Review of international standard ISO 17123-4:2012 for electro-optical distance meters

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SUMMARY

International standard ISO 17123-4 provides procedures for assessing the precision of electro-optical distance measuring instruments. The full test procedure is intended to estimate an instrument's standard uncertainty and zero-point correction. Statistical tests are used to evaluate significance. The simplified test procedure is intended to check an instrument against a specified tolerance. Field tests were conducted to evaluate a Lecia TS60 total station. With the full test, the highest precision measuring mode of the instrument had a precision level of 0.64 millimeter, which was comparable to the manufacturer's specification of 0.6 millimeters. With the simplified test, the instrument performed within the manufacturer's specifications. Applications of the ISO standard are discussed, including options for the flexible implementation of procedures.

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1 INTRODUCTION

The International Organization for Standardization (ISO) provides standards for assessment of technical instrumentation (among other things). ISO Technical Committee 172, *Optics and photonics*, Subcommittee 6, *Geodetic and surveying instruments*, has prepared ISO 17123, a series of standards under the title *Optics and optical instruments – Field procedures for testing geodetic and surveying instruments*. The ISO 17123 series includes guidelines for evaluating instruments such as levels, theodolites, distance meters, total stations, and GNSS equipment. ISO standards for geodetic instruments provide a means to determine and evaluate the uncertainty of measurement results obtained with an instrument and its ancillary equipment. The tests laid out in the standards are intended to be field verifications to assess the suitability of an instrument for a particular surveying task.

The standards of the ISO 17123 series are commonly used in the reference material of instrument manufacturers as an indication of the achievable performance. For instance, according to Leica Geosystems, the Nova TS60 total station is capable of measuring distances with an uncertainty of (0.6 mm + 1 ppm). The quoted uncertainty comes from the standard deviation of a series of observations made using the procedures specified in ISO 17123-4:2012. The year of issue is given by the last four digits of the standard's title.

Distance measuring mode	std. dev. ISO 17123-4, standard prism	Measurement time, typical [s]
Precise	0.6 mm + 1 ppm*	7
Standard	1 mm + 1 ppm	2.4
Fast	2 mm + 1 ppm	2.0
Continuously	3 mm + 1 ppm	< 0.15
Averaging	1 mm + 1 ppm	-

Figure 1: Leica Nova TS60 total station specifications. (Leica Geosystems, 2018)

Users of geodetic instruments should be familiar with the capabilities of their instrument and field procedures. If, for example, a particular project has an allowable error budget at the 1-millimeter level, an instrument (or measuring mode) with 4-millimeter precision will be unsuitable. Likewise, an instrument measuring at ±1 millimeter will likely not be cost-effective for a task with an error budget of ±10 centimeters. ISO 17123-4 provides the surveying community with an internationally recognized standard for assessing measurement uncertainty. This provides a common framework for manufacturers, researchers, and practitioners.

According to ISO 17123-4, the documented tests are intended to assess the measuring uncertainty under *field conditions* and are not proposed for "performance evaluations that are more comprehensive in nature." It should be noted that superior measuring results may be possible in laboratory settings, however such results may not be representative of typical conditions encountered in the field.

The tests of ISO 17123-4 are not equivalent to a *calibration*. In a calibration, the primary objective is to detect *systematic errors*, so that they may be removed via corrections to measurements. By contrast, the primary objective of the ISO 17123-4 standard is to quantify the level of *random errors* in the measurements, via a Type A evaluation of standard uncertainty (i.e., based on statistical analysis of a series of measurements). Such an approach has an implicit assumption that systematic errors are dealt with separately, or if not, that they may contribute to the noise level of the measurements as determined by the testing procedures. With this "black-box approach," the measurement uncertainty of the final result is examined, rather than attempting to identify each contributing factor (García-Balboa et al., 2018).

