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Determination of Laser Tracker Angle Encoder Errors

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Abstract. Errors in the angle encoders of a laser tracker may potentially produce large errors in long range coordinate measurements. To determine the azimuth angle encoder errors and verify their values stored in the tracker's internal error map, several methodologies were evaluated, differing in complexity, measurement time and the need for specialised measuring equipment. These methodologies are: an artefact-based technique developed by NIST; a multi-target network technique developed by NPL; and the classical precision angular indexing table technique. It is shown that the three methodologies agree within their respective measurement uncertainties and that the NPL technique has the advantages of a short measurement time and no reliance on specialised measurement equipment or artefacts.

1 Introduction

Results obtained at the National Physical Laboratory (NPL) from measurements of azimuth angle encoder errors of a laser tracker are presented and compared with the manufacturer's internally stored error values.

The metrological performance of a laser tracker is influenced by many factors including: compensation for atmospheric effects, thermal expansion of the instrument and its mount, thermal distortion of the work piece or artefact being measured, the wavelength of the laser radiation, the internal alignment of the gimbal axes and the linearity and alignment of the internal angle encoders.
Errors in the horizontal and vertical angle encoders of the tracker may potentially produce large errors in measurements made by the tracker. These angular errors result from spacing errors in the gratings of the angle encoders and also centring errors of each encoder relative to its rotary mechanical axis.

To evaluate the horizontal angle encoder errors and verify the values stored in the tracker's error map, several methodologies were used, differing in complexity, measurement time and the need for specialised measuring equipment. The horizontal angle encoder calibration methodologies used were: the National Institute of Standards and Technology (NIST) technique [1], the NPL network technique [2] and the precision angular indexing table technique.

The NIST technique relies on using the tracker to measure a fixed horizontal length whilst the tracker base is rotated to different azimuthal orientations. The NPL network technique involves the measurement of a network of targets from independent tracker positions/rotations. The precision angular indexing table technique is considered to be the reference or gold standard as it compares the rotation of the azimuth encoder with that of a calibrated precision indexing table.

A brief description of each methodology is given and results from the different techniques are compared and discussed. Prior to making measurements with the three techniques, the internal azimuth encoder error map of the tracker was turned off to expose the encoder errors. All the measurement data were acquired using Spatial Analyzer [3].

2 The NIST technique

The NIST technique measures a fixed length placed at different azimuthal positions of the tracker, in a manner similar to the horizontal length tests in the ASME B89.4.19 standard [4]. Unlike the methodology described in [1], where the length is realised using two targets on separate stands, our methodology following the NIST technique, realises the length using two target nests rigidly fixed on a low expansion, stiff, carbon fibre artefact with a nominal target nest separation of 2.318 m; the actual target separation was calibrated before starting the measurements. This achieves better stability compared to the two stands setup and makes use of the already available calibrated artefact.

We performed the NIST technique by setting the tracker at the maximum achievable range from the artefact in order to achieve better sensitivity [1]; in our laboratory

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this range was limited to 6 m. The length between the two nests on the artefact was repeatedly measured in interferometer (IFM) mode (to give more accurate distance measurement). After each set of five repeated length measurements, the tracker base was incrementally rotated by 20° until a total 540° rotation had been achieved. The length measurements, performed initially in front-face mode were then repeated in back-face mode; the entire process took four hours. For each length measurement, angular errors in the tracker-measured target locations (one at each end of the artefact) lead to errors in the calculated length of the artefact.

A non-linear optimisation algorithm was then used to fit the apparent length errors to a geometric model of the NIST setup and obtain the Fourier components of the angle encoder errors, $e(\varphi)$, according to the following equation:

$$e(\varphi) = \sum_{i=1}^{n} a_i \cos(i\varphi) + \sum_{i=1}^{n} b_i \sin(i\varphi) \qquad (1)$$

where φ is the azimuth angle measured by the tracker and a_i and b_i are the Fourier coefficients. In the following results n was set to three. Small differences between front face and back face results were removed by averaging to obtain the final answer. The uncertainties are derived from the covariance matrix of the estimated coefficients.

