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Length standards on a reference wall for verifying the performance of laser trackers based on the recent ISO 10360-10

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Abstract
To complete the traceability of laser trackers along the traceability chain to SI units, the National Institute of Metrology (Thailand) provides length standards which are installed on a planar concrete wall of dimension 13 m × 4 m × 0.4 m (width, height, and thickness) on an isolated floor area of 225 m^2. The length standards are made from carbon fibre rods (carbon fibre-reinforced plastic, CFRP) with 1.5-inch threaded pin nests mounted at both ends. The arrangement of the rods at the wall is designed to fulfil the requirements for detecting length measurement errors of laser trackers according to the recent ISO 10360-10: 2021. By changing positions of the laser tracker, the three-dimensional measurement performance of the laser tracker in the specified measuring volume can be verified. To ensure that the length standards with a coefficient of thermal expansion (CTE) near zero are stable, the CFRP rods are fixed tension free on the wall to prevent thermal stress when the concrete wall undergoes thermal expansion. Long-term stability of the length standards on the reference wall has been studied under controlled laboratory conditions. Ambient temperature is recorded by 10 temperature sensors attached on the wall and 10 sensors around the working area. The length standards are calibrated from point-to-point of the central spherical mounted retroreflector (SMR), which sits on the SMR nests using a laser tracer. The measurement uncertainty is approximately 6.4 μm for the longest length of 8.25 m.

Keywords: Standard length, laser tracker, ISO 10360-10

1. Introduction

Laser trackers are instruments that measure three-dimensional coordinate positions in a spherical coordinate system where the measured data is the distance to the target such as a spherical mounted retroreflector, (SMR) along with two angles. The systematic errors in the measured data are caused by geometric and optical misalignments within the laser tracker due to imperfect assembly. The geometric errors and optical misalignments depend on the structural assembly of each laser tracker. Generally, sources of errors are steering turning mirror tilt and offset, laser beam tilt and offset, transit axis tilt and offset, and horizontal and vertical encoders eccentricity. For improving the accuracy of laser trackers, these errors need to be calibrated and compensated [1-3]. Calibrated test lengths are commonly used as reference artifacts to test the performance of laser trackers based on national and international standards. Physikalisch-Technische Bundesanstalt, PTB has established a reference wall for determining the accuracy of laser trackers according to the Verein Deutscher Ingenieure / Verband der Elektrotechnik, VDI/VDE 2617 Part-10:2011 guideline [4, 6]. This reference wall provides some excellent opportunities for evaluating the performance of laser trackers, for example through two diagonal reference lengths of around 12 m. However, the updated version of the International Organization for Standardization, ISO 10360-10:2021 [7] requires all test lengths to be between 2.25 m and 2.75 m and also specifies a slightly different arrangement of the test lengths, so that standard-compliant testing according to the current standard with this reference wall is currently not possible.

This paper presents establishing length standards which are installed on a planar concrete wall at Large Scale Laboratory, National Institute of Metrology (Thailand), NIMT. The arrangement of the reference lengths at the wall are designed to be sensitive to all know systematic error sources in various laser tracker designs following the recent ISO 10360-10:2021 [7]. The hanging mechanism of the length standards on the wall is designed tension free to prevent bending and thermal stress when the concrete wall undergoes thermal expansion. The reference lengths were measured monthly to determine the stability. The measurement uncertainty for the calibration is evaluated and discussed.

2. Reference wall design

The general concrete wall of dimensions 13 m × 4 m × 0.4 m was constructed on an isolated floor for preventing vibration from the surrounding structure. The wall was left to stabilize for about a year before the reference lengths were installed. The reference lengths were made from carbon fibre-reinforced plastic rods, (CFRP). The rods have a diameter of 50 mm, and a CFRP wall thickness of 1.8 mm including a thin glass layer on the rod's surface to prevent the ingress of moisture. The length of the CFRP rods is 2555 mm, but together with the fixtures the point-to-point distance between the nests for mounting the reflector amounts to 2.75 m in accordance with the ISO standard. CFRP was selected as material for the reference lengths because it is lightweight, has a coefficient of thermal expansion close to zero and it has a higher stiffness to weight ratio compared to other materials considered [8].

