# Laser Tracker Compensation Using Displacement Interferometry

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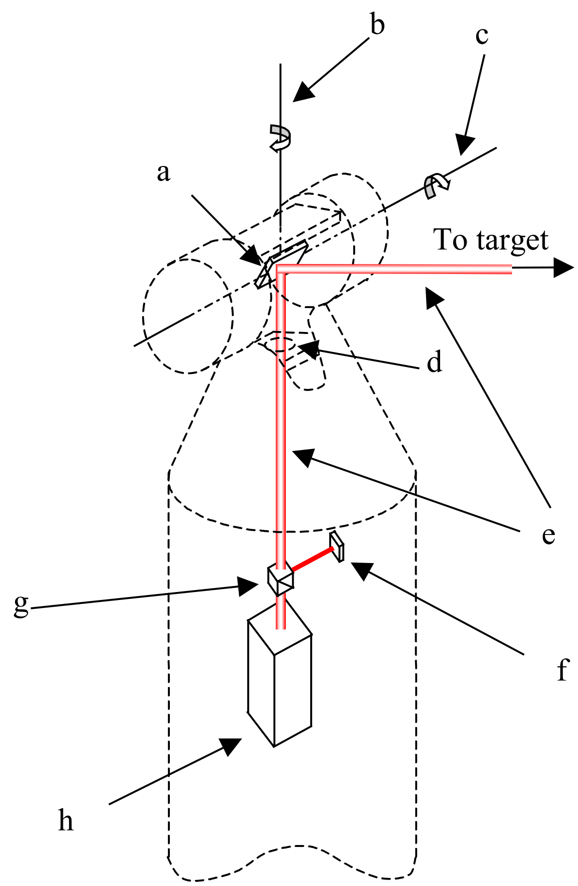
## Introduction

Laser trackers have become the tool of choice for large-scale coordinate measuring needs. The requirement to rapidly validate the performance of these instruments to ensure the integrity of their measurement results is critical. The task is complicated by the fact that the measuring envelope of these instruments is quite large (> 35 meters). Such large measurement volumes often require the use of large length standards, e.g., greater than two meters, to characterize the instrument performance. Physical standards such as large calibrated artifacts, commonly referred to as scale bars, may suffer the problems of being unwieldy to use, difficult to construct and quite often costly to maintain.

In response to the need to characterize the performance of this class of coordinate measuring system, NIST, with funding from the U.S. Navy Calibration Coordination Group (CCG), developed the Laser Rail Calibration System (LARCS). The system includes a linear interferometer and support structure that can be configured to support a three meter calibrated length in any arbitrary position inside the tracker work-volume [1]. The results of displacement measurement tests performed with the LARCS contain valuable information about the laser tracker performance characteristics. However, there are very few tools available to exploit the vast information contained in these data [2][3].

The primary motivation for the investigation provided in this paper, is to provide users of these systems with an example of a systematic approach for utilizing displacement measurement for characterizing the performance of laser trackers. Estimates of the error model parameter obtained from displacement measurements can be used either to compensate the laser tracker or, along with error propagation tools, such as Monte Carlo Simulations, to estimate the point coordinate uncertainty. For this paper we will show that estimates of the error model parameters can be obtained using linear displacement measurements.




a. Beam steering turning mirror
b. Standing or vertical axis
c. Horizontal or transit axis
d. Cover plate
e. Laser beam
f. Position Sensing Device (PSD)
g. Beam splitter
h. Interferometer and laser head

**Figure 1. Laser Tracker Schematic**

**Background**

The construction of laser trackers, similar to a theodolite, makes it possible to measure to a fixed target using two different instrument configurations. That is, the tracker can track to a fixed location measure a target, then the tracking mirror (**Figure 1**) can be rotated 180 degrees about an axis pointing vertically and then rotated about a horizontal axis to point back at the target. Measurements performed in this way are referred to as two-face or frontsight/backsight measurements. These measurements are important because many of the tracker error model parameters are reversed and are thus accentuated using this procedure. (The error model parameters represent physical position and orientation errors of the optical components.)