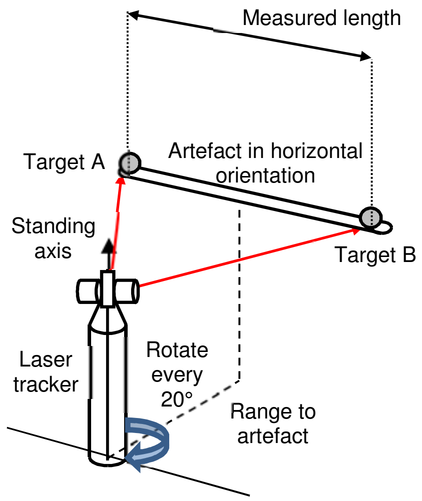

Figure 1. Illustration of the NPL implementation of the NIST technique

An illustration of our realisation of the NIST experiment is shown in Figure 1. An example of the estimation of the azimuth angular errors using the NIST technique together with their k = 2 uncertainties is shown in Figure 2 and compared with the manufacturer's internal azimuth error map. It should be noted that the values stored within the manufacturer’s error map are those which were determined at the time that the tracker was assembled and that these values have not been changed since then. They are used as a guide only and differences between the different technique results and the internal error map may be due to a change in the true error values over time.

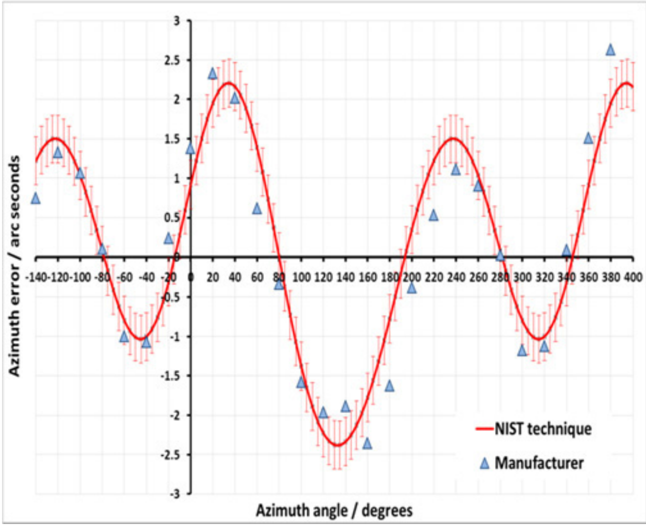

Figure 2. Azimuth encoder errors obtained using the NIST technique, compared with the manufacturer supplied values

3 The NPL network technique

The NPL network test [2] involves the measurement of a network of fifteen to eighteen targets from independent tracker positions/rotations in front-face and back-face modes. In-house developed software uses the collected network of data to solve a nonlinear optimisation problem to obtain the correct positions of the tracker, the location of target nests and all the tracker error correction factors including angle encoder errors and geometrical misalignments.

The duration of an NPL test involving three tracker locations and 18 targets, with some targets measured more than once to check for repeatability, is approximately one hour. An illustration of the NPL network is shown in Figure 3. The coefficients of the azimuth encoder errors obtained from the NPL technique are as in equation (1). The uncertainties are derived from the covariance matrix of the estimated coefficients.

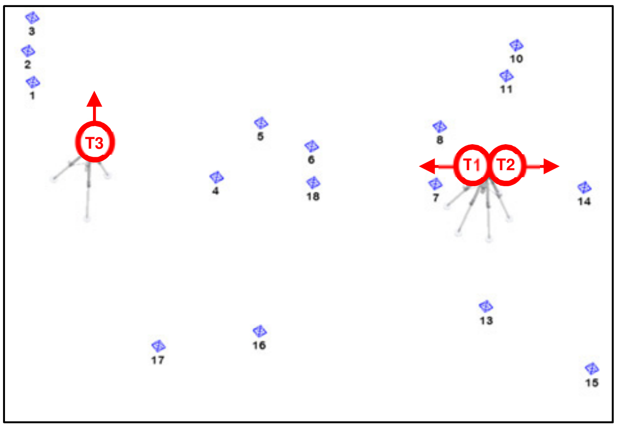

Figure 3. Illustration of an NPL network test showing the location of the 18 targets and the three tracker positions

An example of the estimation of the azimuth encoder errors using the NPL technique together with their k = 2 uncertainties is shown in Figure 4.