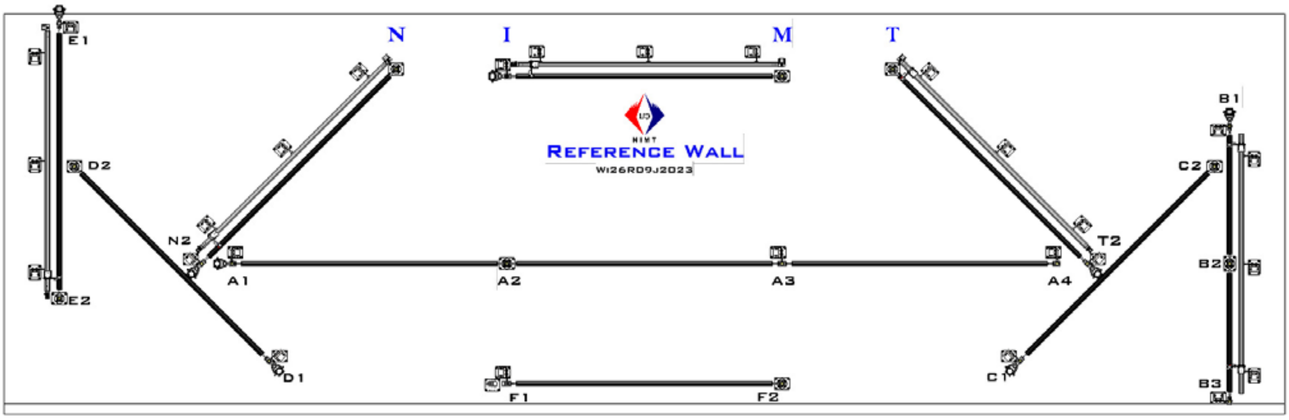

Figure 1. Overview of reference wall design.

Table 1 Arrangement of length standards and the core tests in the ISO 10360-10:2021.

Position number	Test length label	Distance from laser tracker	Azimuth angle	Core test
1	Any adjacent A	As close as practical	Any azimuth	Test for large horizontal angular error, offset between standing and transit axes.
2	B1–B3	As close as practical	Any azimuth	Test for large vertical angular error.
3 to 6	Any adjacent A	3 m	Any 4 azimuths, separated by 90°	Test for eccentricity in the horizontal angle encoder.
7	B1–B3	3 m	Any azimuth	Test for eccentricity in the vertical angle encoder.
8 to 11	C1–C2	3 m	Any 4 azimuths, separated by 90°	Test for squareness between the standing and transit axes.
12 to 15	D1–D2	3 m	Any 4 azimuths, separated by 90°	Test for squareness between the standing and transit axes.
16 to 19	Any adjacent A	6 m	Any 4 azimuths, separated by 90°	Test for combination of errors of the effect of beam offset, beam tilt, and encoder eccentricity.
20 to 23	Any adjacent A	As close as practical	Any 4 azimuths, separated by 90°	Test for beam offsets along the horizontal direction.
24	E1–E2	As close as practical	Any azimuth	Test for beam offsets along the vertical direction.
25 to 28	N2–N or T2–T	As close as practical	Any 4 azimuths, separated by 90°	Test for collimation error such as tilted beam in a laser tracker.
29	I-M	As close as practical	Any azimuth	Test for another component of the vertical angle encoder's eccentricity.
30 to 35	A1–A4	7 m – 9 m	Any azimuth	Test for low even order harmonics in the horizontal angle encoder's scale.
36 to 40	Five ranging test distances at any azimuth			Test for ranging error in a laser tracker.
41	Synthetic length test at any azimuth			Test for validation the temperature compensation capability of a laser tracker.

2.1. Arrangement of length standards

An overview of the new reference wall at NIMT is shown in figure 1. It is a planar array of 21 magnetic nests arranged in 9 differently positioned/aligned lines. The nominal distance between neighbouring nests is 2.75 m, with the longest length being 8.25 m (A1–A4). An exception is line B, where the distance between neighbouring nests is 1.375 m, so that the distance B1–B3 amounts to 2.75 m. Table 1 shows the core tests and positions for the measurements according to ISO 10360-10:2021 [7, 9]. Test length positions 30 to 35 are chosen by the user to reflect common measuring conditions. On the designed wall, the test for horizontal encoder errors can be performed with a test length of 8.25 m and with a distance of 8 m from the laser tracker origin, at azimuth angles of 0°, 30°, 60°, 90°, 120°, and 150°. Test lengths at positions 36 to 40 are performed on a 40 m long interferometry railway and are not explained in this paper. The designed test length labelled F1–F2 offers the possibility for an optional test of another component of the vertical angle encoder's eccentricity. It is horizontal, centred directly below the laser tracker itself as much as possible. In addition, the test lengths labelled B1–B2–B3 are also designed for location error tests (two-face tests) [7]. For the test according to the positions 1, 3 to 6, 16 to 19, and 20 to 23, any of the test lengths labelled A1–A2, A2–A3, or A3–A4 can be used.