2 PROCEDURES OF ISO STANDARD 17123-4:2012

ISO 17123-4:2012 is the latest standard applicable to electro-optical distance meters (EDM instruments) with measurements made to prism reflectors. The standard states that the "field procedures have been developed specifically for *in situ* applications without the need for special ancillary equipment and are purposefully designed to minimize atmospheric influences." Two test procedures are provided and investigated herein.

The *full* test procedure uses a relatively large dataset to determine the precision of the instrument along with its supporting accessories (such as tripods, tribrachs, centering devices, reflectors, and meteorological sensors). Manufacturers' instrument specifications are developed from the full test procedure, thus it is worthwhile for instrument users to understand this procedure.

The *simplified* procedure is based on a limited number of measurements and assesses whether an EDM instrument's precision is within a specified tolerance. It does not provide sufficient information for rigorous analysis of the standard uncertainty. This procedure is intended for surveying practitioners who wish to check their equipment, but do not need to rigorously quantify the instrument's parameters.

2.1. Full test procedure

In the full test procedure, the following quantities are determined for a given instrument.

- s, the experimental standard deviation of a single distance measurement.

- $\boldsymbol{\delta}$ (delta), the zero-point correction, which corrects for a systematic bias in each distance measurement. Some sources refer to such a bias as index error or constant error. Note that the correction has the opposite sign of the instrument's bias.

- $\boldsymbol{s_\delta}$, the experimental standard deviation of the zero-point correction.

After determining the instrument's parameters, statistical tests are used to evaluate their significance.

The full test procedure is based on distance measurements over a test line without known values. All combinations of distances in the test line are observed. Without true distances for comparison, scale errors caused by variations of the EDM instrument's measuring frequency will not be detected. Such errors affect the absolute *accuracy* of the instrument, but the objective of the ISO standard is to determine measuring *precision*. According to the document, "scale errors in general do not have any influence, neither on the experimental standard deviation, s, nor on the zero-point correction, δ." To determine the stability of the instrument's scale, ISO 17123-4 notes that the measuring frequency can be checked with a frequency meter, as discussed in Barković et al., 2012. Test lines with known distances may also be used for assessing scale error (Fronczek, 1980). Manufacturer specifications typically quote uncertainty of scale in parts-per-million, as in Figure 1. In this paper, the tested instrument's scale error will not be evaluated.

ISO 17123-4 provides guidelines about the test line setup, instrument measurements, calculations, and analysis. However, in several cases, specific requirements are unstated and left to the discretion of the operator. This apparently leaves room to realize the standard as necessary for specific applications.

2.2. Configuration of the test line

ISO 17123-4 specifies that seven points be established on a straight line. The overall length of the test line can vary depending on the intended use of the EDM instrument, though a range of 300 to 600 meters is provided as reasonable. Organizations such as the National Geodetic Survey and Leica Geosystems are known to have permanent test lines with lengths of 900 to 3000 meters (Dracup et al., 2019). While the instrument and targets should be stable during test measurements, the construction of points, along with tolerances for collinearity and height differences, is left up to the operator.

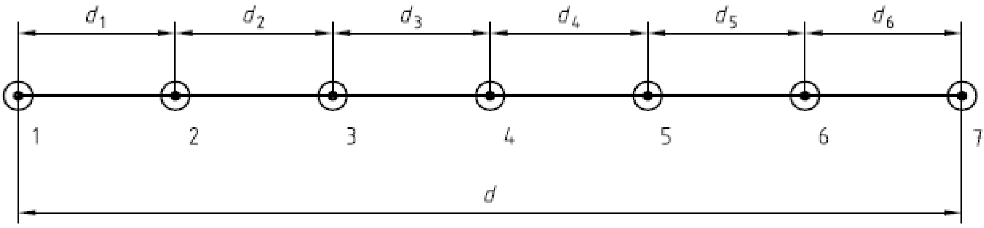

Figure 2: Configuration of test line. (International Organization for Standardization, 2012)

With seven points in the test line, six distances d_1 to d_6 will be formed, leading to 21 unique combinations of points that can be observed. The seven points of the test line should be arranged such that all measured combinations result in different distances (despite the appearance of Figure 2). Multiple methods are proposed to generate the test line distances, and it is suggested to distribute the observed distances over the EDM instrument's unit length to randomize potential cyclic errors. The unit length is the native measuring scale of the instrument based on its modulation frequency and could possibly contain periodic errors throughout its wavelength.

