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A COMPARISON OF TWO WEATHER DATA ACQUISITION METHODS FOR THE CALIBRATION OF THE PTB GEODETIC BASELINE

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Abstract: The Physikalisch-Technische Bundesanstalt has recently refurbished its geodetic baseline in Braunschweig, Germany, and the baseline is now supplied with an inclusive set of environmental sensors for weather observations. The Finnish Geodetic Institute calibrated the baseline in June 2011. In the calibration, the observers also used conventional instruments, common in surveying work, to obtain weather data. By comparing the two weather data sets and the results computed when using them, it is possible to demonstrate the good capability of conventional instruments, when properly used. The results of the comparison, which are applicable in electronic distance measurements for conventional surveying, are presented in this paper.

Keywords: geodetic baseline, long range distance measurements, environmental sensors, weather observations.

1. INTRODUCTION

Observing the influence of air in the propagation of a measurement beam is an essential measure in electronic distance measurements (EDM). The displayed distances are corrected using the first velocity correction, which is computed by using the simultaneously recorded air temperature, pressure and humidity observations, knowledge of the carbon dioxide content and the recommended computation formulas; some instrument-dependent constants are also needed. For a general description of EDM, the textbook by Rüeger [1] provides a thorough introduction.

The ambient circumstances may be easy to determine in laboratory conditions, but the geodetic measurements are performed in more challenging field conditions. No sensor systems are available then; the weather observations have to be measured using a very limited number of single instruments: thermometers, barometers and hygrometers.

Determining the first velocity correction is a major source of uncertainty for EDM; not only the instruments but especially the changing conditions cause uncertainty. The new Physikalisch-Technische Bundesanstalt (PTB) facilities bring laboratory-level conditions to the open air for first time, making it possible to compare weather data obtained using surveyors' conventional instruments or using an environmental sensor system.

The PTB's recently refurbished geodetic baseline in Braunschweig, Germany consists of eight observation pillars in line at 0, 50, 100, 150, 250, 350, 500 and 600 metres [2]. The height difference between the end pillars is 1.52 m. The baseline design makes it possible to measure every distance from 50 m to 600 m, at 50 m intervals. The baseline is now supplied with an inclusive set of calibrated environmental sensors: 60 Pt-100 temperature sensors at 10 m intervals, six Testo humidity sensors and two Setra 470 pressure gauges. The environment is farmland on one side and woodland on the other side, and the baseline is fenced for laser safety (Fig. 1).

The Finnish Geodetic Institute (FGI) calibrated the baseline in June 2011. The origin of the traceable scale is the FGI's Nummela Standard Baseline (Fig. 2); the scale was transferred from this national measurement standard using a high-precision EDM instrument, the Kern Mekometer ME5000, as a transfer standard. The Mekometer equipment is the property of the Department of Surveying at Aalto University. The scale of the 864-m Nummela Standard Baseline is based on interference measurements performed in 2007 with the Väisälä interference comparator and on the quartz gauge system that is used with it [3].

The FGI calibrated the transfer standard at the Nummela Standard Baseline before and after performing the measurements at the PTB baseline. The observers obtained the weather data with conventional instruments using two psychrometers and two aneroid barometers; the instruments are commonly used in EDM for baseline calibrations or for more practical applications (Fig. 3). In Braunschweig, the second set of weather data was extracted from the recordings of the environmental sensor system.

Figure 1 The first 100 metres with the first ten environmental sensor poles at the PTB geodetic baseline. The instrument and office room is next to the roofed zero pillar. The baseline is fenced for laser safety.

Figure 2 Calibration facilities at the FGI's Nummela Standard Baseline. New instrument and office rooms serve the 80-year-old baseline. The underground markers and observation pillars are fenced.

Figure 3 Calibration of a Kern ME5000 EDM instrument at the 0-m observation pillar of the Nummela Standard Baseline, with two aneroids on the pillar on the left and a psychrometer hanging from the roof.