2.2. Hanging mechanism

Since the CFRP rods are very lightweight (approximately 0.75 kg/m) the mechanism for mounting them on the reference wall was designed as simple as possible. One end is fixed on the concrete wall by a steel post, and the other end is hung by a pair of thin brass sheets as shown in figure 2. For the reference lengths from A1 to A4 the fixed point is at position A2 while the remaining positions are hung. For Line B, the position B2 is a fixed point while B1 to B3 are also hung. A pair of thin brass sheets, each approximately 1 mm thick, is used as a suspension between the CFRP rod and the parts that are fixed on the concrete wall. The brass alloy has a high tensile strength and is flexible without losing strength. As a result, this hanging mechanism is tension free to prevent thermal stress and allows a slight bending when the concrete wall undergoes thermal expansion while the reference lengths remain constant. The tilted mirror is also mounted in line with the reference length for the alignment of the laser beam during the length calibration.

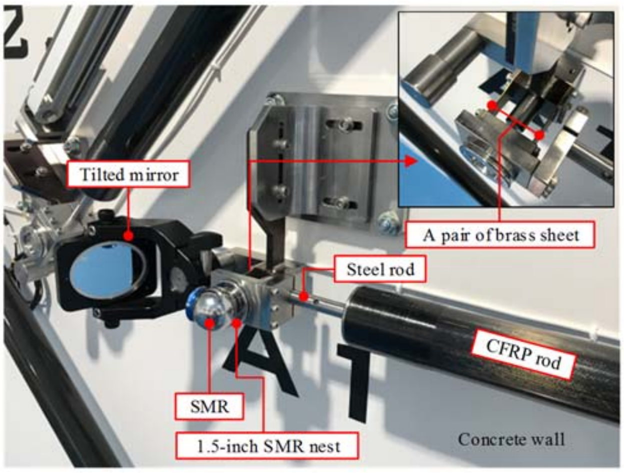

Figure 2. Length standard hanging mechanism.

3. Reference lengths calibration

Before the reference wall can be used to verify laser trackers, it is necessary to calibrate the distances of the test lengths with the labels shown in table 1 to provide the reference lengths for the comparison and therefore to establish the measurement traceability. The point-to-point distances are measured by a Laser Tracer, (LT, a self-tracking laser interferometer).

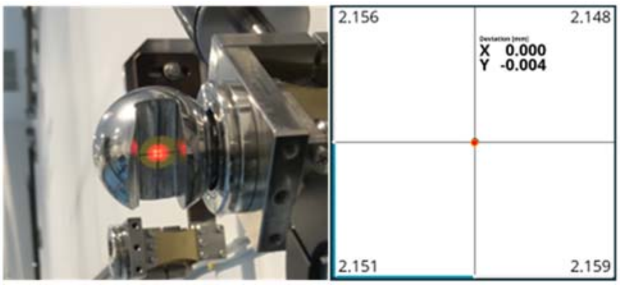

Figure 3. Rough alignment (left) and fine alignment (right) of laser beam before performing the measurement.

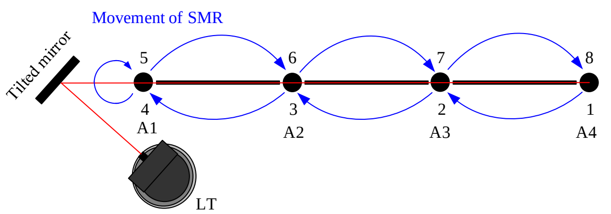

Figure 4. Procedure for one measurement cycle in case of 4 nests.