2.2.1. Measurements

All 21 unique distances are to be measured between the seven points. They should be measured on the same day and corrections applied for systematic effects such as atmospheric refraction. As with the test line design, there are several aspects of measurement that are not stated and subject to the operator's preferences. Among them:

- The number of individual readings taken in a distance measurement.
- 1 face measurements vs. 2 face measurements.
- Method and location of meteorological observations.
- Method of correction for atmospheric refraction.
- The use of slope distances vs. horizontal distances.
- Method for reducing measured distances to a particular elevation.
- Shading of the instrument.

Such factors can be important for obtaining the best possible results and may be specified in the procedures of an instrument *calibration*. Since they are not stipulated in the ISO standard, the operator may test the instrument according to the procedures anticipated for actual field work. Note that if some desired level of precision is not reached, the issue may be with the instrument, the procedures, or both.

2.2.2. Calculation

After completing reductions for systematic effects such as test line geometry and atmospheric refraction, the measured distances are evaluated by a least squares adjustment. Per ISO 17123-4, all measurements are given equal weight and considered to be uncorrelated. The Gauss-Markov model is used to estimate the unknown parameters: the six distances d_1 to d_6 and zero-point correction δ. With further calculation, the desired quantities of s (standard deviation of a single distance measurement) and s_δ (standard deviation of the zero-point correction) can be found.

2.2.3. Statistical tests

Three statistical tests are recommended for interpretation of the results. With 21 measured distances and 7 estimated parameters, the solution has 14 degrees of freedom (ν). The tests, which are evaluated at the 5% significance level (α, where $1-\alpha = 95\%$ confidence), are summarized as follows (with all variables defined below).

Question	Null hypothesis	Alternative hypothesis
a	$s \leq \sigma$	$s > \sigma$
b	$\sigma = \tilde{\sigma}$	$\sigma \neq \tilde{\sigma}$
c	$\delta = \delta_0$	$\delta \neq \delta_0$

Table 1: Statistical tests from ISO 17123-4.

Question a: Is the experimental standard deviation, s, smaller than a predetermined value of the population standard deviation, σ? Examples of predetermined values could be the requirements of an intended measuring task or a manufacturer's acceptance criteria for production. Using a χ^2 test,

$$s \leq \sqrt{\frac{\chi^2_{1-\alpha}(\nu)}{\nu}} \times \sigma \quad \Longrightarrow \quad s \leq 1.30\,\sigma\,.$$

Question b: Do the experimental standard deviations from two different measurement samples, s and $\tilde{s}$, belong to the same population? Using an F test,

$$\frac{1}{F_{1-\alpha/2}(\nu,\nu)} \leq \frac{s^2}{\tilde{s}^2} \leq F_{1-\alpha/2}(\nu,\nu) \quad \Longrightarrow \quad 0.34 \leq \frac{s^2}{\tilde{s}^2} \leq 2.98\,.$$

Question c: Is the zero-point correction, δ, equal to a predetermined value, δ_0, such as zero? Using a t test,

$$|\delta - \delta_0| \leq t_{1-\alpha/2}(\nu) \times s_\delta \quad \Longrightarrow \quad |\delta - \delta_0| \leq 2.14\,s_\delta\,.$$

The findings from the statistical tests can be used to assess the EDM instrument and procedures. Comparing the results to reference values or other measurement samples may show the agreement (or disagreement) between different instruments or observing procedures. Likewise, different sample results from a single instrument could be compared to monitor its consistency over time.