For the computation, the FGI determined the group refractive index of air for the first velocity correction using a computation method first proposed by Ciddor [4], as recommended in Resolution no. 3 of the International Association of Geodesy (IAG) General Assembly in 1999, and the computation program written by S. K. Johnson and J. M. Rüeger of the School of Geomatic Engineering, University of New South Wales, Australia. The FGI performed the final computation using common least squares adjustment algorithms.

2. CALIBRATION PROCEDURE AND WEATHER DATA ACQUISITION

The FGI began the calibration procedure at the Nummela Standard Baseline on 9-11 May 2011 with projection measurements, which connect the stable underground benchmarks to the aboveground observation pillars. The projection measurements are based on precise angle measurements. Weather observations are not needed.

Using the observation pillars, each equipped with an individual forced-centring plate, three calibrations of the Kern Mekometer (no. 357094) and a prism reflector (no. 374414) were performed on May 16th, 23rd and 30th. For every calibration, all 15 of the known pillar intervals, ranging from 24 m to 864 m, were measured from both ends. Every measurement consists of at least two single observations. After making the first velocity corrections, geometrical corrections due to height differences and least-squares adjustments, the three calibrations resulted in scale correction values of (with standard uncertainties from the adjustments) +0.28 mm/km ±0.17 mm/km, +0.13 mm/km ±0.10 mm/km and +0.28 mm/km ±0.12 mm/km.

The observers measured the dry and wet temperatures with 0.1 °C resolution using a psychrometer both at the Mekometer and at the prism reflector. The thermometers in the psychrometers are ventilated with an aspirator. Based on the validation certificates for the FGI's Assmann-type, Thies-Clima psychrometers, the calibration corrections for the single, liquid-in-glass thermometers range from 0.00 °C to +0.15 °C, and the uncertainty of the measurement is ±0.08 °C. The relative air humidity was calculated from the temperature difference between the dry and the moistened thermometers.

The observers measured the air pressure using two Thommen aneroid barometers. Both of the instruments were placed at the Mekometer, since all redundant transporting of a delicate mechanical instrument has proved to be somewhat disadvantageous. The dependence of air pressure on height was not corrected (and practically not observable with the aneroids, nor was the pressure difference due to the weather differences between the ends), but the minor influence can be eliminated when all of the distances are measured from both ends.

The observers compared the two aneroids with the FGI's mercury barometer before and after performing the measurements at the PTB. One aneroid was slightly damaged when it was being transported to the PTB, and its stability could not be verified in the latter comparison. Therefore, the observations made with it were not used in the final computation, which is based on observations with one aneroid only. For this instrument, the comparisons with the mercury barometer yielded a correction of –20 Pa ±10 Pa.

For the calibration of the PTB baseline, the observation procedure was quite similar as for the calibration of the Mekometer. Unlike at Nummela, the instrument scale at Braunschweig was traceably known and the baseline section lengths were unknown; the results are shown in Section 4. In five days, all 28 of the different distances between the eight observation pillars were observed from both ends during three calibrations, yielding a total of 168 distances. The two observers read the psychrometers at least twice for every distance, and one observer read the aneroids once. The environmental sensor system (Fig. 4) was running continuously, recording the average values every 30 seconds and making 6–16 recordings (3–8 minutes) for every distance. The applicable average values for every distance were computed afterwards with the help of the start and end times of the observations.

The uncertainties for the corrected temperature, pressure and relative humidity from the sensor system are estimated to be smaller than 80 mK, 5.1 Pa and 0.35 %, respectively. Variations around the baseline pillars and sensors are treated separately, as presented in detail by Pollinger et al. [2]. Significantly larger uncertainty estimates were used for the computation with the data from the conventional instruments: 0.3 K, 30 Pa and 5%; these values include the uncertainty estimate for weather variations.

