A TEST FACILITY FOR VERIFICATION OF LENGTH MEASUREMENTS

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***Abstract**: This paper describes the design and measurement of an internal test facility for length measurements. The purpose of setting up this control baseline is mainly to verify precision instruments of a few millimeters such as geodetic total stations and laser scanner instruments for educational and research activities. The paper describes the measurement process for the baseline reference distances using an absolute laser tracker and the statistical results of the tests using the baseline for two proprietary total stations.*

***Keywords:** geodetic instruments, length measurement, baseline, absolute tracker, least squares.*

I. Introduction

One of the key purposes of the surveying profession is to develop, maintain and improve the survey and mapping infrastructure by means of making standards and guidelines for achieving an acceptable level of survey quality and integration.

In light of the above and due to the fact that all surveying instruments suffer from some errors, it is critical to achieve a high standard of quality in measurements. This paper deals with Electronic Distance Measurement (EDM) equipment and describes the baseline calibration and instrument comparison activities, in order to provide traceability of length for surveying EDM equipment (total stations, reflectorless total stations, laser scanners). The process by which the link between the physical measurement and the relevant standard (or SI unit) can be proven is known as traceability. There are different approaches to establish SI traceability of geodetic baselines. One important perquisite for SI traceability is the correct estimate of the associated measurement uncertainty.

To determine the magnitude of the errors and their statistical properties of distance measurements of EDM equipment, baselines (outdoor or laboratory based) are commonly used (e.g. Braun et al., 2014; De Wulf, 2011; Lechner, 2008; Jokela, 2006). However, establishing a direct link to the SI definition with low measurement uncertainty is a laborious procedure and can only be made for selected so-called reference baselines. Verification of distance meters at the baselines can be carried out as regular checks (following standards), further as legal metrological control of measurement or for error detection and more accurate results (Rüeger, 1990).

This paper aims to describe a test facility for distance measurements verification that has been developed to cover the educational and research activities of the Technical Educational Institute of Athens. The reference points were set up and the absolute distances between the points were determined with a standard deviation of 0.03mm using the Leica Absolute Tracker AT401. The baseline was also used for testing the distance meters of two total stations, by comparing the actual lengths between the pillars ("true values") with the measured lengths. This paper presents the first series of measurements for this baseline facility and discusses the issues pertaining the installation of such a control baseline.

2. Establishment of a control baseline for length measurements

In the underground area of the Technical Educational Institute of Athens (TEI Athens) building complex (tunnel length of approximately 300m and rectangular section 2m high and 3m wide) a test facility for length measurement control of various geodetic instruments has been designed and measured. The purpose of setting up this control base is mainly to verify precision instruments of a few millimeters such as geodetic total stations and laser scanner instruments for educational and research activities.

The total station instruments can be checked for (i) zero error ("instrument-reflector constant"), and (ii) its measured length's standard deviation and its compatibility with the specified one by the manufacturer.

In addition, reflectorless total stations and laser scanners can be verified against the manufacturer's specifications and tests regarding their behavior against various materials in order to define correction functions (in relation to material and distance) can be possible. It is emphasized that instruments either of time-of-flight principle or phase difference or using both principles can be tested.

The control field was implemented with seven specially designed bases made by steel (following ISO 17123-4 specifications). These were embedded in the wall at specified distances in such a way that their heads were on the same horizontal plane (of few mm accuracy). The dedicated design of the bases are designed so that their head carries an integrated 5/8 bolt to be able to attach a tribach in a unique way ("forced centering") to place instruments and accessories (Fig. 1).

Fig. 1. Specially designed bases

The distances between the bases (baseline reference distances) were measured with the Leica Absolute Tracker AT402 (quoted accuracy ± 10μm, maximum reflector measurement of 320m, distance performance resolution of 0.3μm) (Fig. 2). Specifically, the distances between the bases were measured on 8th October 2017 with the Leica Absolute Tracker AT402 (Table 1, as per Brochure Hexagon Specifications p.15), using three sets of observations with a time difference of one hour between them.

