Thermal Stability of Laser Tracking Interferometer Calibration

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ABSTRACT

Uncompensated thermomechanical errors in laser tracking interferometers are examined by evaluating the difference between tracking interferometer compensations in a controlled laboratory environment versus being compensated in a factory environment. The hypothesis under test was that compensation in a factory environment does not adversely affect, and may actually improve, the uncertainty of laser tracker systems. This hypothesis was confirmed by measuring a standard (i.e., linear interferometer) using laboratory-compensated and certified instruments, and then compensating the instrument in the factory environment and re-measuring the standard. The results showed that in-shop compensation generates less variation in the measurement of the standard when compared to the laboratory-compensated and certified instruments. Certified weather stations are used to compensate for the uncontrolled atmospheric effects on the range measurement. The standard calibration measurements include 27 two-face and 10 temperature-compensated scale-bar positions. The comparison of two-face results showed that in-shop compensation reduced the variance in pointing-error induced by uncompensated thermal-mechanical changes from the laboratory. The effort demonstrates that shop floor compensation of a laser tracker produces a more reliable and accurate instrument than using the same instrument compensated at laboratory temperature and then used at different ambient temperatures. The results show uncompensated thermomechanical errors of laser tracker systems produce less than optimum angular measurements. Compensation on the shop floor eliminates most of these errors.

Keywords: Compensate, Calibrate, Certification, Laser Tracking Interferometer, and Uncertainty

1. INTRODUCTION

The long-standing practice of calibrating metrology systems in a controlled laboratory prior to its use in factory applications is being challenged. Compensating and calibrating on the factory floor is providing improved uncertainties and greater system utilization. Optical metrology system developers are integrating software processes that are able to lead operators through specific data collection steps for compensation algorithms. The process statistically solves for environmentally sensitive alignment parameters and then provides a report that documents the health of the alignment. This report provides a mechanism for establishing a controlled traceable process that can satisfy certification requirements. This paper documents the tests and results for one particular optical metrology system, Laser Tracking Interferometers.

2. LASER TRACKING INTERFEROMETER DESCRIPTION

A laser tracking interferometer system provides real-time three-dimensional measurements in large volumes. It is portable and easily moved to the measurement site. Laser trackers are spherical measurement systems that measure a three-dimensional location of a retroreflector. It records the position of the retroreflector using a single beam interferometer (IFM), usually a HeNe laser, to find its range while optical encoders to find the horizontal and vertical angular positions. The major components of the system are the sensor unit (i.e., measurement head), the laser tracker controller, an application processor, an environmental monitor, and the retroreflector [4].

The sensor unit reads the raw angles and distances to the retroreflector. The laser tracker heads use either a tilting mirror or a prism to steer the HeNe (IFM) and a position-sensing diode to track a retroreflector. The relative distance of the retroreflector from a known location is determined by counting the HeNe interference fringes. If the HeNe beam is broken it loses track of the retroreflector and the measurement will have to be repeated.

The application processor is usually a personal computer that contains system alignment routines (i.e., the numerical compensation that corrects optical-mechanical alignment) in addition to providing the human interface.

The laser tracker controller contains its own central processing unit which applies environmental corrections to the angle and distance values measured by the angle encoders and IFM. Environmental factors such as changes in atmospheric pressure, temperature, and humidity affect the wavelength of the IFM and are corrected by the controller. Accurate environmental measurements are usually automatic input from an environmental monitor.

Laser trackers depend upon a retroreflector for measurement. The open-air retroreflector has an acceptance angle of ±40° for tracking. It was chosen because it does not generate refraction errors like the glass prism and costs much less than a cat-eye reflector.

3. PROCESS DECRIPTION

Classic calibration procedures require that laser tracker pointing compensation and calibration be performed only in a metrology laboratory. This very stable environment provides precise compensation for quantifying mechanical error. The drawback of laboratory compensation is that the actual use temperature can be significantly different from the temperature in the laboratory, and this induces measurement error. In general, temperature changes cause microscopic mechanical changes in the precise tracker-pointing head. These changes can be measured and compensated on the shop floor, which allows the laser tracking system to make optimum measurements. In summary, this paper examines the balance between the classic compensation method and the in-shop compensation method. The classic compensation method has low uncertainties associated with the laboratory compensation and a higher uncertainty associated with thermomechanical errors when used at a different ambient temperature. In-shop compensation has a higher uncertainty for calibration in an uncontrolled environment and a lower uncertainty for thermomechanical errors because both compensation and actual use are at the same temperature.

