National Physical Laboratory

NPL REPORT ENG 30

Validation of the network method for determination of laser tracker alignment errors: NIMTech deliverable 3.7

Ben Hughes, Alistair Forbes, Karim Nasr, Wenjuan Sun, Dan Veal

January 2011

National Measurement System

Report ENG 30

Validation of the network method for determination of laser tracker alignment errors: NIMTech deliverable 3.7

Ben Hughes, Alistair Forbes, Karim Nasr,
Wenjuan Sun, Dan Veal

Engineering Measurement Division
National Physical Laboratory

ISSN 1754-2987

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of NPLML by Dr Andrew Lewis, Assistant Knowledge Leader, Engineering Measurement Division

CONTENTS

1 SCOPE

This report fulfils deliverable D3.7 - Report on the evaluation of a multi-sensor network validation experiment, of the iMERA Plus project New Industrial Metrology Techniques (NIMTech). The report describes the verification of the procedure for calibration of laser tracker alignment errors based on a multi-sensor network approach described in NIMTech deliverable report D3.1(1).

2 INTRODUCTION

NIMTech deliverable report D3.1(1)[1] describes an experimental procedure for calibration of laser tracker alignment errors using a multi-sensor network measurement approach. In this report we present an experimental verification of this procedure and hence of the multi-sensor network methodology.

The network approach to laser tracker calibration involves measuring the coordinates of a number of fixed points using the laser tracker. The same points are measured from several different locations. The results of these measurements are then processed by fitting a mathematical model describing the experimental set-up (tracker locations and orientations, target locations) and the errors of the laser tracker using a least-squares parameter estimation method.

To verify this approach, the performance of an API T3 laser tracker has been verified to the ASME B89.4.19 standard using correction parameters obtained using the network method and these results compared with a similar ASME B89.4.19 test performed using the manufacturer’s calibration data.

The model describing the alignment errors of the laser tracker used for this work[2] was adapted from that described previously[1,3] into a more generic form.The new model is described briefly in section 3. Section 4 contains results obtained from a network test, and section 5 describes briefly the ASME B89 test and the results obtained.

3 LASER TRACKER ERROR MODEL

3.1 LASER TRACKER MISALIGNMENTS

An ideal laser tracker - one that is based on the “theodolite-like” design, with the interferometer located on the gimbal – can be represented schematically by the set-up in Figure 1 (left). The standing and transit axes are orthogonal and co-planar, the laser beam intersects both axes at a centre point and radiates outward with no angular offset. Additionally, the elevation and azimuth encoders are perfectly centred on and perpendicular to the transit and standing axes with no distortions or scale errors.

In reality, all laser trackers are subject to miss-alignments and offsets and other mechanical imperfections as a result of manufacturing tolerances. Thus a more realistic geometry is similar to that shown in Figure 1 (right). The standing, transit, and laser beam axes are no longer orthogonal and intersecting; both angle encoders have scale errors and distortions; and the laser beam does not radiate from the intersection of the axes and has and has an angular offset so that it is no longer normal tot eh transit axis. These mechanical imperfections lead to systematic errors in the range and angle readings, which would result in measurement errors if left uncorrected. In practice, laser tracker controllers implement software correction of the raw sensor data to provide the user with accurate measurement data. This correction is based on a model of the error sources and the results of measurements of the model parameters stored in the controller. The objective of the calibration procedure under test in this experiment is to determine the parameters of the model and their associated uncertainties.

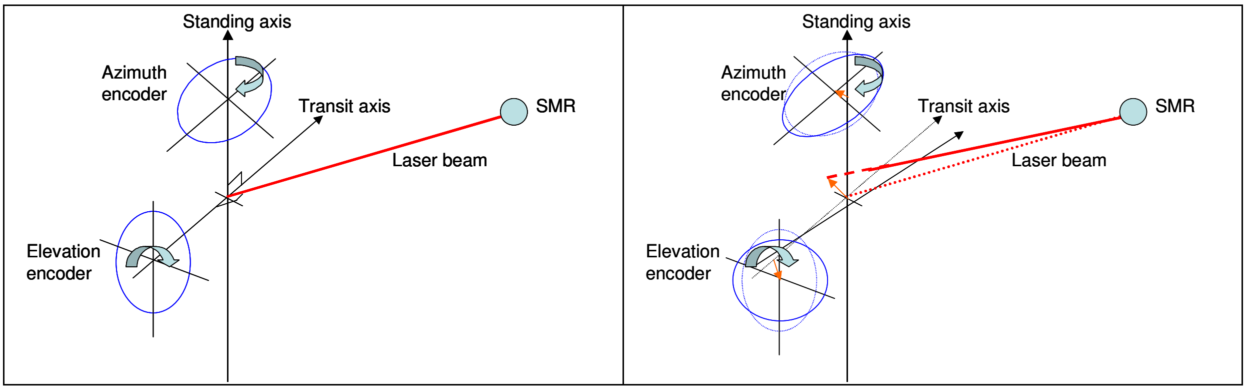

Figure 1 Schematic comparison of idealized tracker (left) and the misalignment errors of an actual, imperfect tracker (right). The error parameters in Table 1 quantify these and other errors empirically.