The laser beam is aligned at the centre of a SMR from the first to the last nest of the reference length to be measured. At the beginning, a rough alignment is performed on a spherical target, then the laser beam is observed on the LT's built-in position sensing device, (PSD) on the software screen for fine adjustment. Figure 3 shows an example of laser beam alignment. The angle between laser beam and measured line is approximately aligned to be within 10 arcsecond. The purpose of aligning the laser beam as parallel to the measured line as possible is to avoid cosine errors, and on the other hand to achieve the best reproducibility. To cancel out hysteresis effects, forward and reverse measurements are performed as shown in figure 4. The length measurement starts at the end opposite the tilted mirror. The SMR has then to be moved to the next position without breaking the beam. The measurement points are detected and recorded automatically by detecting the laser beam standstill. The measurement procedure is repeated at least 5 times resulting in 10 values for each distance.

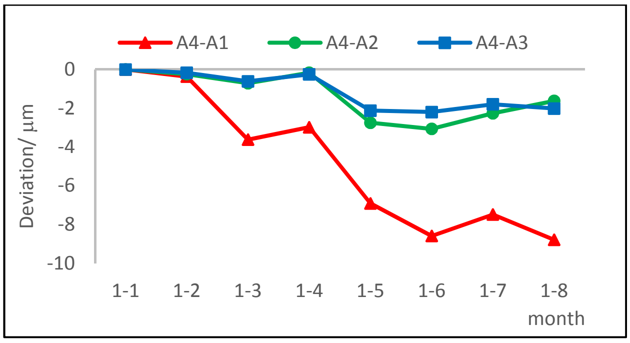

Figure 5. Stability of reference length line A.

Long-term stability of the length standards on the reference wall have been studied under controlled laboratory conditions (20 ± 1) °C, (50 ± 10) %RH. It is measured monthly to determine the deviations compared with the first measurement. For the longest length of line A, results and discussion are presented in this paper. Figure 5 shows a stability graph of the lengths of the lines A4–A1 (8.25 m), A4–A2 (5.50 m), and A4–A3 (2.75 m). The maximum deviation is approximately 9 µm, when compared with the first measurement results, which was measured immediately after the installation was completed. The lengths became more stable after five months, after which only a deviation of around 3 µm was observed and apparently tend to become more stable over time. From the graph, it is clear that the longer length has higher drift than the shorter lengths.

In addition, the reference lengths of line A were also measured by a laser tracker used in interferometer mode. The alignment and measurement were carried out in the same way as when using a LT. The deviations between both measuring systems were 0.9 µm, 1.1 µm, and 0.8 µm for A4–A1, A4–A2, and A4–A3, respectively. However, when using a laser tracker, the measurement uncertainty is larger than using a LT because of the limited accuracy compared to the LT.

4. Measurement uncertainty

The measurement uncertainty was evaluated in accordance with the guide to the expression of uncertainty in measurement, (GUM) [10]. The contributions can be separated into two groups. One comprises the absolute uncertainties and the other contains relative uncertainties, the latter depending on the measured length, L as shown in table 2. All standard uncertainties are assumed to be uniformly distributed except for the uncertainty of the LT that is normally distributed. The uncertainty due to the repeatability of the measurement is evaluated from the maximum range of 5 repetitions (i.e. from 10 values for each length) for which the maximum range is approximately 2 µm. The expanded uncertainty of the LT is specified by the manufacturer as 0.2 µm + 0.3 µm/m × L, where the first term is considered as an absolute uncertainty while the second term is relative to length. The resolution of the LT system is 10 nm which corresponds to a standard uncertainty of 3 nm due to semi-range limit. The SMR used in the measurement has the centring accuracy of 2.54 μm (manufacture specification). The roundness of the SMR was calibrated and resulted in a value of 0.78 μm ± 50 nm. The total runout of magnetic nests is 1 μm (manufacturer specification). In order to estimate the influence of these three error sources on the measured lengths, repeat measurements were carried out, whereby the reflector was repositioned in the nest each time and also rotated around the beam axis. The results are shown in figure 6. The range of the repeated measurements was about 1.6 μm, leading to a standard uncertainty of 0.46 μm.