Because of the error reversal property of two-face measurements, manufacturers often employ this technique to calculate estimates of the error model parameters. Sets of two-face measurements are performed and estimates of the model parameters are obtained using a least squares algorithm. These measurements however do not encompass a large portion of the model parameters that do not reverse and, thus, are not accentuated by this technique. To estimate these parameters, additional measurements are often employed. These obligatory measurements typically utilize an un-calibrated fixed length artifact, a rotating ball bar, so that at no time during the compensation is scale introduced into the calibration procedures. Such procedures are frequently referred to as self-calibration techniques or closure techniques and are perfectly valid [4].

Although closure techniques are a very powerful tool the use of a calibrated reference artifact for tracker compensation can be advantageous. The benefit of using an independently calibrated interferometer system is that all measured lengths are traceable to the SI unit of length, *i.e.*, the meter. Additionally, measurement positions can be selected so that they are sensitive to all of the tracker error model parameters.

**Compensation Algorithm**

The LARCS system is designed to establish and position a reference length in any arbitrary orientation and location inside the tracker work-volume. Although the software provided with the LARCS has provisions for performing two-face measurements, the most common use for the system is to compare the reference length to the values for the same length measured by the laser tracker. The output of a measurement is the distance and horizontal and vertical angles to each point that comprise a length measurement, as well as the calibrated value for the lengths.

Ideally the calibrated value and the measured value for the length would be equal. However, because of the presence of the geometry errors in the construction of the tracker, other systematic errors not included in the model and random effects this is almost never the case. This measurement error which is also calculated and stored by the LARCS software is the distance as measured by the laser tracker minus the calibrated value for the length or equivalently:

$$\varepsilon = D(\vec{Y},\vec{X}) - D_{calib} \quad \text{................(1)}$$

Where $D(\vec{Y},\vec{X})$ is the distance function in spherical coordinates, Y is a vector of the measured coordinates and X is a vector containing the unknown alignment parameters. We can write the function in this form because the corrected coordinates are a function of the measured coordinates and the unknown alignment parameters. If multiple lengths are performed Equation

(1), after linearization, can be expressed in matrix notation by the following equation:

$$\vec{\varepsilon} = J(\vec{X}) + \upsilon \text{.....................}(2)$$

Where $\vec{\varepsilon}$ is the vector of measured errors, $\vec{X}$ is the vector of unknown alignment parameters, J is the Jacobian and ν is a vector of residuals [5]. This equation has the familiar form AX=b+ν and can be solved easily using standard mathematical techniques [5][6][7].

**Procedures and Results**

The above algorithm was programmed in MATLAB. The simulation generates a random set of alignment parameters. The error model is used along with a set of randomly generated point pairs to create a set of displacement measurement errors (simulated measurement errors). These errors are used in the least squares fit algorithm described above to test the correct implementation of the model. Additionally, the simulation provides an invaluable tool for selecting measurement positions that are sensitive to a significant portion of the alignment parameters. That is, it is not an easy task to determine in which positions and orientations the reference length should be measured. By generating random measurement positions and calculating the model parameter sensitivity coefficients, the placement of the reference length can be judiciously selected to be sensitive to the largest number of the model parameters. Analysis of variances is employed and model parameter confidence intervals calculated to determine the number of requisite measurement positions. Obviously as the number of measurement positions increases the confidence intervals for the model parameters get narrower. For this test, only 54 unique measurement positions where employed this is a compromise between an acceptable level of confidence and the available time to perform measurements. **Figure 2** shows a frequency of the residual length measurement errors before and after compensation. The standard deviation of the residual length errors where decreased by a factor of two.