To calibrate an instrument (i.e., comparison to a standard)[1] a reference must provide a definitive result that can be repeated and be shown traceable to an accepted standard [1]. In this test, the linear interferometer with the calibrated weather station is that standard.

Traceability means that a certain measurement is related by documented means to the definition of the unit of the measurand. In other words, the measurement is trusted because the unit is defined and expressed through comparison to a standard. Additionally, the measurement instrument conforms within the definition of this unit to a limited uncertainty[2],[3].

4. HYPOTHESIS

The hypothesis under test is that compensation in a factory environment does not adversely affect and may actually improve the uncertainty of laser tracker systems. Test the hypothesis by measuring a standard (i.e., linear interferometer) using laboratory-compensated instruments. Following this, the instrument is compensated in the factory environment and the standard is remeasured. The result should show that in-shop compensation generates less variation in the measurement of the standard when compared to the cal/cert laboratory-compensated and certified instruments.

Performing measurements with the instruments in two orientations tests the existence of thermomechanical error. Measurements "in-line" with the interferometer standard should show little, if any, thermomechanical error.[2] Measurements adjacent to the interferometer standard should show substantial thermomechanical error.

5. METHOD

The test examined three laboratory-compensated and calibrated laser tracker systems (with accuracies of 10 ppm-2σ) against a certified linear interferometer (with an accuracy of 2 ppm-2σ) on an 85-foot long test rail in a shop environment that was at least 10 degrees Farenheit different from the compensation laboratory temperature. A series of data were collected in both the radial and lateral orientations relative to the interferometer on the test rail. Figures 1 and 2 show the radial test setup; figures 4 and 5 show the lateral test setup. The laser tracker systems were then in-shop compensated using the supplier's routine, and the test was repeated.

A corner-cube-holding fixture (i.e., target sled–see figure 3) was moved bidirectionally along the rail by an operator who stopped at roughly five-foot increments. Four independent runs were completed. Each instrument utilized environmental wavelength compensation. At each stop, the linear interferometer measured the actual distance moved from the initial reference. The systems under test (the LTD-500 and/or the SMX-4500) measured their targets at each stop. The tracker measurements and linear interferometer measurements were then compared. Four sets of data were collected. Each instrument utilized environmental wavelength compensation.

The tracking interferometers were then compensated in the factory, and were again calibrated to a standard–the environmentally-compensated linear interferometer. The difference between each tracking interferometer and linear interferometer versus the linear interferometer distance was

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[1] International standards define calibration as "the set of operations which establish, under specified conditions, the relationship between the values indicated by the measuring instrument and the corresponding known values of a measurand." In other words, calibration of an instrument verifies the accuracy of the instrument.

[2] Simple error analysis shows that if the total included angle for measurement is less than 5 degrees, the uncertainty of the tracking interferometer is dominated by the uncertainty of it interferometer, and not the uncertainty of the pointing angles.

plotted (see data results section.) Then a comparison between calibrations was made to ascertain if compensation in a factory environment reduces variation and uncertainty.

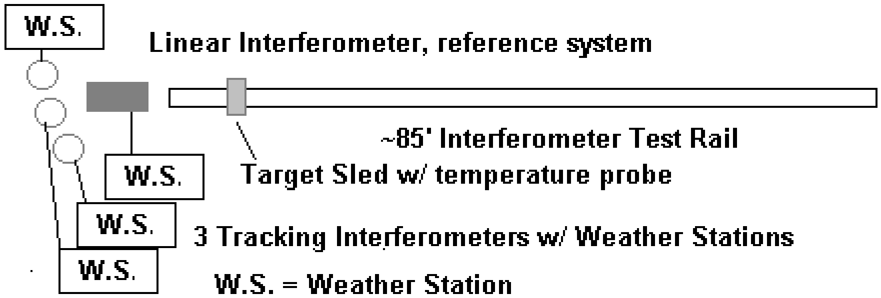

Figure 1: Equipment setup for radial test

Figure 2: Radial test setup with 3 laser tracking interferometers.

The operator moved the target sled along test bed. The total distance traveled was approximately 85 feet. Measurements from the tracking interferometers and linear interferometer instruments were taken bidirectionally at approximately 5-foot intervals along the rail.

Figure 3: Target sled setup for lateral test. (Lines-of-sight for three tracking interferometers and the reference interferometer have been added.)

The interferometer rail and tracking interferometers were set up as shown in figures 4 and 5 so that initial measurements by the tracking interferometers are primarily angular. Placement of the tracking interferometers were such that the total angle subtended by the tracker from near-end to far-end of the rail was at least 135°.