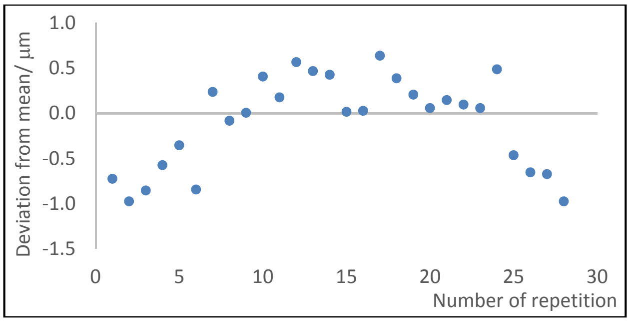

Figure 6. The influence of the SMR and magnetic nests on the measured lengths.

The reference lengths have steel rods with 100 mm length on both ends of the CFPR rod for mounting on the reference wall. The coefficient of thermal expansion, (CTE) of the steel rods is assumed to be 11.5×10^{-6} K^{-1}. This contributes with an absolute uncertainty of approximately 0.55 μm for two steel rods when the temperature of the steel rods deviates from the reference temperature (20 °C) by 0.24 K. The laser beam was aligned better than 10 arcsecond for the longest measuring length. This is approximately corresponding to a standard uncertainty of 0.02 μm for the longest length.

Table 2 Source uncertainties of measurement.

Uncertainty source	Standard uncertainty
Absolute uncertainty	
Repeatability	0.58 μm
Uncertainty of LT	0.10 μm
Finite resolution of LT	0.003 μm
Influence of SMR and magnetic nests	0.46 μm
Uncompensated CTE of steel rods	0.55 μm
Error due to laser beam alignment	0.02 μm
Combined absolute uncertainty	0.93 μm
Relative uncertainty	
Uncertainty of LT	$1.50 \times 10^{-7}L$
Refractive index of air compensation	$1.27 \times 10^{-8}L$
Air temperature variation (0.45 K)	$2.48 \times 10^{-7}L$
Variation of air humidity (6.6 %RH)	$3.24 \times 10^{-8}L$
Variation of air pressure (50 Pa)	$7.75 \times 10^{-8}L$
Uncompensated CTE of CFRP	$8.83 \times 10^{-8}L$
Combined uncertainty	$3.15 \times 10^{-7}L$

The relative uncertainties which relate to the measuring lengths are the relative uncertainty of the LT, refractive index of air compensation, and uncompensated CTE of CFRP. The expanded measurement uncertainty of the LT is given by the manufacturer as $3 \times 10^{-7}L$, which corresponds to a standard uncertainty of $1.50 \times 10^{-7}L$. The uncertainty of the compensation due to the refractive index of air depends on the fluctuation of the ambient condition such as air temperature, air humidity, and air pressure during measurement, and also on the accuracy of the associated sensing devices. However, only variations of the ambient conditions are taken into account as contributions to the uncertainty as they are dominant compared to the accuracy of the used sensing devices. Under controlled laboratory conditions, the maximum variation during the measuring time is 0.45 K, 6.6 %RH, and 50 Pa for air temperature, air humidity, and air pressure, respectively. The maximum temperature deviation of the CFRP rods from the reference temperature was measured as 0.51 K. This yields a standard uncertainty of 8.83×10^{-8} L where the CTE of CFRP rod is estimated as -0.3×10^{-6} K^{-1} (manufacturer information). According to the uncertainties in table 2, the expanded measurement uncertainties are 2.8 μm, 4.4 μm and 6.4 μm for the length standards of 2.75 m, 5.50 m, and 8.25 m length, respectively.

5. Conclusion

With the newly built reference wall, the National Institute of Metrology (Thailand) can offer interested users from industry the possibility of testing the performance of their laser trackers by means of comparative measurements with calibrated reference lengths and therefore enables the traceability of laser trackers to be completed along the traceability chain to SI units. The expanded measurement uncertainty for the calibration of the reference lengths is approximately 6.4 μm for the longest length of 8.25 m.

The arrangement of the reference lengths at the wall are designed according to ISO 10360-10:2021 and are sensitive to all known systematic error sources in various laser tracker designs. By varying the positions of the laser tracker, this reference wall enables to verify the three-dimensional deviation behaviour of the laser tracker in the specified measuring volume.

Monthly measurements under controlled laboratory conditions using a LT show good long-term stability of the length standards with a drift of the measured lengths of approximately 3 μm in a period of 3 months starting from the fifth month after completion of the installation. Since this is small compared to the maximum permissible errors of typical laser trackers, it is not necessary to calibrate the reference lengths each time when performing a test of a laser trackers, which saves a lot of working time.

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