While the manufacturer specific implementations of the basic tracker mechanism may vary, trackers of the theodolites-like design will always be subject to these same fundamental types of misalignments, allowing the error model description of section 3.2 to be applicable to any laser tracker of this class of laser tracker, including current models from Faro, API and the latest Leica AT401. Older Leica models do not conform to this model.

3.2 NPL ERROR MODEL

The model used for this experimental validation is different from that presented previously, in D3.1(1), but it represents the same physical miss-alignments and offsets.

The NPL model is:

$$x_i = \mathrm{b}\left(\theta_i^*, \phi_i^*, \mathrm{h}\right) + d_i^* \mathrm{n_B}\left(\theta_i^*, \phi_i^*, \mathrm{h}\right)$$

$$d = (1+\mu)d^* + \lambda + e_D$$

$$\theta = \theta^* + a_{A,0} + \sum_{q=1}^{n_Q}\left[a_{A,q}\cos q\theta^* + b_{A,q}\sin q\theta^*\right] + e_A$$

$$\phi = \phi^* + a_{E,0} + \sum_{q=1}^{n_Q}\left[a_{E,q}\cos q\phi^* + b_{E,q}\sin q\phi^*\right] + e_E$$

where x_i describes the target coordinates in terms of laser beam start position, **b**, direction, $\mathbf{n_B}$, which depend on error parameters, **h**, and length d_i^*. The values d, θ and ϕ are observed values of range, horizontal, and azimuth angles and d^*, θ^* and ϕ^* are true values of the measurands.

Table 1 - Error parameters of the model and their physical origin.

i	Parameter	Description	Type
-	λ	range offset	distance
-	μ	scale factor for range	value
1	e_x	transit (*E*) axis offset from standing (*A*) axis	distance
2	$b_{y,0}$	beam offset (*y*-direction) from origin	distance
3	$b_{z,0}$	beam offset (*z*-direction) from origin	distance
4	α	transit axis angle in *yz*-plane	angle

5	γ	beam axis angle in *xy*-plane	angle
6	$a_{A,1}$	azimuth scale error, first order	angle
7	$b_{A,1}$	azimuth scale error, first order	angle
8	$a_{A,2}$	azimuth scale error, second order	angle
9	$b_{A,2}$	azimuth scale error, second order	angle
10	$a_{E,0}$	elevation angle offset	angle
11	$a_{E,1}$	elevation scale error, first order	angle
12	$b_{E,1}$	elevation scale error, first order	angle
13	$a_{E,2}$	elevation scale error, second order	angle
14	$b_{E,2}$	elevation scale error, second order	angle

4 EXPERIMENTAL RESULTS

A network of 15 targets was measured from 5 different tracker locations. The network is shown in elevation and plan views in Figure 2 and Figure 3.