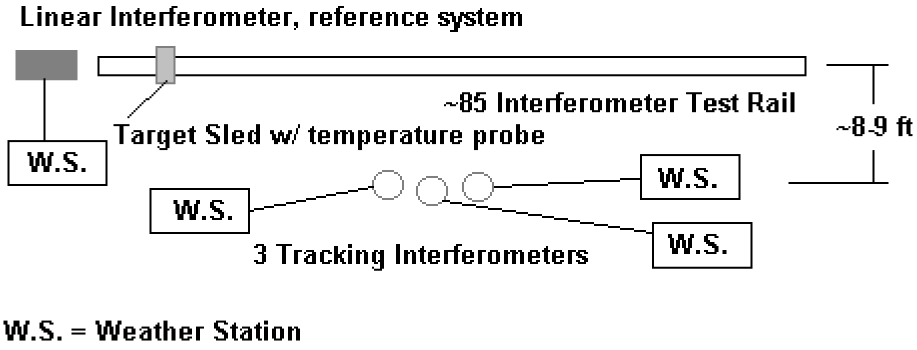

Figure 4: Equipment setup for lateral test.

Figure 5: Lateral test setup of three laser tracking interferometers with the reference linear interferometer in the foreground.

Two sets of data with three Leica LTD-500 instruments and two sets with three SMX4500 laser trackers were collected. The two sets with the Leica instruments were at shop temperatures of 58 and 85 °F which is significantly different from the laboratory temperature (~68 °F). The SMX tracker tests were at 82 and 88 °F.

6. REFERENCE INTERFEROMETER TEST RESULTS

The interferometer rail test results are presented in a series of charts shown in figures 6 through 11. Only one (the 85 °F temperature set) of the four sets of results is shown. The other three sets present similar results. Figures 6 and 7 represent the data collected from the three laboratory-compensated instruments that were in an 85 ºF shop environment against the reference linear interferometer. Figures 8 and 9 show the data collected from the same three instruments following a full compensation and calibration against the reference linear interferometer. Figures 10 and 11 contrast the laboratory vs. in-shop floor compensation.

Radial test data is shown in figures 6 and 8. The figures show the distance traveled by the target sled as measured by the reference interferometer on the x-axis against the difference error between the reference measurement and laser tracker system on the y-axis. The interferometer distance was determined using the first point on each run as the reference.

The data in the figures is bounded by interferometer specification lines of ±max (0.0005 in, range × 2ppm). In each case, with laboratory and in-shop floor compensation, the three systems under test met the specification. This result was anticipated by the hypothesis because there is little contribution to the thermomechanical pointing errors from in-line measurements. An important side note is that the interferometer in the laser tracker meets the 2-ppm specification.

Lateral test data is shown in figures 7 and 9. The charts are formatted like the radial test results. The point closest to the group of three trackers was used as the reference point for comparison. This point was chosen because it was the point of minimal uncertainty for the laser tracker measurements. Consequently, the chart shows the errors of the other points relative to the reference point. The lateral test consisted of six independent runs: down and back, down and back, and down and back.

The data in the figures is bounded by system specification lines of 10-ppm combined with the interferometer uncertainty added in quadrature. The uncertainty relationship is $\pm\sqrt{\left(\sqrt{2}\times r_{TR}\times 10\,ppm\right)^2+\left(d_{LI}\times 2\,ppm\right)^2}$ inches. Where r_{TR} is the range between the tracker and the reflector and d_{LI} is the distance between the target sled and the reference interferometer. These upper and lower bounding curves represent test specification limits (i.e., the combined test uncertainty of the laser tracker and the linear interferometer).

The lateral test results for the laboratory-compensated instruments (figure 7) shows the majority of the data within the specification limits. However, some of the measurements are outside the specification limit. Figure 7 also shows three groups of data associated with each tracker for the first half of the data collection. This tends to imply that the thermal-mechanical errors may be distinct for each instrument. Results from the same instruments after pointing compensation (figure 9) shows all of the measurements within the specification limits.

Figures 10 and 11 are histograms of the relative percentage of the specification used in the radial and lateral tests, respectively. Since the specification for each test was a function of the range between the trackers and retro-reflector, the relative percentage of the specification provides a consistent criterion for comparing test results. The figures group all three trackers and the independent runs together (those shown in figures 6 through 9) and then allows an objective test for comparing laboratory verses shop compensation and calibration. To provide a consistent comparison the area under each curve was normalized.