2.3. Simplified test procedure

The full test procedure uses a test line without known distances to quantify the spread of measurements. This spread represents the level of random error inherent to the instrument and procedures used and is expressed as the experimental standard deviation of a measured distance. By contrast, the simplified test procedure compares measured distances to known distances to check if the level of agreement is acceptable.

2.3.1. Configuration of the test field

The test field consists of five points: one for the instrument and four with targets set out at known distances d_1 to d_4. Collinearity of distances is not required. The distances are not prescribed in the standard but can be within the "usual working range of the particular EDM instrument (e.g. from 20 m to 200 m)". If such a test field is not already available, one may be set up using an EDM instrument and procedures of higher accuracy than those to be tested. When laying out the test field, multiple measurements should be meaned. Care should be taken with atmospheric corrections and derived from meteorological readings at both the instrument and targets.

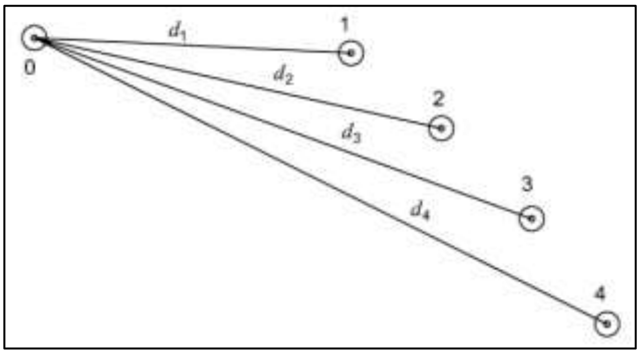

Figure 3: Simplified test field with four known distances. (International Organization for Standardization, 2012)

2.3.2. Measurements and calculation

To evaluate an instrument on the test field, each distance will be measured three times and meaned. Atmospheric corrections should also be applied. As with the full test procedure, specifics about instrument configurations and the application of corrections are unstated and therefore left to the operator. The measured distances are differenced with the known distances and their deviations checked.

Per ISO 17123-4, all differences “shall be within the specified permitted deviation $\pm p$ … for the intended measuring task.” The permitted deviation may be based on the user’s requirements for acceptable tolerance limits. If none are given,

$$p = |x_{measured} - x_{known}| \leq 2.5\ s$$

may be used, where s is the instrument’s standard uncertainty resulting from the full test procedure, as previously determined by the manufacturer or user. If the measured deviations are within the allowable tolerance, the instrument’s performance is accepted as satisfactory.

The deviations should also be checked for indications of systematic error. If all deviations have the same sign with roughly uniform magnitude, the instrument may have a zero-point error. If the magnitude of deviations increases with distance, the instrument may have a scale error. With additional investigation (and possibly repair service), such errors may be determined and corrected.

3 TESTING A LEICA TS60 TOTAL STATION ACCORDING TO ISO 17123-4

The guidelines of ISO 17123-4 were used to evaluate a Leica Geosystems Nova TS60 total station.

3.1. Full test procedure

3.1.1. Experimental test line

For the full test procedure, a test line was established at the National Geodetic Survey’s Testing and Training Center in Woodford, Virginia. Seven points were set with temporary monuments (nails in the ground) in flat to gently rolling terrain. An overall length of 600 meters was chosen, with nominal distances given in Table 2.

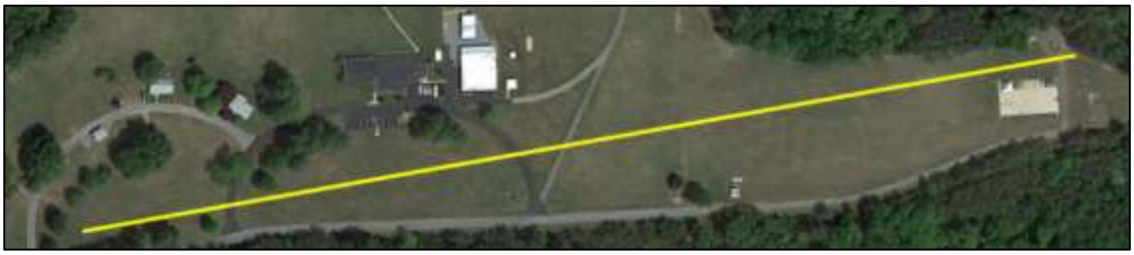

Figure 4: Experimental test line, with Point 1 at the east side of the NGS Testing & Training Center campus.