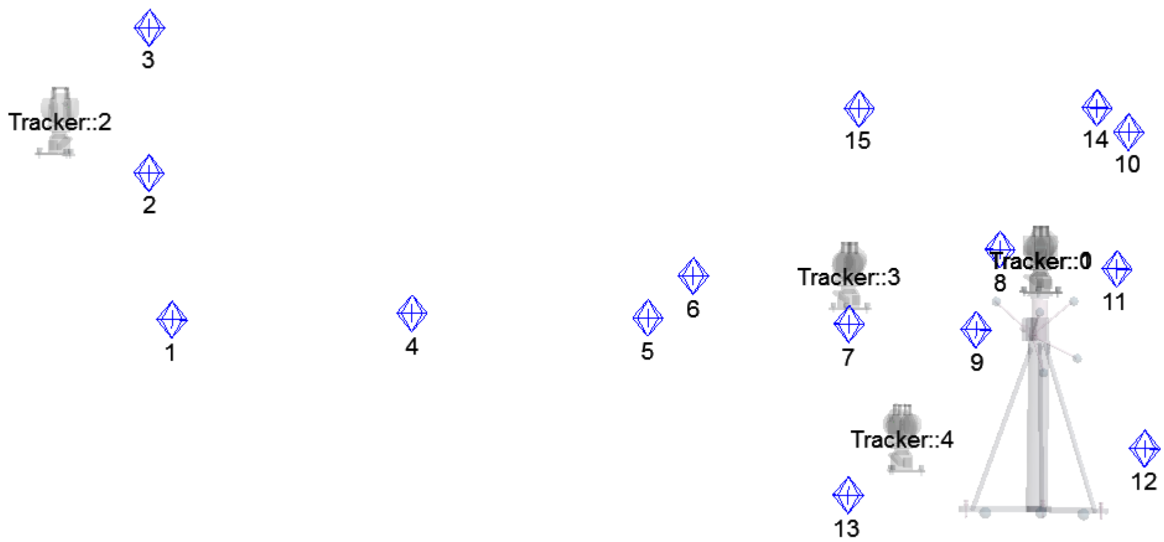

Figure 2 - Network layout - elevation view. Blue diamonds represent target locations.

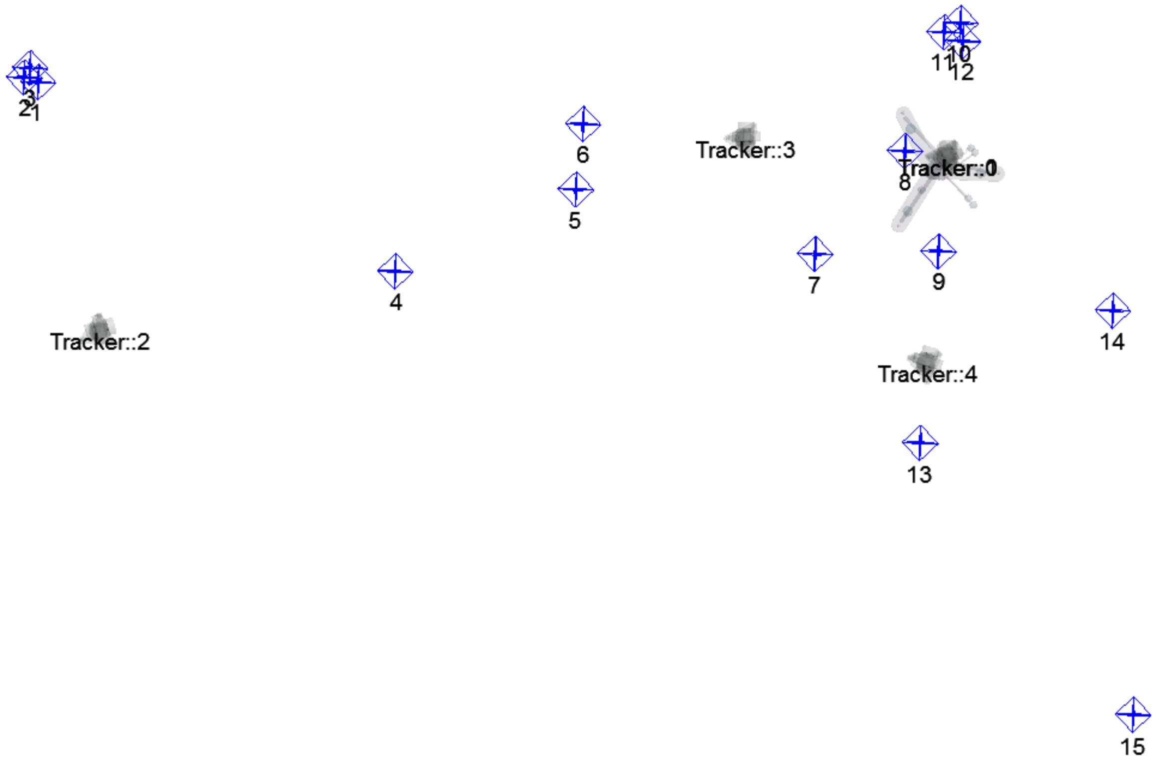

Figure 3 - Network layout - plan view. Tracker positions 0 and 1 are co-located.

The target points were chosen to cover a large angular range and distance range relative to the tracker. Figure 4 and Figure 5 show the relative positions of the targets with respect to the tracker.