The advantages of the NPL technique are that no specialised equipment (*e.g.* precision angular indexing table or an artefact) is needed and that all error parameters are determined simultaneously together with their uncertainties.

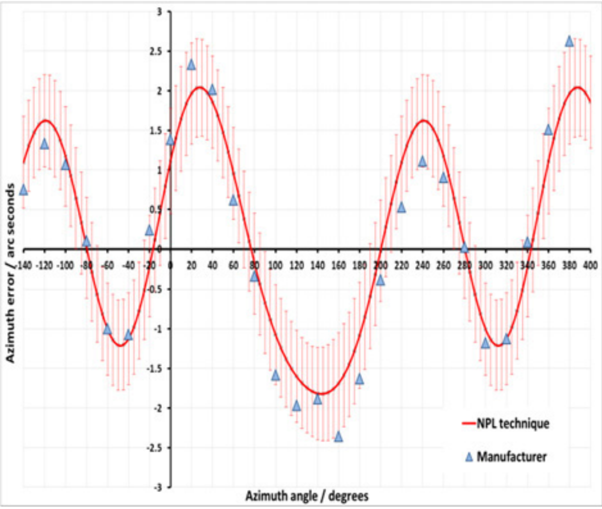

Figure 4. Azimuth encoder errors obtained using the NPL technique, compared with the manufacturer supplied values

4 The angular table technique

This technique is considered as the reference or gold standard to evaluate/verify the errors of a laser tracker azimuth angle encoder. The setup used for this evaluation is similar to that reported in [5]. The tracker was mounted on top of a previously calibrated precision angular indexing table.

The table used for the measurements is an eight inch diameter precision angular indexing table manufactured by Moore Special Tool Co. Inc. USA. The table has 2160 serrations enabling angular increments of 10 minutes of arc to be indexed. Disengagement of the teeth is effected by means of a hydraulic lifter. The calibration certificate of the Moore table shows that departures from the nominal angular settings have a maximum of 0.04 arc second and hence are considered negligible. The expanded uncertainty (k = 2) has been calculated to be $\pm$ 0.05 arc second.

Levelling of the tracker was achieved using a tilting table mounted on top of the indexing table - the vertical rotation axis of the tracker was aligned parallel with the table rotation axis to within ~ 0.001 degree. The target nest was mounted on a vertical micrometer stage which was then adjusted until the elevation angle of the target, as measured by the tracker was 90°. The tracker was approximately centred on the table by eye - the mounting eccentricity error is removed in the data processing.

The table was rotated in 20° increments and at each orientation of the table the position of the target was measured five times. After completing the measurements in front-face mode, they were then repeated in back-face mode. A single set of table measurements at 20° interval in front-face and back-face modes, takes approximately one and half hours.

A geometric model of the precision angular indexing table and the tracker and a non-linear optimisation algorithm are used to estimate the angular eccentricity errors resulting from the table-tracker misalignment and to compensate for them. The geometric model used to evaluate the table/tracker angular eccentricity error is shown in Figure 5. The setup used for measurements is shown in Figure 6.

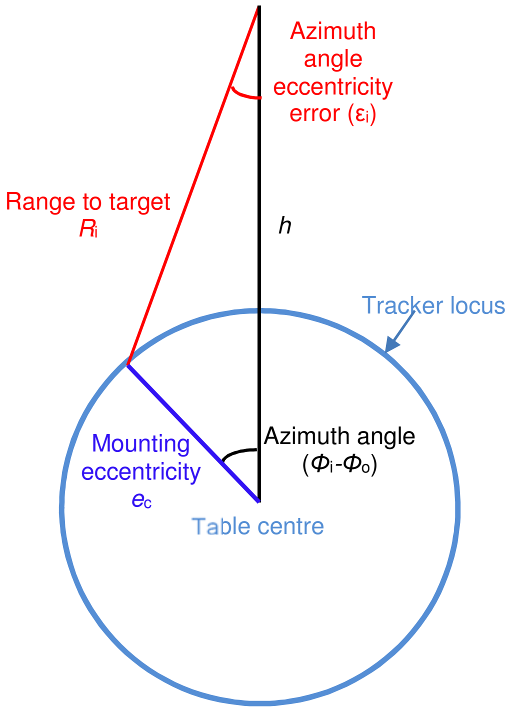

Figure 5. Geometric model used to compensate for tracker-table mounting eccentricity