Table 1. Manufacturer specifications of the Absolute Tracker AT402

Leica AT402	
Maximum reflector measurement	320 m
Minimum reflector measurement	1.5 m
Distance performance resolution	0.3 μm
Accuracy	± 10 μm

The mean of the three sets of horizontal distances, corrected by atmospheric effects, is shown in Table 2. The RMS was estimated as ± 30 μm.

Fig. 2. Leica Absolute Tracker AT402 and its special targets

Table 2. Horizontal distances of baselines measured by the Absolute Tracker AT402

Baselines	**Distances (mm)**	**Baseline**	**Distances (mm)**
$T_1 - T_2$	5070.4272	$T_1 - T_2$	5070.4272
$T_1 - T_3$	15059.0870	$T_2 - T_3$	9988.6598
$T_1 - T_4$	30901.9628	$T_3 - T_4$	15842.8758
$T_1 - T_5$	60227.3604	$T_4 - T_5$	29325.3976
$T_1 - T_6$	95187.4720	$T_5 - T_6$	34960.1116
$T_1 - T_7$	119675.7437	$T_6 - T_7$	24488.2717

A meteorological data logger was installed near the baseline to check the stability of the atmospheric conditions during the measurement period and provide values for the necessary adjustments to the measured lengths due to atmospheric conditions.

The height differences between the seven base stations were measured using high accuracy levelling with the digital level LEICA DNA03 (standard deviation ± 0.3mm per km double run using invar staff). The results are shown in Table 3:

Table 3. Height differences of the base stations

Baseline	ΔH (mm)
$T_1 - T_2$	0.2
$T_2 - T_3$	- 0.1
$T_3 - T_4$	0.2
$T_4 - T_5$	-0.5
$T_5 - T_6$	0.2
$T_6 - T_7$	-0.1

3. Test procedure for the verification of EDM instruments

The procedure for the verification of Electromagnetic Distance Measuring instruments (EDM) is described in Part 4 of ISO 17123-4 entitled "Optics and optical instruments - Field work for the control of geodetic and topographic instruments - Part 4: electromagnetic instruments measuring lengths (EDM instruments) " (ISO 17123-4:2012, https://www.iso.org).

A two-step procedure is proposed:

- The *Simplified Test* Procedure, which examines the internal accuracy of the instrument and whether the measurements are close to each other. The results are derived from a limited number of measurements and therefore do not fully account for the uncertainty in the measurement of the length.

- The *Full Test* Procedure, which is applied to determine the accuracy of an E.D.M. and its ancillary equipment. It is based on length measurements with all possible combinations in a verified control base, without requiring nominal (standard) values. The experimental standard deviation of one measurement is calculated by least squares adjustment techniques.

In this work, effort has been made to follow as closely as possible the full test procedure described in ISO 17123-4 in order to warrant that through the measurements for a tested instrument on the new control baseline it is possible to evaluate the:

- Zero error ("instrument-reflector constant")

- The standard deviation of the length measurement and its compatibility check with the one specified by the manufacturer.

In addition, the comparison with standard values, enables other instruments such as reflectorless total stations and laser scanners to be verified in the control baseline.

The control baseline is shown schematically in Fig. 3, and the measurements of the lengths that are required for the full test procedure are shown in Fig. 4.