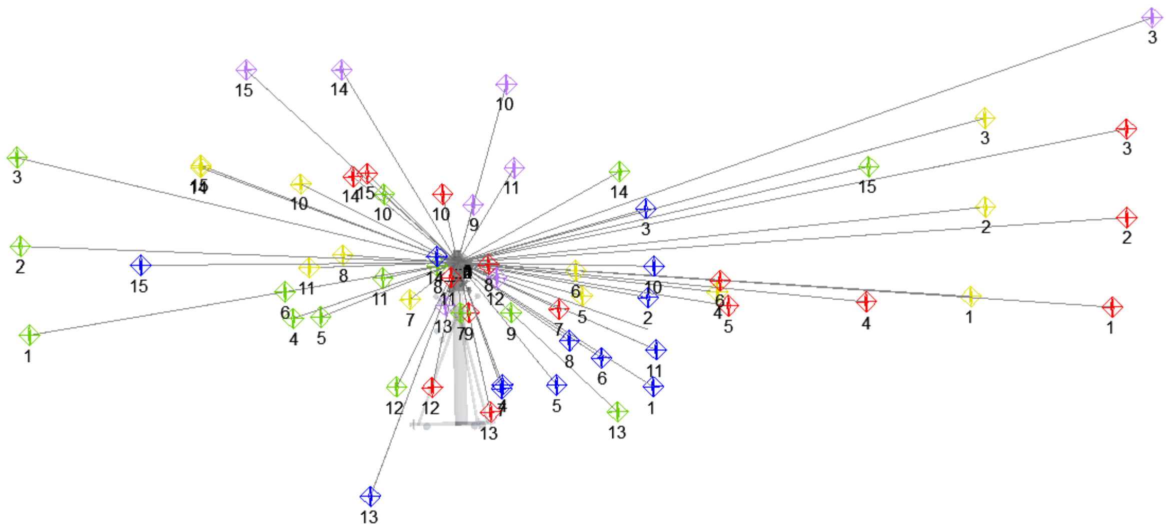

Figure 4 - Elevation view of relative position of targets with respect to tracker origin.

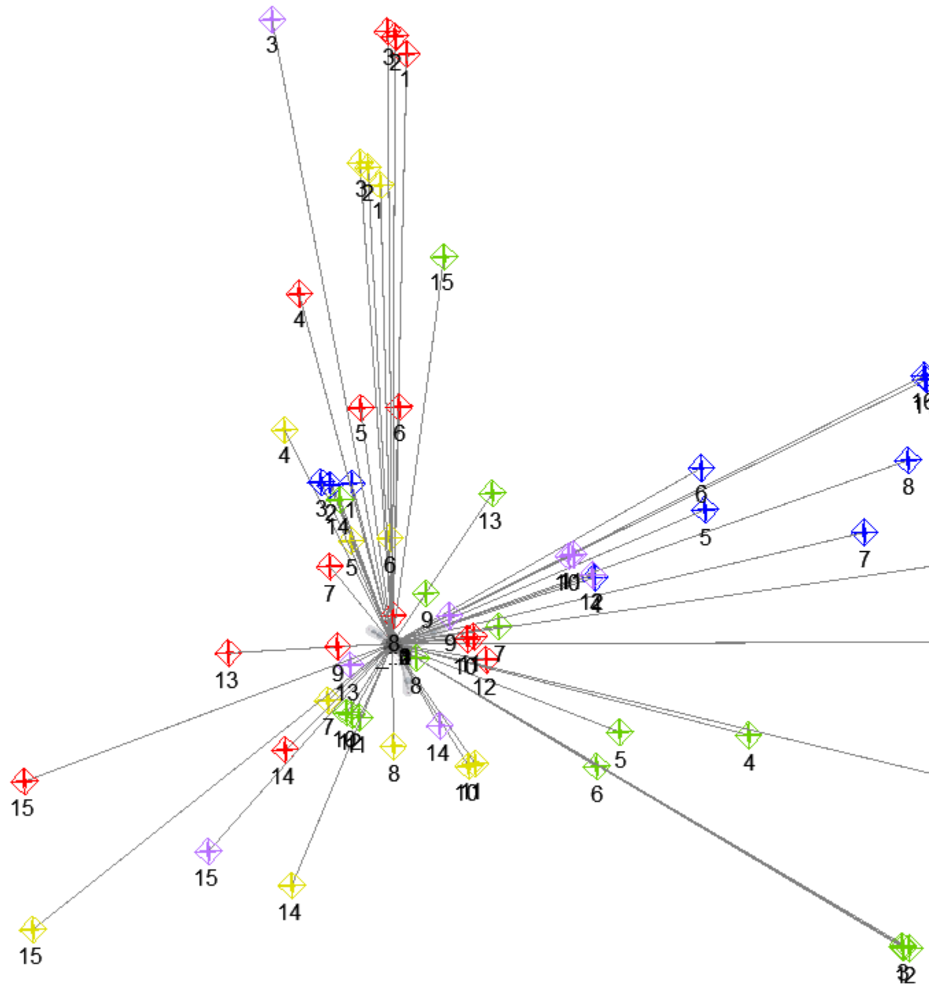

Figure 5 - Plan view of relative position of targets with respect to tracker origin.

The results of the network test are shown along with their respective standard uncertainties in Table 2 and Table 3.

Table 2 - Determined error parameters – distances, scale factor, and their uncertainties.