Distance segment	d_1	d_2	d_3	d_4	d_5	d_6
Distance (meters)	9.5	19.1	38.1	76.2	152.3	304.8

Table 2: Test line nominal horizontal distances. Overall length, d=600.0 meters.

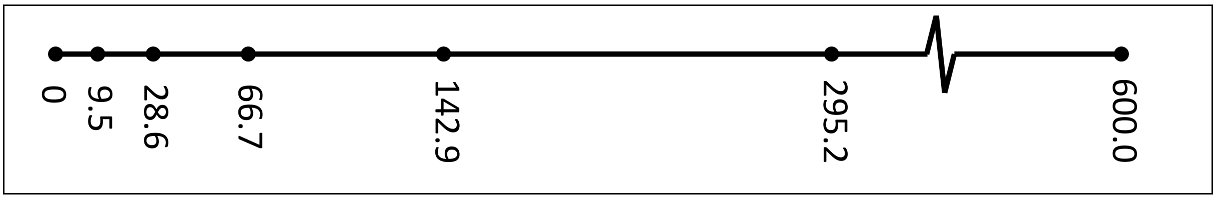

Figure 5: Nominal horizontal distances of points along the test line.

The seven points of the test line were arranged with a goal of distributing the measured distances across the total length. Figure 6 shows the frequency of inter-point segment distances. Distances are distributed from 0 to 600 meters, with a gap between about 300 to 450 meters.

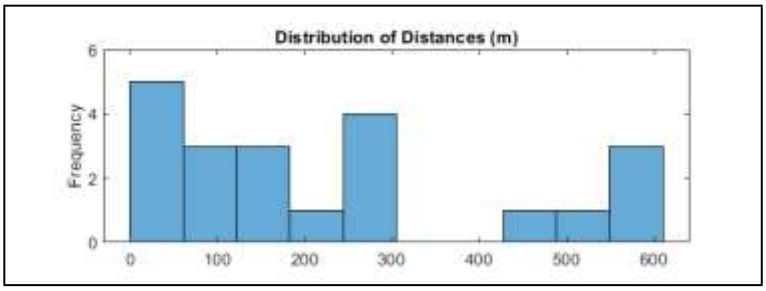

Figure 6: Distribution of test line distances.

In designing the test line, another goal was to disperse the sampling of the EDM instrument's unit length. The Leica TS60 has a periodically-recurring unit length of 1.5 meters. The distribution achieved by the selected nominal distances is shown in Figure 7. Suitable distributions would also be expected with other common unit lengths such as 2, 3, 4, or 5 meters.

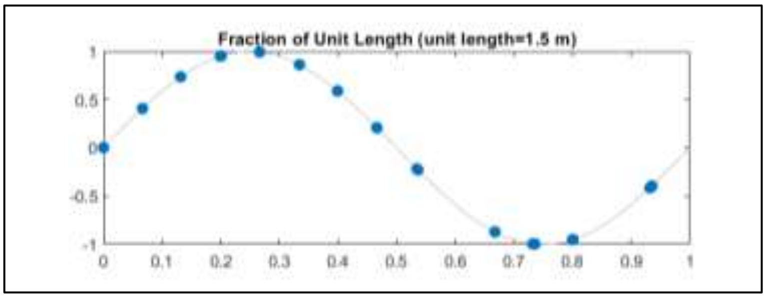

Figure 7: Sampling of the EDM instrument's unit length.