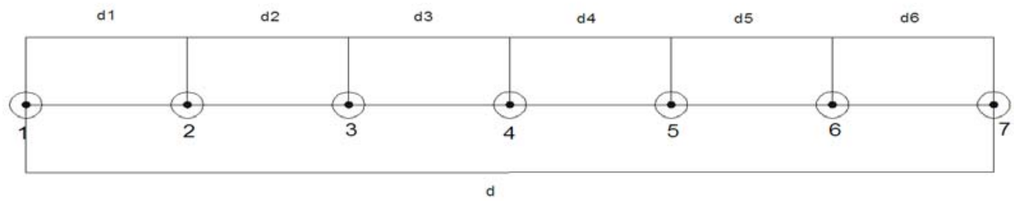

Fig. 3. Schematic of control baseline

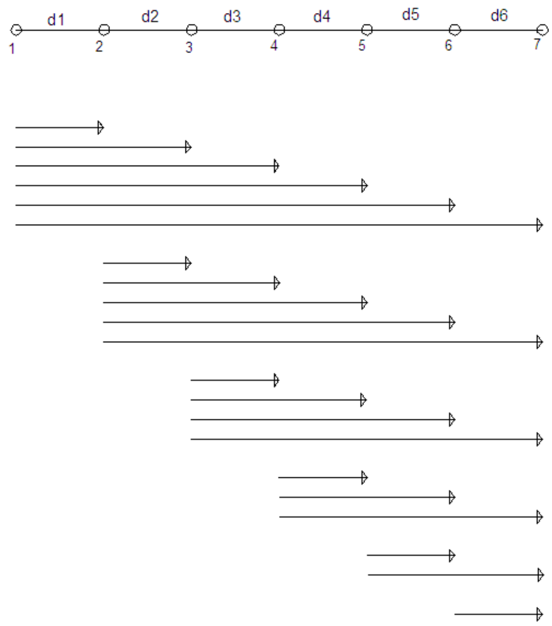

Fig. 4. Length measurement procedure

The corrected values of the measured lengths are calculated using least squares method. The unknown parameters are the six distances $\overline{d}_1, \overline{d}_2, ..., \overline{d}_6$ and the zero error correction δ . All distances are considered to be of equal weight.

The form of the observation equation is:

$$a_{i1}d_1 + a_{j2}d_2 + a_{i3}d_3 + a_{4i4} + a_{i5}d_5 + a_{i6}d_6 + a_{i7}\delta = S_{ij} + \upsilon_i \qquad (1)$$

where,
a_{ij} are the parameters of the design matrix A (Eq. 3)
S_{ij} are the measurements (as showed in Fig.2)
υ_i are their residuals

The mathematical model comprises 21 length measurements for the determination of 7 independent determinants (DOF-degrees of freedom r = 14).

The solution is given by least squares method (Method of indirect observations) through the normal system

$$\mathbf{A}^{\mathbf{T}}\mathbf{A}\hat{\mathbf{x}} = \mathbf{A}^{\mathbf{T}}\ell \qquad (2)$$

Where,
A is the design matrix
$\hat{x}$ is the vector of the independent determinants
ℓ is the vector of the measurements

The matrices that form Eq. (2) are as follows:

$$A=\begin{vmatrix}1&0&0&0&0&0&1\\1&1&0&0&0&0&1\\1&1&1&0&0&0&1\\1&1&1&1&0&0&1\\1&1&1&1&1&0&1\\1&1&1&1&1&1&1\\0&1&0&0&0&0&1\\0&1&1&0&0&0&1\\0&1&1&1&0&0&1\\0&1&1&1&1&0&1\\0&1&1&1&1&1&1\\0&0&1&0&0&0&1\\0&0&1&1&0&0&1\\0&0&1&1&1&0&1\\0&0&1&1&1&1&1\\0&0&0&1&0&0&1\\0&0&0&1&1&0&1\\0&0&0&1&1&1&1\\0&0&0&0&1&0&1\\0&0&0&0&1&1&1\\0&0&0&0&0&1&1\end{vmatrix}\quad \overline{X}=\begin{vmatrix}\overline{d}_1\\\overline{d}_2\\\overline{d}_3\\\overline{d}_4\\\overline{d}_5\\\overline{d}_6\\\delta\end{vmatrix}\quad \ell=\begin{vmatrix}S_{12}\\S_{13}\\S_{14}\\S_{15}\\S_{16}\\S_{17}\\S_{23}\\S_{24}\\S_{25}\\S_{26}\\S_{27}\\S_{34}\\S_{35}\\S_{36}\\S_{37}\\S_{45}\\S_{46}\\S_{47}\\S_{56}\\S_{57}\\S_{67}\end{vmatrix} \qquad (3)$$

After calculating the residuals υ, the *a posteriori* standard error of one measurement $\hat{\sigma}_o=\sqrt{\frac{[\upsilon\upsilon]}{r}}$ is calculated, which is the required experimental deviation **s** of each measurement at the control base. From the *a posteriori* variance – covariance matrix $\hat{V}_{\overline{X}}$, the errors of d_i and δ estimations are obtained.