After the measurements at the PTB baseline, the transfer standard was calibrated again at the Nummela Standard Baseline, now twice, on 13–14 June and on 14–15 June. At that time, scale correction values of +0.02 mm/km ±0.10 mm/km and +0.19 mm/km ±0.12 mm/km were obtained. In the final computation, the average value from five equally weighted calibrations was used: +0.181 mm/km ±0.139 mm/km. Here the standard uncertainty estimate also includes the uncertainty of the Nummela Standard Baseline: ±0.100 mm/km for the interference measurement procedure and the quartz gauge system, and ±0.083 mm/km for the projection measurements. The additive constant was +0.039 mm ±0.022 mm.

Figure 4 The southern end of the PTB geodetic baseline. The weather sensor system records temperatures next to the measurement beam at 10 m distance intervals and 30 s time intervals.

Table 1 Air temperature (*t*), pressure (*p*) and relative humidity (*rh*) during the three calibration measurement periods at the FGI and PTB baselines.

	Nummela May 16/23/30	**Braunschweig June 6–10**	**Nummela June 13–15**
t **(°C)**	8.2–15.9	15.6–27.8	10.8–15.7
p **(kPa)**	99.42–100.14	99.30–100.86	99.40–99.66
rh **(%)**	54–100	35–99	71–99

The observers used the same psychrometers and aneroids equally at the two baselines, which decreases some instrument-dependent uncertainty components. The weather conditions at the time when the transfer standard and the PTB baseline were being calibrated are listed in Table 1. The different temperature conditions as well as the rather equal pressure conditions may be noteworthy when analyzing the distance measurement results.

The calibration procedure was ended in new projection measurements, which were completed on 20–22 June. The differences between the two sets of five projection corrections ranged from –0.10 mm to +0.27 mm. This shows the reproducibility of the measurement, or, rather, how accurately the less than 10^{-7} degree of uncertainty for the interference measurements was transferred for the calibration of the EDM instruments. In also confirms the short-term stability of the Nummela Standard Baseline. They also contribute to the global uncertainty estimate of the calibration procedure for the PTB baseline.

3. THE TWO WEATHER DATA SETS

On average, the psychrometers showed dry temperatures that were 0.27 °C lower than from the sensors (Fig. 6). An obvious reason for this is that the psychrometers were always in shade; the average difference was just 0.01 °C on the third cloudy measurement day, when all the instruments were in the shade. The largest single differences were –1.8 °C and +1.1 °C. The differences were not dependent on the distances.

In order to understand the discrepancies in temperatures, it is instructive to investigate the statistical distribution of the temperature readings of the individual sensors along the baseline. For optimum conditions, i.e. cloudy weather with slight rain, the standard deviation for the complete set of 60 temperature sensors remains well below 0.1 K, as can be seen in Fig. 5 for the data of June 8th.

During times of maximum sun exposure, however, the temperature distribution becomes extremely inhomogeneous along the baseline. For example, the standard deviation on June 6th, which was the sunniest day of the calibration campaign, reached an average of 1.0 K in the morning hours. In general, the standard deviation is a direct measure of the achievable measurement uncertainty for the effective temperature and, thus, the overall length measurement [2].

In the latter case, the uncertainty of the temperature measurement limits the length-dependent part of the uncertainty of the length measurement to $10^{-6}\,L$ ($k = 1$), while in the former case the temperature-induced uncertainty is one order of magnitude lower. The two extreme cases demonstrate that, despite the large effort to monitor the temperature at the PTB baseline, the achievable uncertainty of the effective temperature remains strongly weather-dependent. The deviation between the single readings and mean values of the 60-sensor ensemble can even be as much as several Kelvins (Fig. 5). Hence, local deviations might explain part of the observed deviations between psychrometer readings and the readings of the PTB sensor system. Besides, the data set also clearly demonstrates how an extremely unlucky placement of the temperature sensor might induce a systematically erroneous velocity correction in the order of several ppm.