Symbol	Value	Uncertainty
λ	2.467 6 mm	0.403 µm
μ	1.000	5×10^{-7}
e_x	4.988 µm	0.122 µm
$b_{y,0}$	91.201 µm	0.654 µm
$b_{z,0}$	-13.318 µm	0.974 µm

Table 3 - Determined error parameters - angles and their uncertainties.

Symbol	Value / seconds of arc	Uncertainty / seconds of arc
α	16.751	0.128
γ	9.647	0.079
$a_{A,1}$	0.526	0.064
$b_{A,1}$	-0.562	0.080
$a_{A,2}$	0.177	0.073
$b_{A,2}$	1.530	0.090
$a_{E,0}$	0.154	0.223
$a_{E,1}$	-1.736	0.152
$b_{E,1}$	-0.677	0.183
$a_{E,2}$	0.375	0.214
$b_{E,2}$	0.437	0.179

5 VERIFICATION OF NETWORK CALIBRATION THROUGH ASME B89.4.19 TEST

To validate the calibration results, we have chosen to verify the calibration using the output parameters to *effectively* rewrite the laser tracker's internal error map, and then determine whether or not the tracker is able to pass a standard performance verification test[i]. The standard used was the ASME B89.4.19-2006 "Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems"[4] (hereafter referred to as B89 test).

Furthermore, we can verify the network calibration approach[5] by using the calculated uncertainties in the fitted parameters to predict the performance of the corrected laser tracker in the B89 test. On average, 95 % of the B89 measurements should fall within the predicted expanded uncertainty (k = 2).

5.1 B89 TESTING STANDARD

The B89 test involves measurement of a calibrated length artefact by the laser tracker under test with the artefact placed in several different orientations with respect to the tracker and at distances ranging from 0.25 m to 6 m and with the tracker rotated at 0°, 90°, 180°, and 270° about the standing axis with respect to the artefact. Figure 6 shows some examples of the measurement setups defined in the standard.

[i] In practice, we did not update the tracker's internal error map since we can't be sure the internal correction software uses the same error model. So we used our model and the measured parameters to correct raw, un-corrected tracker data off-line. To ensure the laser tracker was not applying any correction to the data, all correction parameters stored on the controller were set to zero.

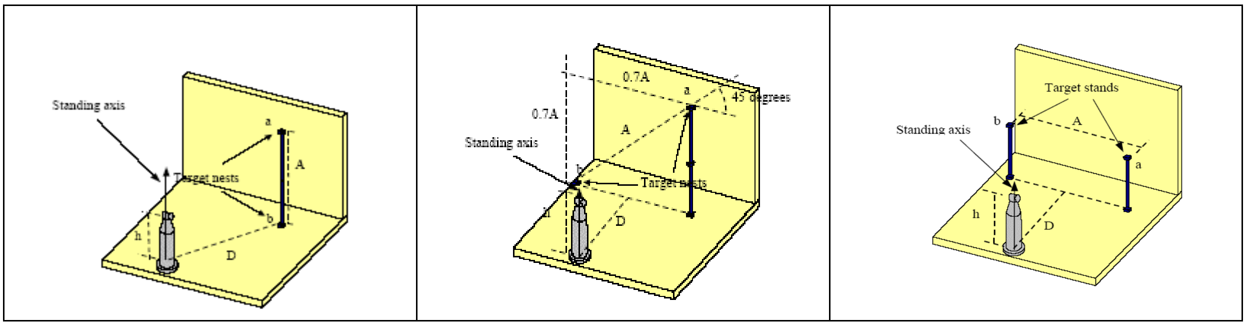

Figure 6 Example of B89 target positions with respect to tracker, with targets oriented vertically (left), diagonally (middle), and horizontally (right).

Each orientation and distance combination involves three length measurements (calculated from six point measurements) in both interferometer (IFM) and absolute distance meter (ADM) mode.

For these experiments, a 2.31 m carbon fibre length artefact shown in Figure 7 was used. The artefact has been shown to be stable to within 1 µm (with 0.4 µm standard deviation) over the course of several weeks when measured in two different laboratories using an NPL calibrated laser tracker in *boresight* mode[ii].

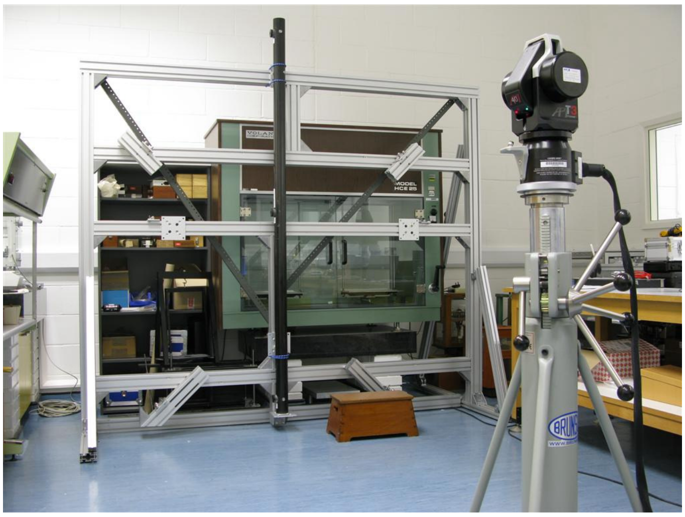

Figure 7 B89 test frame with artefact in vertical position and API T3 laser tracker on stable, adjustable height tripod.