The interferometrically measured range to target data R_i is used to fit the following equation using a non-linear optimisation algorithm:

$$R_i = \sqrt{h^2 + {e_c}^2 - 2\,h\,e_c\cos(\Phi_i - \Phi_o)} \quad (2)$$

The non-linear optimisation algorithm estimates the mounting eccentricity e_c, the offset angle Φ_o and the distance h. The angular eccentricity error at each indexing table rotation angle, ε_i, is then calculated using the following equation:

$$\varepsilon_i = sin^{-1}(\frac{e_c}{R_i} sin(\Phi_i - \Phi_o)) \quad (3)$$

The angular encoder error is calculated by subtracting the measured azimuth angle from the indexing table angle and ε_i. The uncertainty contributions are derived from the covariance matrix of the estimated coefficients, the standard deviation of the repeated measurements and the table calibration certificate. Finally, the obtained angular errors are then fitted to the model of equation (1) for comparison with the other techniques. Figure 7 shows the azimuth error obtained from the precision index table and the corresponding Fourier series fit together with k = 2 uncertainties.

Figure 6. Setup used for the precision indexing table measurements

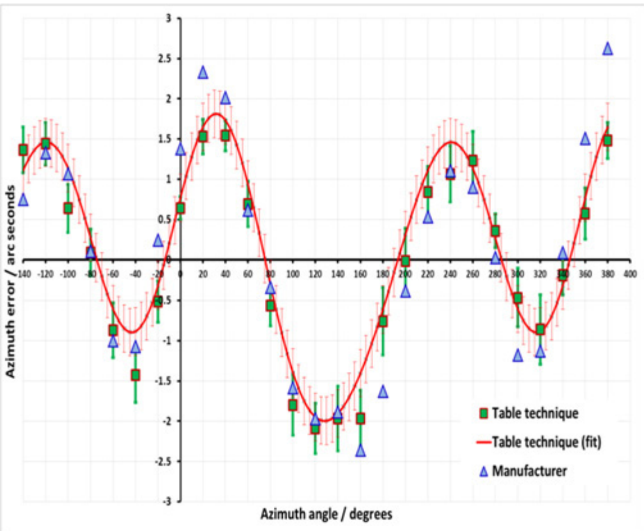

Figure 7. Azimuth error and function fit using the angular table

5 Comparison of results and conclusions

Figure 8 summarises the results obtained from the three techniques. The maximum difference between the estimations of the azimuth error is less than 0.4 arc second which results in a lateral error of less than 20 micrometres at a range of ten metres. It is shown that all three techniques agree within their respective k = 2 uncertainties. The NPL network technique has the advantages that it does not need any specialised equipment such as an artefact or a precision index table and that it offers the shortest measurement time.

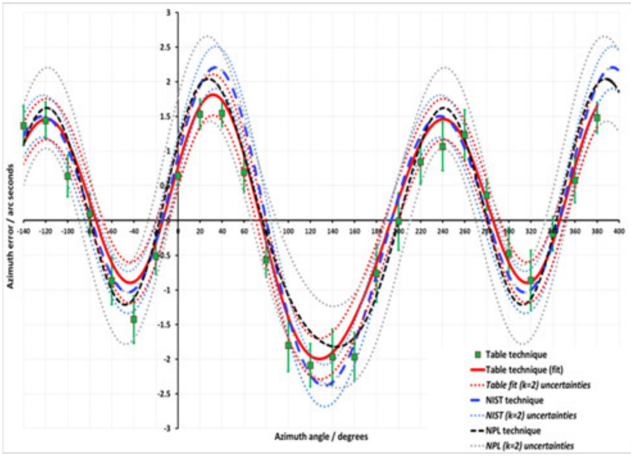

Figure 8. Summary of all the results

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