Through this process, the following questions can be answered (these checks are performed for a 95% confidence level, where 1-a = 0.95 and DOF r = 14):

1. Is the calculated experimental standard deviation less (or equal) to the corresponding σ value given by the manufacturer (or some other predetermined value)?

The hypothesis is valid if $s\le\sigma\sqrt{\frac{x^2_{1-a}(r)}{r}}$ (4)

$s\le\sigma\sqrt{\frac{x^2_{0.95}(14)}{14}}$, where $x^2_{0.95}(14)=23.68$

$$s \le \sigma\sqrt{\frac{23.68}{14}} \;\rightarrow\; s \le 1.30 \cdot \sigma$$

2. Can two different standard deviations s_1 and s_2 of two different samples (s) of measurements belong to the same population if the two samples have the same degree of freedom? (The question applies to two samples of the same instrument at different times or to two samples of different instruments).

The hypothesis is valid if $$\frac{1}{F_{1-\frac{a}{2}}(r,r)} \le \frac{s_1^{\,2}}{s_2^{\,2}} \le F_{1-\frac{a}{2}}(r,r) \qquad (5)$$

$$\frac{1}{F_{0.975}(14,14)} \le \frac{s_1^{\,2}}{s_2^{\,2}} \le F_{0.975}(14,14)\,, \text{ where } F_{0.975}(14,14) = 2.98 \;\rightarrow\; 0.34 \le \frac{s_1^{\,2}}{s_2^{\,2}} \le 2.98$$

4. Verification of total stations Leica TS02 and Leica TS30

As an implementation of the proposed procedure, two total stations and specifically the Leica TS02 and Leica TS30 precision geodetic stations (accuracy [±1mm ±2ppm], [±0.6mm ±1ppm]) were checked on 11th October 2017. The resulting measured values of the baseline lengths (results in m) are:

$$\ell_{TS02} = \begin{vmatrix} 5.070 \\ 15.058 \\ 30.901 \\ 60.226 \\ 95.185 \\ 119.676 \\ 9.988 \\ 25.831 \\ 55.157 \\ 90.117 \\ 114.606 \\ 15.843 \\ 45.168 \\ 80.128 \\ 104.617 \\ 29.325 \\ 64.284 \\ 88.774 \\ 34.960 \\ 59.449 \\ 24.489 \end{vmatrix} \qquad \ell_{TS02} = \begin{vmatrix} 5.0701 \\ 15.0593 \\ 30.9020 \\ 60.2273 \\ 95.1883 \\ 119.6767 \\ 9.9892 \\ 25.8324 \\ 55.1572 \\ 90.1176 \\ 114.6067 \\ 15.8437 \\ 45.1744 \\ 80.1292 \\ 104.6182 \\ 29.3256 \\ 64.2847 \\ 88.7747 \\ 34.9609 \\ 59.4499 \\ 24.4894 \end{vmatrix}$$

After the least squares adjustment, the results are:

<u>For the total station Leica TS02</u>:

$$\hat{x}_{TS02} = \begin{vmatrix} 5.070 \\ 9.98778 \\ 15.844 \\ 29.326 \\ 34.959 \\ 24.489 \\ 0.001 \end{vmatrix} (m) \quad \hat{\sigma}_{o,TS02} = \pm 1.3mm \quad \text{and} \quad \hat{\sigma}_{i,TS02} = \pm 0.9mm$$

For the total station Leica TS30:

$$\hat{x}_{TS30} = \begin{vmatrix} 5.0700 \\ 9.9885 \\ 15.8432 \\ 29.3251 \\ 34.9598 \\ 24.4885 \\ -0.0002 \end{vmatrix} (m) \quad \hat{\sigma}_{o,TS30} = \pm 0.5mm \quad \text{and} \quad \hat{\sigma}_{i,TS30} = \pm 0.2mm$$