5.2 TEST RESULTS

In order to demonstrate the effectiveness of our technique, we used it to perform a full error determination of a laser tracker (API model T3). We temporarily disabled the parameters of the tracker's error map. Using the tracker's interferometer, we performed the IFM volumetric tests prescribed in standard ASME B89.4.19. The results are shown graphically in Figure 8, in which we plot measured deviation from calibrated artefact length. Length measurement errors of up to 1.9 mm can be observed which are far in excess of the 18 µm to 68 µm maximum permissible error (MPE)

[ii] Boresight Mode – measuring the length of the artefact using the laser tracker with the interferometer beam aligned along the length of the artefact. In this way uncertainties due to the angle encoders are eliminated and the uncertainty achieved is that of the interferometer alone. This is the most accurate method of using the laser tracker.

values specified by the manufacturer for a properly operating tracker. These results show the importance of calibrating and compensating for the geometric errors of the tracker.

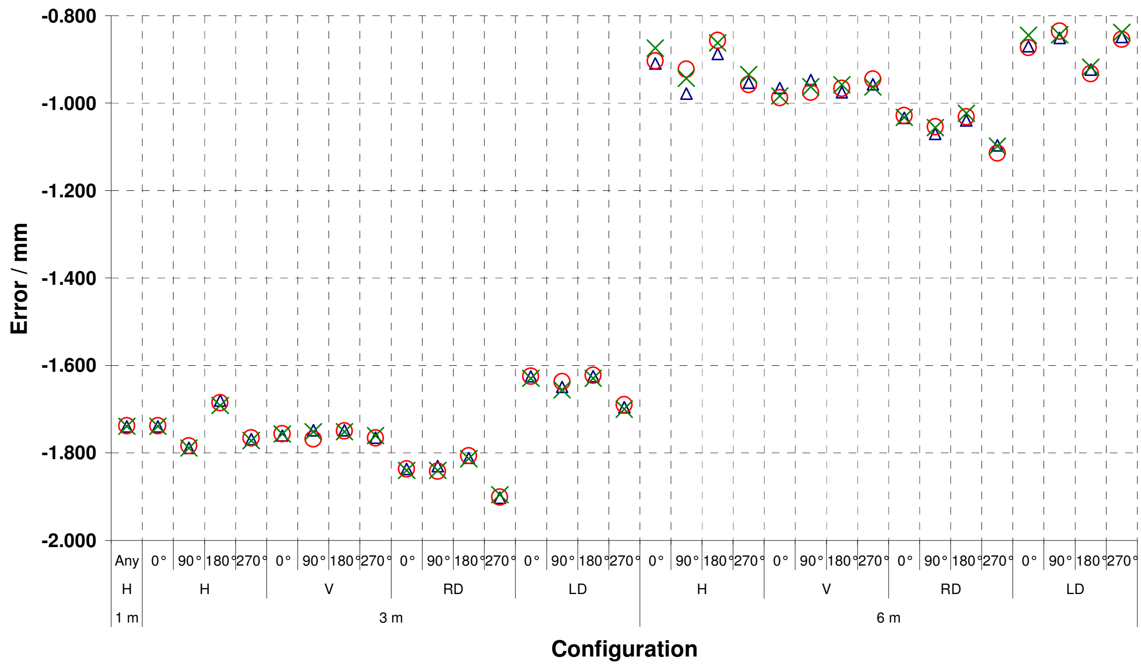

Figure 8 B89 volumetric test results with tracker error map disabled. Configuration parameters are as prescribed in ASME B89.4.19 and relate to three tracker-to-test artefact distances (1 m, 3 m, 6 m) and four azimuth rotations of the tracker (0° to 270°). The orientation of the artefact (horizontal, vertical, and the left and right diagonals) is also indicated. Three measurements are made in each configuration (red, green blue).

We then used our error model to perform *post hoc* correction of the results shown in Figure 8. This is equivalent to operating the laser tracker using the NPL error model with values of the error parameters determined from the network test. The results are plotted in figure 10.