3.1.2. Measurements and calculation

The test line was used to evaluate the measuring uncertainty of a Leica TS60. The total station's electronic distance measuring component is coaxial with its telescope. Ancillary equipment included surveying tripods (Leica GST120-9 and Wild GST20 models), tribrachs (Wild GDF23 and GDF21), a retroreflector prism (Leica GPH1P), and a meteorological sensor (Kestrel 5000).

The TS60 features multiple measurement modes that balance precision and efficiency (see Figure 1). The ISO 17123-4 full test procedure was repeated multiple times with the following modes.

- “Highest precision” using 2 instrument faces. The expected population standard deviation of distance measurements was 0.6 mm, from the manufacturer’s specifications. Results presented below will focus on one of the samples taken in this mode.

- “Repeatedly & average” using 8 readings in 1 instrument face. The expected population standard deviation was 1 mm.

- “Once & fast” in 1 instrument face. The expected population standard deviation was 2 mm.

The points of the test line were occupied with tripods and tribrachs that were left in place throughout the testing period for forced centering. With the temporary monumentation, the true distances between points were not known or needed, so precise centering over the point was not required along the direction of the test line. Nevertheless, a specialized Leica NL collimator was used for centering to check that the instrument setup was on line in the transverse direction and to confirm occupation stability over time.

The instrument’s onboard software, Leica Captivate, was used to manage the field data, as is common for surveying projects. This included instrument/target heights, atmospheric corrections, and reductions of slope distances to horizontal. Meteorological readings of temperature, pressure, and relative humidity were taken at one end of each measured line. Formulas for the applicable systematic corrections may be found in the instrument user manual (Leica Geosystems, 2018). During measurement, the instrument was not shaded from the sun.

After completing all 21 unique combinations of points, the data was downloaded to a computer for further analysis. To perform the calculations described in ISO 17123-4, a program was developed in the MATLAB computing environment.

3.1.3. Results and statistical tests

For each dataset, the test line segment distances were estimated, along with the parameters of the instrument. The results from a measurement sample using the instrument’s highest precision, 2 face mode are shown.

$$\hat{x} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \\ d_6 \\ \delta \end{bmatrix} = \begin{bmatrix} 9.5011 \\ 19.0983 \\ 38.0992 \\ 76.2002 \\ 152.3019 \\ 304.8012 \\ -0.00045 \end{bmatrix} meters$$

$$\boldsymbol{s} = 0.64\, mm\,, \qquad \boldsymbol{\delta} = -0.45\, mm\,, \qquad \boldsymbol{s_\delta} = 0.29\, mm$$

Examination of the residuals from the least squares adjustment showed that the random error of the measurements had a roughly normal distribution.

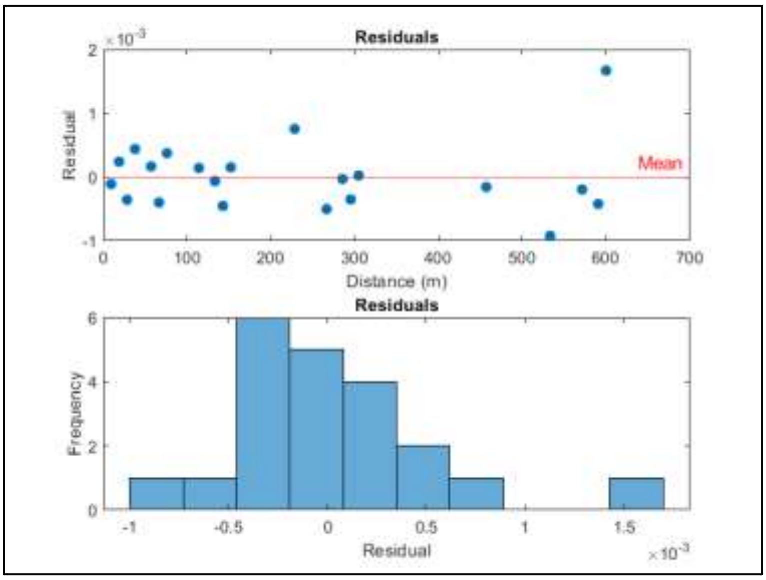

Figure 8: Residuals from adjustment of measured test line distances.

