589.438 m, was chosen as the reference level (Fig. 2). Other heights are (2) 589.341 m, (3) 589.150 m, (4) 588.812 m, (5) 588.438 m, (6) 588.187 m, and (7) 587.673 m. The formula for vertical geometrical reduction *ds*, including the inclination correction and the height correction, is

$$ds = \sqrt{\left[\left(s^2 - \left(h_j - h_i\right)^2\right)\right] / \left[\left(1 + h_j/\mathrm{R}\right)\left(1 + h_i/\mathrm{R}\right)\right]} - s\,,$$

where s is the distance between i and j to be reduced, h_i and h_j are heights above the reference height level h_0, and R is the radius of the Earth, R = 6 370 km. The reverse formula for transforming the reduced distances s_{red} back to slope distances s_{slope} is

$$s_{slope} = \sqrt{s_{red}^2\left(1 + h_j/\mathrm{R}\right)\left(1 + h_i/\mathrm{R}\right) + \left(h_j - h_i\right)^2}\,.$$

Horizontal deviations from a straight line are usually determined by precision tacheometry. At the BEV baseline these deviations are large (Fig. 2), prompting the use of proper geodetic network adjustments instead of ordinary procedures for baselines with a common design. If all distances are projected onto the line between pillars 1 and 7, corrections for horizontal nonparallelism range up to –10.27 mm for pillar interval 6–7.

4.3 Least-squares adjustments

Several procedures for least-squares adjustment of observed and corrected lengths are available. Two least-squares adjustment programs, written at the FGI, were used in the computations. One program, originally constructed for the first-order triangulation, reduces the observed distances onto the GRS80 ellipsoid or other reference surface using levelled and geoidal heights, and solves the trilateration network. Vectors between pillars are then solved from the resulting geodetic coordinates with the formulas for geodetic reverse problem, and reduced back to the slope distances.

The second program performs a straightforward three-dimensional network adjustment without any height reductions. Both programs resulted in equal vector lengths and residuals at micrometre level. The results are presented in Table 4.

5. ESTIMATION OF TOTAL UNCERTAINTY

Factors of the total uncertainty of measurement have been presented in the previous sections. Standard uncertainties (k=1) are combined in the computation in Table 3. The values presented with the lengths in Table 4 are extended uncertainties (k=2).

5.1 Uncertainty of the length of Nummela Standard Baseline

Standard uncertainties from the latest interference measurements at the Nummela Standard Baseline range from ±0.02 mm to ±0.07 mm for section lengths 24 m to 864 m (Jokela et al. 2009). This evaluation comprises the traceability chain from the definition of the metre through the quartz gauge system and interference measurements with the Väisälä comparator to baseline lengths between underground markers.

5.2 Uncertainty of the scale transfer

Estimation of total uncertainty of measurement includes standard uncertainties (k=1) as listed here. Uncertainties from the adjustments of observations at the BEV baseline are based on statistical analysis of a series of observations (Type A), and the values for other components are based on previous results and experiences (Type B).

Table 3. Estimation of uncertainty of measurement.

Type of uncer-tainty	Description	Quantity x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Standard uncertainty, fixed component (mm)	Standard uncertainty, proportional component (µm × L, L in m)
A	21 distances from the adjustments (including centring and levelling)	from 30 m to 1080 m	from 0.068 mm to 0.163 mm	1	from 0.068 to 0.163	0.000
B	scale from Nummela	1.000000000	0.000000086	L	0.000	0.086
B	projection measurements	0 mm	0.070 mm	1	0.070	0.000
B	EDM scale correction	1.000000151	0.000000049	L	0.000	0.049
B	EDM additive constant	0.079 mm	0.014 mm	1	0.014	0.000
B	temperature observations	from 279.8 K to 289.4 K	0.30 K	1×10^{-6} K^{-1} L	0.000	0.300
B	temperature instruments	0 K	0.11 K	1×10^{-6} K^{-1} L	0.000	0.110
B	pressure observations	from 94.62 kPa to 95.32 kPa	20 Pa	3×10^{-9} Pa^{-1} L	0.000	0.060
B	pressure instruments	0 Pa	10 Pa	3×10^{-9} Pa^{-1} L	0.000	0.030
B	humidity observations	fr. 42 % to 92 %	2 %	1×10^{-8} $\%^{-1}$ L	0.000	0.020
	Total standard uncertainty				**from 0.098 to 0.178**	**0.343**

Table 4. Slope distances between pillars of the BEV baseline, with extended uncertainties.