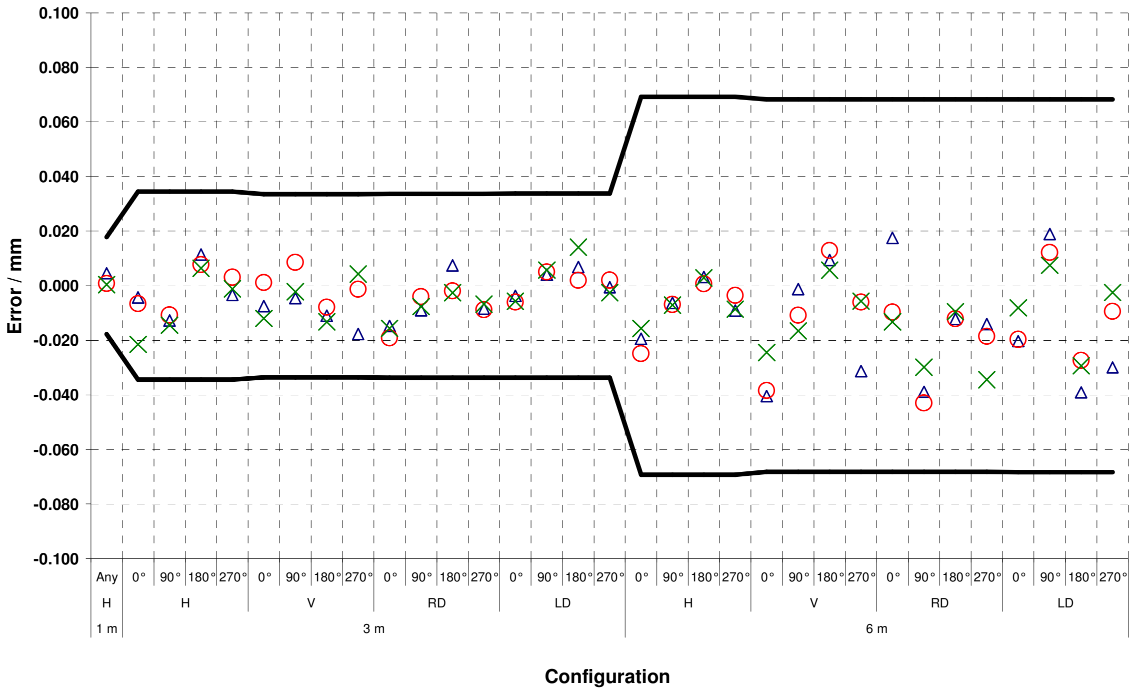

Figure 9 B89 volumetric test results from figure 7, *post hoc* corrected using NPL error model and parameters derived from the network measurement. Bold lines show the manufacturer supplied MPE values.

The errors have been significantly reduced and the instrument now passes this performance verification test. For comparison, the manufacturer's standard error map was then re-instated and the artefact re-measured using this error map. The results, plotted in Figure 10, show a similar level of performance.