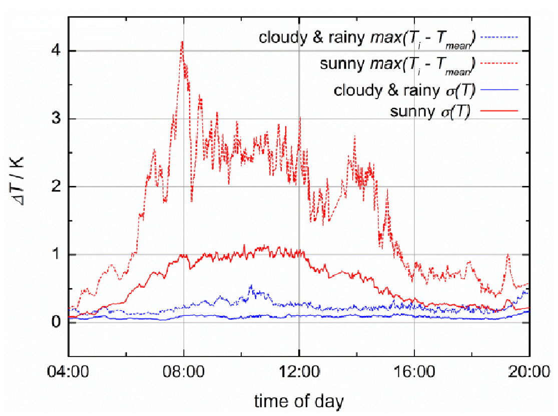

Figure 5 Distribution of temperature readings from the individual sensor heads along the complete 600 m range of the PTB baseline on two different days during the calibration. The standard deviation $\sigma(T)$ is represented by solid lines. Dashed lines indicate the maximum deviation of the individual temperature readings from the corresponding mean value. Data taken on June 6th is depicted in red, and data taken on June 8th is depicted in blue.

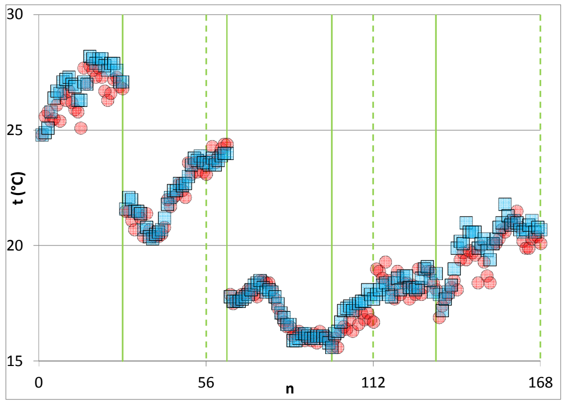

Figure 6 Average temperature during the 168 distance measurements at the PTB geodetic baseline. The red circles depict the data obtained with the FGI weather instruments and the blue squares depict the data obtained with the PTB sensor system. The dashed green lines separate the data for the three calibrations, and the solid green lines separate the five measurement days (on 6–10 June, 2011) with different weather conditions. The third day was the most favourable (mostly cloudy and rainy), whereas the other days were mostly clear or partly cloudy.

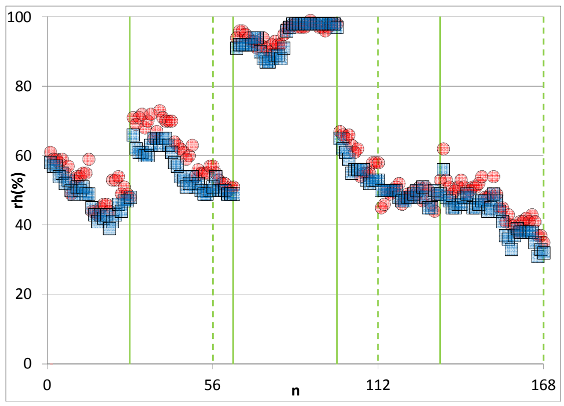

Figure 7 Average relative humidity during the 168 distance measurements at the PTB geodetic baseline (for an interpretation, see the caption for Figure 6).

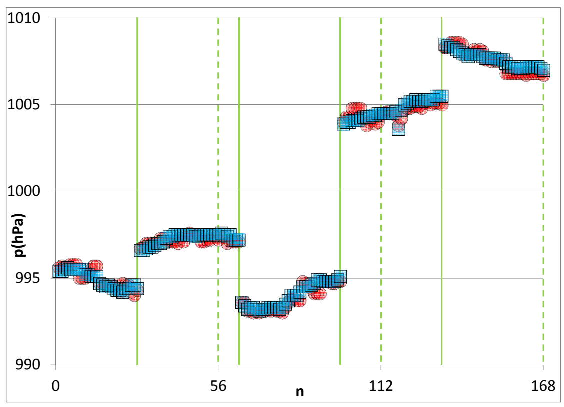

Figure 8 Average air pressure during the 168 distance measurements at the PTB geodetic baseline (for an interpretation, see the caption for Figure 6).