The vertical lines in the radial test histogram (figure 10) marks where 95% of the measurements are to the left of these lines. As expected from the hypothesis, the histogram data for the radial test shows relatively little improvement. The lateral test histogram shows a significant improvement. When the instrument was compensated in the shop, 95% of the measurement used 55% of the specification. The laboratory-compensated instruments require 95% of the specification to contain 95% of the measurements. While the laboratory-compensated instruments were not outside of the specification limits, an improvement was realized by compensating the instrument in the shop.

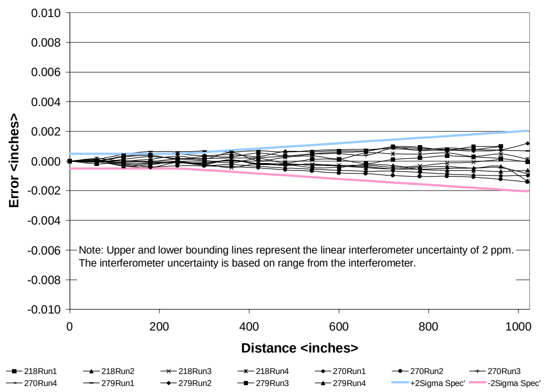

Figure 6: Radial Test of 3 Trackers at 85 °F (Laboratory Compensated & Calibrated Trackers at 68 °F)

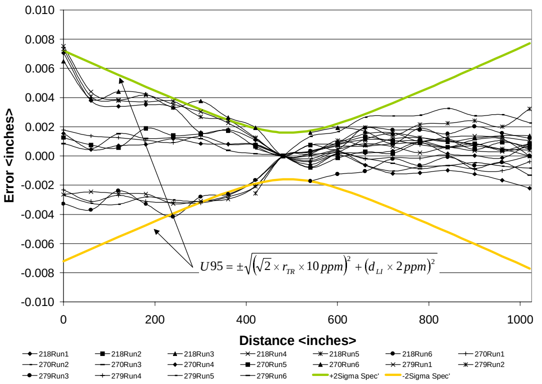

Figure 7: Lateral Test of 3 Trackers at 85 °F (Laboratory Compensated & Calibrated Trackers at 68 °F)

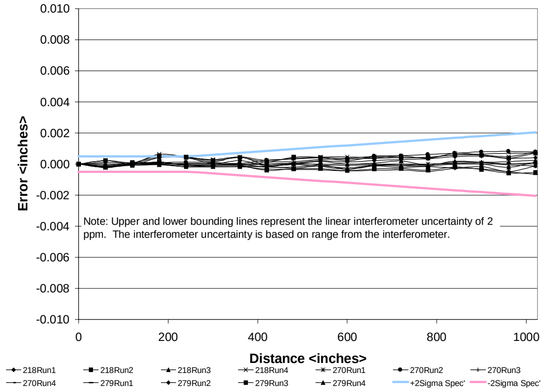

Figure 8: Radial Test of 3 Trackers Trackers vs. Linear Interferometer at 85 °F (Shop Compensated & Calibrated Trackers at 85 °F)

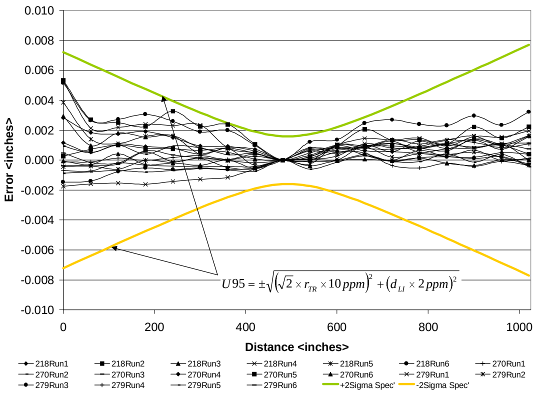

Figure 9: Lateral Test of 3 Trackers vs. Linear Interferometer at 85 °F (Compensated & Calibrated in the Shop at 85 °F)