Question a: In the highest precision mode, the manufacturer's specification is $\sigma = 0.6\, mm$. Did the experimental results meet this level of precision?

$$s \leq 1.30\, \sigma \quad \Longrightarrow \quad 0.64 \leq 0.78$$

The test statistic is less than the critical value and the null hypothesis is accepted. At the 95% confidence level, the measurements on the test line confirm that the measuring uncertainty is within the tolerance defined by ISO 17123-4.

Question b: Another measurement sample was taken in the instrument's "once & fast" mode, resulting in an experimental standard deviation of $s = 0.82\, mm$, as compared to the "highest precision" mode result of $s = 0.64\, mm$. Despite the difference, is it possible that the two samples are drawn from the same population?

$$0.34 \le \frac{s^2}{\tilde{s}^2} \le 2.98 \quad \Longrightarrow \quad 0.34 \le \frac{0.64^2}{0.82^2} \le 2.98 \quad \Longrightarrow \quad 0.34 \le 0.62 \le 2.98$$

The test statistic falls within the range of critical values, so we cannot rule out the possibility that the highest precision and once & fast modes have equal variance.

Question c: The zero-point correction was computed as

$$\delta \pm s_\delta = -0.45 \pm 0.29\, mm.$$

Is this value significant, assuming the true value is $\delta_0 = 0\, mm$?

$$|\delta - \delta_0| \le 2.14\, s_\delta \quad \Longrightarrow \quad 0.45 \le 0.62$$

The test statistic is less than the critical value and the null hypothesis is accepted. Thus, we cannot rule out the possibility that the true correction is zero.

3.2. Simplified procedure

3.2.1. Experimental test field

The NGS Testing & Training Center has a permanently monumented test line for the calibration of EDM instruments. The 900-meter test line consists of five pillars with forced-centering adapters. Inter-point distances were previously established such that the horizontal inter-point distances are known very accurately, with error estimates of 0.1 millimeter (National Geodetic Survey, 2022).

$$x_{known} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \end{bmatrix} = \begin{bmatrix} 149.9993 \\ 299.9993 \\ 600.0010 \\ 899.9938 \end{bmatrix} meters$$

3.2.2. Measurements

Distance measurements were taken with the Leica TS60's highest precision mode in 2 faces. Meteorological readings were made at both the instrument and target and atmospheric corrections applied.

$$x_{measured} = \begin{bmatrix} \bar{d}_1 \\ \bar{d}_2 \\ \bar{d}_3 \\ \bar{d}_4 \end{bmatrix} = \begin{bmatrix} 149.9994 \\ 299.9995 \\ 600.0007 \\ 899.9936 \end{bmatrix} meters$$

3.2.3. Results

Differences of the measured and known distances were found as follows.

$$x_{measured} - x_{known} = \begin{bmatrix} +0.1 \\ +0.2 \\ -0.3 \\ -0.2 \end{bmatrix} mm$$

The manufacturer's specification of $\sigma = 0.6\ mm$ was used to develop the permitted deviation.

$$p = |x_{measured} - x_{known}| \leq 2.5\ \sigma \quad \Rightarrow \quad p \leq 1.5\ mm$$

All observed deviations are within the permitted deviation, therefore the instrument is considered satisfactory. Furthermore, the deviations vary in sign and magnitude. No systematic errors of zero-point or scale are apparent.

4 DISCUSSION

The results of the full and simplified test procedures show the different methods of instrument assessment possible with ISO 17123-4. The term "instrument" is used here to also include ancillary equipment and observing techniques. In the full test procedure, a relatively large dataset is used to determine the expected uncertainty of a single distance measurement at the 1-sigma, 68% confidence level. The zero-point correction, reflecting constant bias, is also determined. With statistical tests, the results can be evaluated for significance.