According to Eq. 5, if σ is the value given by the manufacturer and s is the calculated experimental standard deviation ($s = \hat{\sigma}_o) \rightarrow s \leq 1.30 \cdot \sigma$

For TS02: $s = \hat{\sigma}_{o,TS02} \leq 1.30 \cdot \sigma \rightarrow 1.3mm \leq 1.3 \times 1.5mm \cong 2mm$

For TS30: $s = \hat{\sigma}_{o,TS30} \leq 1.30 \cdot \sigma \rightarrow 0.5mm \leq 1.3 \times 1.0mm \cong 1.3mm$

This hypothesis is valid for both instruments.

Using the results of the laser tracker (LT) (table 3) the differences between them and the adjusted values of TS02 and TS30 can be calculated (table 4).

Table 4. Differences between the results of LT and those derived from the two total stations

Baselines	**Laser tracker (in mm) I**	**TS02 (in mm) II**	**TS30 (in mm) III**	**I – II (mm)**	**I – III (mm)**
$T_1 - T_2$	5070.4272	5070.03	5070.03	0.5	0.40
$T_1 - T_3$	9988.6598	9987.8	9988.49	0.9	0.17
$T_1 - T_4$	15842.8758	15844.1	15843.21	-1.2	-0.35
$T_1 - T_5$	29325.3976	29325.6	29325.07	-0.2	0.33
$T_1 - T_6$	34960.1116	34959.4	34959.78	0.7	0.33
$T_1 - T_7$	24488.2717	24488.49	24488.49	-0.7	-0.22

The standard deviations for the differences are $\sigma_{I-II} = \pm 0.9$ mm and $\sigma_{I-III} = \pm 0.2$ mm.

If we accept that the results of the laser tracker's measurements are the best estimations of the "true" values of the distances between the bases, then these differences (I-II and I-III) are checked for systematic errors using the normal distribution.

For 95% confidence level, z = 1.96. Thus the differences must be in the confidence interval: for TS02 between [-1.8mm, 1.8 mm]

for TS30 between [- 0.39mm, 0.39mm].

As it is shown in Table 4, there are not systematic errors.

5. Concluding remarks

The specifications ISO 17123-4: 'Optics and optical instruments - Part 4: Electro-optical distance meters (EDM instruments)', is the document describing the standardised procedure to be followed and the calculations to be made when verifying geodetic instruments as well as providing description on the control field of the length measurement bases and the calculations to be made. Its understanding, therefore, is critical in the procedures involved for the calibration of length measuring instruments.

In this paper an attempt has been made to simplify and explain the procedures and calculations described in ISO 17123-4 in order to be fully understood by the surveyor engineer who wishes to verify total station instruments.

An internal metrological test of length measuring instruments was created, following the full test procedure described in ISO 17123-4. The specific ISO standard does not require knowledge of reference values between the control bases of the baseline. In this case, however, this was achieved using the Laser Tracker Leica AT402 so that the control base can be used not only to control the zero error ("instrument-reflector system constant") and the standard deviation of the length measurement (checking its compatibility with the manufacturer's specification), but also be able to control reflectorless total stations and TLS. Moreover, it is possible to statistically check the behavior of various materials in the use of these instruments (determination of correction functions in relation to the material and distance).

The installation of the meteorological data logger has demonstrated the stability of the conditions prevailing in the area where the control baseline is located and has helped to correct the measured lengths due to pressure and temperature.

The whole control process has proved to be both flexible and short, both in the measurement phase and in the calculation phase. The results were extracted using the Least Squares method.

The two instruments tested (Leica TS02, Leica TS30) provided results compatible with the manufacturer's specifications.

The cost of installing the base was more costly to handle the construction of special instrument mounts and accessories.

The future plans include collimators for horizontal and vertical angular control, as well as two fixed points on the floor, with high precision altimetry, are planned to be placed in the same space so that altimeter systems can be controlled.

6. References

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