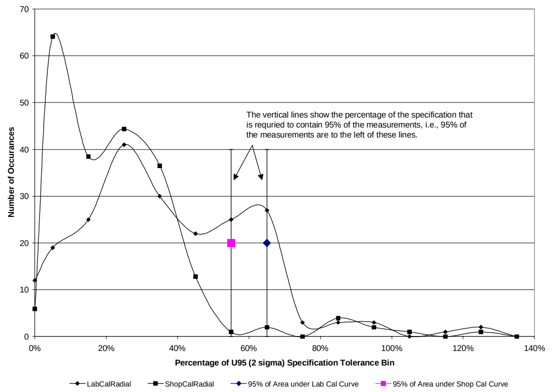

Figure 10: Tracker Compensation Histograms used at 85 °F Radial Direction

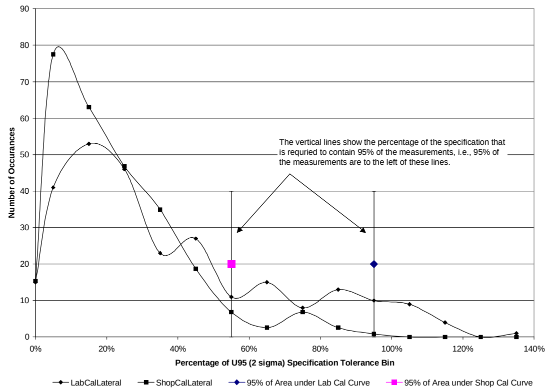

Figure 11: Tracker Compensation Histograms used at 85 °F Lateral Direction

The radial test data (figures 6 and 8) document and confirm that the system's interferometer is a 2-ppm instrument. This test data establishes the opportunity for the system's interferometer to be used to calibrate the 10-ppm coordinate measurement specification.

A series of statistical tests are performed on the data forming the two histograms to confirm or reject the hypothesis. An F-test (see table 1) is used to yield the one-tailed probability of whether the variances in different populations are the same or significantly different [5]. The F-test compares the variances of two sets of data obtained from the two methods to establish their relative precision. The F statistic is calculated using the relationship $F = s_1^2 / s_2^2$. Where s_1^2 is the variance for the shop-compensated instrument and s_1^2 is the variance for the laboratory-compensated instruments. The F statistic is compared to a tabulated value at a specified confidence level—95% and N - 1 degrees freedom. If the calculated value is smaller than the tabulated value then s_1 is more precise than s_2. Otherwise there is no significant difference and the values are consistent. The confidence level is 95% for all the analysis presented (i.e., the alpha value is one minus the confidence interval).

	ShopCalLateral	*LabCalLateral*	*ShopCalRadial*	*LabCalRadial*
Mean (percentage of the spec)	0.20865	0.361249	0.223525	0.365796
Variance	0.034452	0.098223	0.040792	0.060166
Observations	324	276	216	213
df	323	275	215	212
F	0.350754		0.677988	
F Critical one-tail	1.211697		1.253268	

Table 1: F-Test Two-Sample for Variances results using a 95% Confidence Interval

The value of F should fall below the F critical values for the tail. The test hypothesis is: "compensation in a factory environment does not adversely affect and may actually improve the uncertainty of laser tracker systems." Using the percentage of the specification for the laser tracker systems, the F-test results in table 1 confirmed the test hypothesis that shop floor compensation does not adversely effect performance, and showed that shop compensation significantly improves system performance.

7. TWO-FACE MEASUREMENT TEST RESULTS

The compensation performed in the shop optimizes the tracker's pointing system for the slight mechanical changes that were induced in the measurement head by the temperature change. To quantify the pointing improvement–a series of two-face measurements were performed before and after the compensation in the shop. Two-face measurements are made by pointing the system to a fixed reflector from a fixed station in face one and then reversing the tracker and pointing to the same point in face two. Two-face measurements to a fixed location should give the same pointing with only random differences. The two-face tolerance for use in the shop is 0.0030° within the pointing envelope. The laboratory-compensation and shop-compensation two-face data is shown in figure 12.