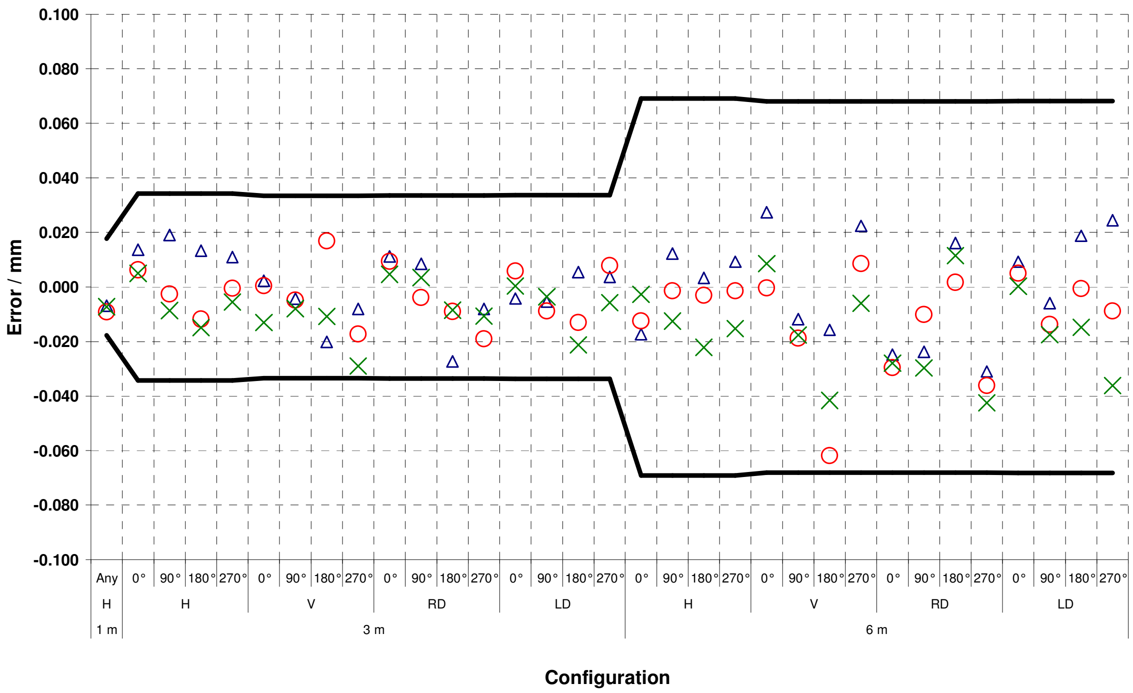

Figure 10 B89 tests using manufacturer's error map. Bold lines show the manufacturer specified MPE values.

Figure 11 below, shows the same B89 test results as shown in Figure 9, together with the predicted values and associated measurement uncertainty predicted from the correction parameter uncertainties from the network test.

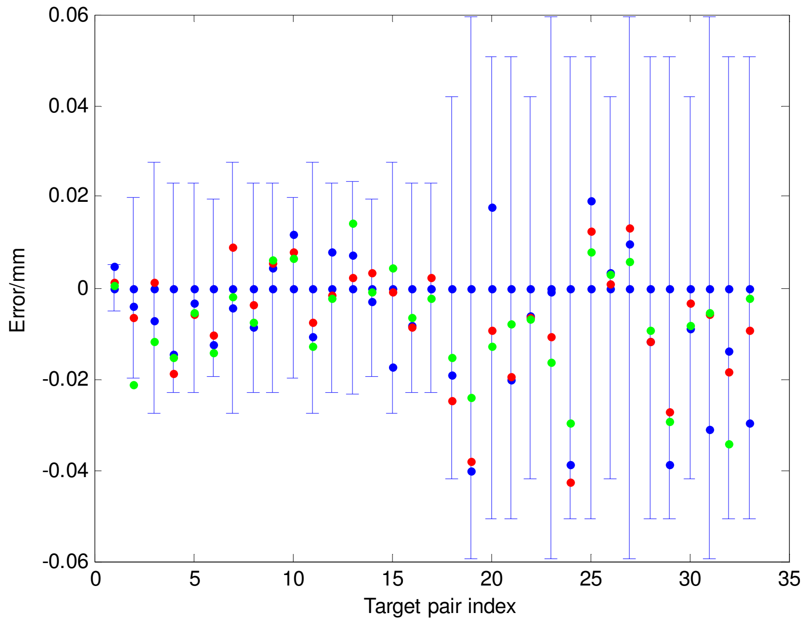

Figure 11 Results of the B89 test using the correction parameters obtained from the network calibration, along with the predicted values (all zero) and their associated uncertainties (k = 2) based on the parameter uncertainties.

If the correction parameters obtained from the network test are valid, then we would expect that, on average, 95 % of B89 test results would fall within the predicted expanded uncertainty (k = 2). In this case, all the B89 test measurements are within the predicted expanded uncertainty. This statistical consistency between prediction and observation can be interpreted as strong validation of the multi-sensor network approach to laser tracker calibration

6 CONCLUSIONS

We have described briefly a new model of laser tracker geometric errors and shown how the parameters of the model can be determined, to high precision, using a simple series of measurements of a network of fixed targets. We have also shown that the model and the model parameters obtained using the network measurement approach can be used to successfully correct the raw data obtained from an un-corrected instrument. A comparison between the results of a performance verification to ASME B89.4.19 of an instrument corrected using the manufacture's calibration data and the same instrument corrected using the network method show no significant difference.

We have also shown that the B89 test results are statistically consistent with predictions based on the parameters and their associated uncertainties obtained from the network test. These results validate the network technique for calibrating laser trackers.

7 REFERENCES

[1] NPL Report. Procedure for calibration of laser tracker alignment errors using a network measurement: NIMTech deliverable report D3.1(1). B Hughes, A Forbes, W Sun, January 2011.
[2] Hughes B, Forbes A, Lewis A, Sun W, Veal D, Nasr K, Laser tracker error determination using a network measurement. (Submitted to Meas. Sci. Technol. January 2011.)
[3] Hughes B, Sun W, Forbes A, Lewis A, 2010 Determining laser tracker alignment errors using a network measurement *CMSC Journal* Autumn 2010, 26-32.
[4] ASME B89.4.19 Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems (2006).
[5] Forbes A, Hughes B, Sun W. Characterisation and verification of multi-station co-ordinate measuring systems. Technical report. National Physical Laboratory, Teddington, 2011. NIMTech Deliverable 3.3.1.