On average, the psychrometers gave relative humidity values that were three percentage points higher than from the sensors, with the variation ranging from –6 to +12 (Fig. 7). When determining relative humidity with psychrometers, the same problems with shading exist as with the temperature observations.

On average, the aneroids showed air pressure that was 8 Pa lower than from the pressure gauges, with the largest single differences being –80 Pa and +70 Pa (Fig. 8). Aneroids are mechanical measurement instruments and it is essential to regularly calibrate them, preferably with a long time series to track the possible drift.

In favourable weather conditions, the differences are in accordance with the uncertainties estimated in Section 2, but much larger variations are common in sunny weather. A 0.27 K "error" in temperature, applied in the formula for the first velocity correction, changes the scale of the EDM by nearly 0.27 mm/km, which means 0.16 mm or less for baseline distances of 600 m or less. Such minor differences are difficult to discern from other sources of uncertainty and they are barely visible in the results.

4. RESULT OF CALIBRATION

The results of the calibration for the PTB baseline are presented in Table 2. The FGI estimated that the combined standard uncertainty is

$$u(l)_{k=1} = \sqrt{(9.9 \times 10^{-5}\mathrm{m})^2 + (3.4 \times 10^{-7} l)^2} \qquad (1)$$

for the adjusted individual distances when only using the conventional weather observation instruments. The distances were also computed with the data from the sensor system; the changes in the results remain clearly within the estimated measurement uncertainty.

Based on our current limited knowledge of the long-term stability of the baseline, using the result of the calibration and utilizing the environmental sensor system the PTB currently estimates that the standard uncertainty for further calibration of geodetic instruments at the baseline is

$$u(l)_{k=1} = \sqrt{(3.1 \times 10^{-4}\mathrm{m})^2 + (3.7 \times 10^{-7} l)^2}, \qquad (2)$$

if the ambient conditions are favourable [2].

Table 2 The adjusted horizontal distances, when corrected using weather data obtained with conventional weather instruments, and the difference, when corrected using the environmental sensor system data. The uncertainties are expanded (k = 2) values.

Pillar interval	**Horizontal distance (mm)**	**Difference (mm)**
0–50	49 997.80 ±0.20	–0.07
50–100	49 995.56 ±0.19	+0.03
100–150	50 011.59 ±0.18	0.00
150–250	99 993.83 ±0.19	+0.03
250–350	100 002.73 ±0.19	+0.01
350–500	149 997.08 ±0.21	+0.04
500–600	99 990.02 ±0.20	+0.09
0–50	49 997.80 ±0.20	–0.07
0–100	99 993.36 ±0.22	–0.05
0–150	150 004.95 ±0.24	–0.05
0–250	249 998.78 ±0.28	–0.02
0–350	350 001.51 ±0.33	0.00
0–500	499 998.59 ±0.41	+0.03
0–600	599 988.61 ±0.47	+0.12

5. CONCLUSION

If the path of a measurement beam alternates between a shaded and sunny environment and is also always affected by the air turbulence, it is difficult to determine the temperature differences along the beam with any instrumentation. This results in multiple variations in the measurement results compared with favourable weather conditions. Independent of the method, temperatures should be measured as close to the measurement beam as possible, both horizontally and vertically.

The two geodetic baselines discussed in this paper are outstanding resources for long-range, outdoor length metrology. Naturally, when two sets of weather data are practically identical, the determined refractive index and first velocity corrections are also equal, having little effect on the resulting baseline lengths. A basic set of conventional, high-quality weather observation instruments may thus be sufficient, even in high-precision surveying work, at least during favourable weather conditions. For more scientific work, a system of environmental sensors yields a much larger set of crucial information. For achieving reliable results, reasonable planning of baseline structures and facilities, their careful maintenance, regular calibrations and capable users are all essential for both data acquisition methods. Regardless of the method, estimating the uncertainty of measurement in field conditions remains troublesome; observations in unfavourable weather conditions should be avoided.

6. ACKNOWLEDGEMENTS

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