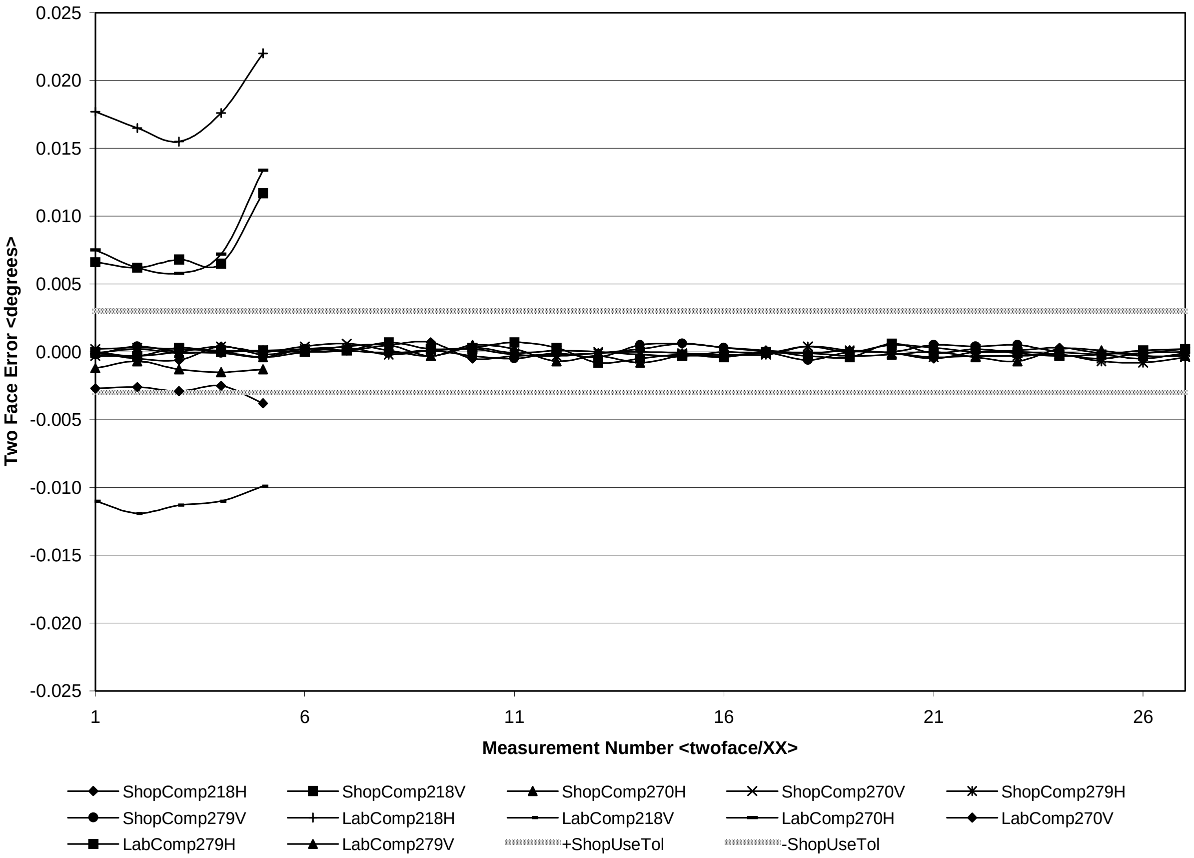

Figure 12: Two-Face Comparison, Lab vs. Shop Compensation of Laser Trackers at 85 °F

The two-face results show that each of the laser tracker instruments were out-of-tolerance when used with an alignment performed at a laboratory temperature of ~68 °F and then used at the shop temperature of 85 °F. The 28 °F temperature difference had induced pointing misalignments in the head which were up to seven times the acceptable tolerance. Performing the alignment at the working temperature in the shop and then checking each two-face measurement yielded acceptable results.

It should be pointed out that although the two-face measurements were out-of-tolerance, the measurements of the interferometer were within tolerance. This may indicate that the two-face measurements are more sensitive to thermomechanical change than measurements of a length standard. This may be an area of future investigation that can simplify the in-shop calibration process.

8. CONCLUSIONS

An analysis of the collected data confirmed the test hypothesis that shop floor compensation does not adversely affect performance; and it showed that in-shop compensation significantly improves system performance.

In general, these results are not difficult to explain. In-shop compensation, which has larger uncertainty for calibration in an uncontrolled environment and lower uncertainty for thermomechanical errors, has a smaller overall uncertainty than the classic compensation method. The low uncertainties are associated with the laboratory compensation and the higher uncertainty is associated with thermomechanical errors when the instrument is used at a different ambient temperature. By compensating the instrument in its environment before being used, better measurements are expected. The conundrum in this case is that these improved in-shop compensations would traditionally be invalid because they were not performed in a metrology laboratory.

The series of two-face measurements and the system's environmentally-compensated interferometer provided the means of compensating and calibration on the shop floor. By noting that the tracker used in the in-line mode is within the uncertainty of the interferometer standard, a length standard can be made for calibrating tracker measurements where there are large excursions of the pointing head.

Optical metrology systems (e.g., Trackers) are designed to be, and the system developers recommend they be, compensated and calibrated in the environment in which they are used. The process and data shown in this paper demonstrate the process is stable and traceable (i.e., via the interferometer) to measurement standards.

9. REFERENCES

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