The full test procedure may be undertaken whenever the instrument's inherent level of random error needs to be established. An obvious instance of such a need is by the instrument manufacturer. By testing their instruments with the ISO standard, they may check the quality of production and classify their products according to achievable precision. An informed customer may then judge whether the model is likely to suit their requirements based on the instrument's specifications.

Manufacturers may be most likely to utilize the full test procedure, but nothing prevents a survey practitioner from performing the same. By doing so, the operator will find the parameters of their individual instrument "from scratch," rather than relying on values for an entire product line. These parameters (the uncertainty of distance measurements and the zero-point correction) could then be used as *a priori* values for subsequent work. The surveyor may also use the full test procedure to evaluate the influence of different observing techniques on the level of random error to determine the instrument's suitability for an intended measuring task.

As noted, the instrument uncertainty determined by measurements on a test line is a "black box" approach that does not distinguish between error sources, such as those stemming from variations of the measuring frequency. Figure 8 shows that the largest residuals of adjusted measurement occurred at the greatest distances. This suggests a distance-dependent component of uncertainty that is not adequately modeled by the single value of experimental standard deviation. Indeed, the manufacturer's full instrument specifications also quote a parts-per-million uncertainty that scales with distance. For identifying such errors (be they random or systematic), ISO 17123-4 briefly mentions the use of a frequency meter.

Using the full test procedure, a surveyor *can* compare their instrument's level of uncertainty to the manufacturer's predetermined value. However, the full test may not be necessary for this purpose. The simplified test procedure provides a less stringent option for merely answering the question "is the instrument performing within a specified tolerance: yes or no?" The tolerance can be developed from the manufacturer's specifications. By checking four measurements against known distances, the user will quickly obtain a sense for their instrument's condition. In the field test of the simplified procedure, all measurements were within the permitted deviation and no systematic errors were apparent. For many practitioners, this non-rigorous assessment may be all that is needed. Such a test could be undertaken upon delivery of an instrument or whenever a question arises about performance.

Of course, the simplified procedure requires reference distances that are already known. For these, a user may establish a new test line with special care or look to institutional infrastructure. The National Geodetic Survey provides publicly available test lines with known distances via its Calibration Base Line program (National Geodetic Survey, 2022). These test lines have the additional benefit of ties to length standards that promote accuracy, not just relative precision, providing another method for examining an instrument's scale.

5 CONCLUSION

International standard ISO 17123-4 is widely used by manufacturers as a measure of the precision achievable with EDM instruments. By becoming familiar with the procedures of the standard, instrument users will better appreciate their measuring capabilities and suitability for an intended task. In this experiment, the full and simplified test procedures were investigated and used to evaluate a Leica TS60 total station (along with associated equipment and techniques).

The objective of the full test procedure is to estimate the instrument's standard uncertainty and zero-point correction. To that end, a test line of seven points was established and all combinations of distances measured with redundant observations. In the instrument's highest precision mode, the resulting standard uncertainty was 0.64 mm, which reflects the measuring system's level of random error. This value was comparable to the manufacturer's specification, which quote ISO 17123-4.

The objective of the simplified test procedure is to check adherence to a certain level of precision, without a rigorous analysis of the instrument parameters. This test was conducted using an existing test line with known distances. The results showed that the instrument performed within the manufacturer's specification of 0.6 mm.

ISO 17123-4 is useful in that it provides guidelines to the surveying community for evaluating instruments and techniques under field conditions without the need for special equipment. While information is given about test line design, measurements, and analysis, the standard is notably flexible in terms of its implementation. If the procedures themselves are to be analyzed, areas of further research might include the number of test line points and comparisons to other methods of instrument evaluation. Still, the ISO standard is a valuable document that facilitates consistency among all parties that use EDM instruments.

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BIOGRAPHICAL NOTES

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