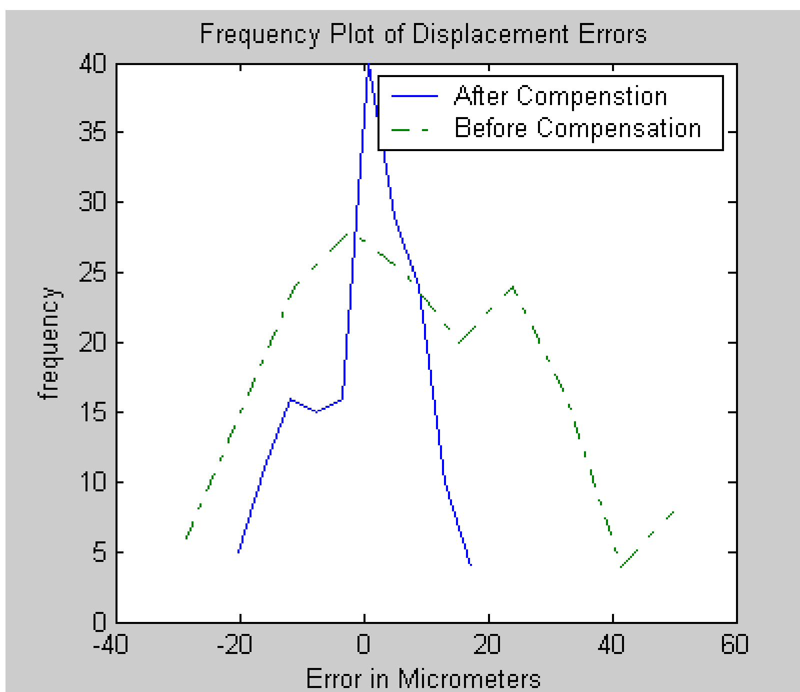


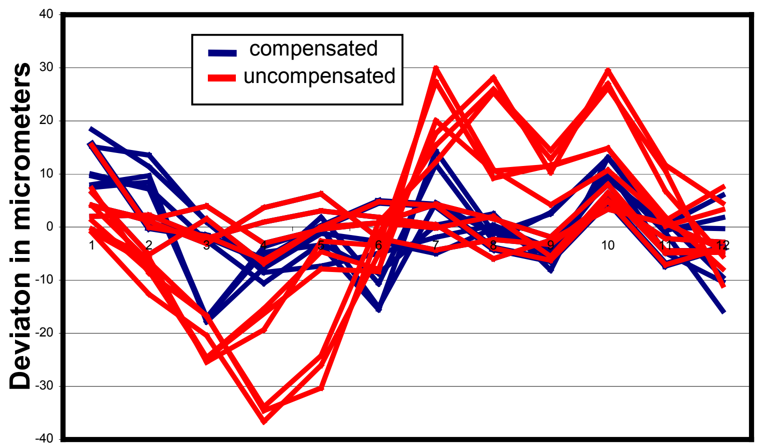

**Figure 2. Residual length errors before and after correction**

After obtaining estimates of the error model parameters, a simple test was performed. The tests consisted of measuring 12 targets rigidly mounted to a thermally stable structure. The position of each of the target nest was measured with the tracker placed in 4 different locations and orientations relative to the support structure. Each set of twelve measurements was fit together in a rigid body least squares sense. The deviation from the average calculated position for each target nest is plotted for both the compensated and uncompensated points. Chart 1 implies that a significant reduction in the systematic variation in the measured points can be obtained using this methodology. It is important to note that the deviations shown in the chart are within the manufacturer's specification yet significant systematic variations still exist. This variation may, however, be due to poor calibration of the laser tracker. At the time of this writing the laser tracker is being compensated again using the manufacturer's recommended practice. A set of new model parameters will again be calculated using the methods described here. A similar analysis will be performed to determine if in fact the residual point variation is caused by operator error or lack of sensitivity of the recommended compensation procedures to all of the error model parameters.

## Conclusion

Length measurement results show that displacement measurements can be used to obtain estimates of laser tracker error model parameters. Experimental measurements imply that displacement methods can significantly reduce the variation in the point coordinate variation by nearly one half. When used with simulation tools such as Monte Carlo simulation software, this methodology might in the future be used to calculate point coordinate uncertainty for any measured coordinate.

**Chart 1. Deviaton From Mean Value**




Work will continue to apply this methodology to other similar trackers. It is our hope that this method can be extended for use with trackers with other kinematic configurations as well.

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