Interval	Distance (mm)	Interval	Distance (mm)
1 2	30 038.63 ±0.21	3 4	149 971.99 ±0.22
1 3	120 036.12 ±0.21	3 5	359 953.18 ±0.32
1 4	270 008.10 ±0.28	3 6	629 956.42 ±0.48
1 5	479 989.28 ±0.38	3 7	960 005.73 ±0.75
1 6	749 992.50 ±0.56	4 5	209 981.40 ±0.25
1 7	1 080 041.18 ±0.81	4 6	479 984.48 ±0.39
2 3	89 997.56 ±0.21	4 7	810 035.19 ±0.64
2 4	239 969.55 ±0.26	5 6	270 003.85 ±0.30
2 5	449 950.69 ±0.37	5 7	600 054.80 ±0.50
2 6	719 953.97 ±0.54	6 7	330 063.22 ±0.36
2 7	1 050 002.60 ±0.79		

6. RESULTS

Results, slope distances between pillar intervals of the BEV baseline with extended uncertainties, are listed in Table 4, and ready to be used as traceable reference values in further calibrations of EDM instruments. Extended uncertainties range from ±0.21 mm to ±0.81 mm; for the longest distance this is equal to ±0.75 mm/km.

6.1 Comparison with previous results

The BEV measured the Innsbruck baseline for the first time already in September 2006, when all the 21 pillar intervals were observed once from both ends. Every observation included three pointings. The new results of September 2008 from the adjustments were first compared with the velocity-corrected, but non-adjusted previous data set. No significant scale difference could be discerned, but a few tenths of millimetres systematic difference, attributable to instrument corrections, was evident.

To determine and correct the additive constant, the data of September 2006 was adjusted with the formulas presented by Rüeger 1996, p. 203–206. Net adjustments were not used now, because of small amount of observations and an unfavourable geometry. Instead, vertical reductions due to height differences were applied to the slope distances, and horizontal nonparallelism was corrected by projecting the distances on the line between pillars 1 and 7. Adjusted baseline lengths were solved along with the additive constant +0.250 mm ±0.024 mm (k=1). After this correction, and transforming the results back to the slope distances, the results of September 2006 are in good accordance with the results of September 2008, as we can see in Fig. 6. This indicates good short-term stability of the baseline and equal scale in the measurements.

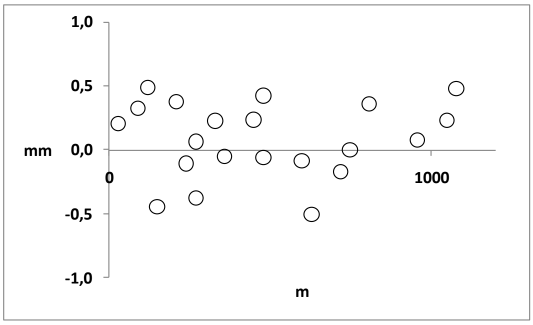

Figure 6. Differences of distances from measurements in September 2006 to September 2008.

7. CONCLUSIONS

A topical example of the best current practice and state-of-the-art in scale transfer for geodetic baselines is presented in this contribution. The new results of calibration of the BEV baseline are directly usable in calibration of EDM instruments, and also meet the needs for validation of new instruments. The environment is not optimal for all kind of metrological research and development, but on the contrary is similar to conditions in many practical applications; availability of a set of different kinds of baselines indoors and especially outdoors is advantageous for length metrology.

The extended uncertainty of ±0.7 mm/km now obtained for the baseline length of 1 080 m is larger than the expected ±0.5 mm/km. As usual, the main source of the uncertainty is temperature measurements, and in more favourable weather conditions the expected value might be reached with the present instrumentation.

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BIOGRAPHICAL NOTES

All the authors work for the European Metrology Research Programme (EMRP) Joint Research Project “Absolute long distance measurement in air”.

Mr. Jorma Jokela, born 1961, is specialist research scientist and Laboratory Head of the National Standards Laboratory of Length in the Department of Geodesy and Geodynamics in the Finnish Geodetic Institute. Mr. Pasi Häkli, born 1976, is senior research scientist in the same department, and Prof. Markku Poutanen, born 1955, is the Head of the Department.

Mr. Rupert Kugler, born 1959, is Head of Department Verification and Cadastral Offices. Mr. Helmut Skorpil, born 1970, is Head of the Cadastral Office of Bruck an der Mur and expert for EDM-Instruments. Mr. Michael Matus, born 1961, is specialist research scientist and Laboratory Head of the National Standards Laboratory of Length in the Directorate of Metrology of the Federal Office of Metrology and Surveying.

CONTACTS

Finnish Geodetic Institute
PL 15 (Geodeetinrinne 2), FI-02431 Masala
FINLAND
Tel. +3589295550
Fax +358929555200
Email: jorma.jokela@fgi.fi, pasi.hakli@fgi.fi, markku.poutanen@fgi.fi
Web site: www.fgi.fi

Bundesamt für Eich- und Vermessungswesen – Federal Office of Metrology and Surveying
Schiffamtsgasse 1-3, A-1020 Vienna
AUSTRIA
Tel. +431211103701 (Mr. Kugler)
Fax +431211103623 (Mr. Kugler)
Email: rupert.kugler@bev.gv.at, helmut.skorpil@bev.gv.at, michael.matus@bev.gv.at
Web site: www.bev.gv.at