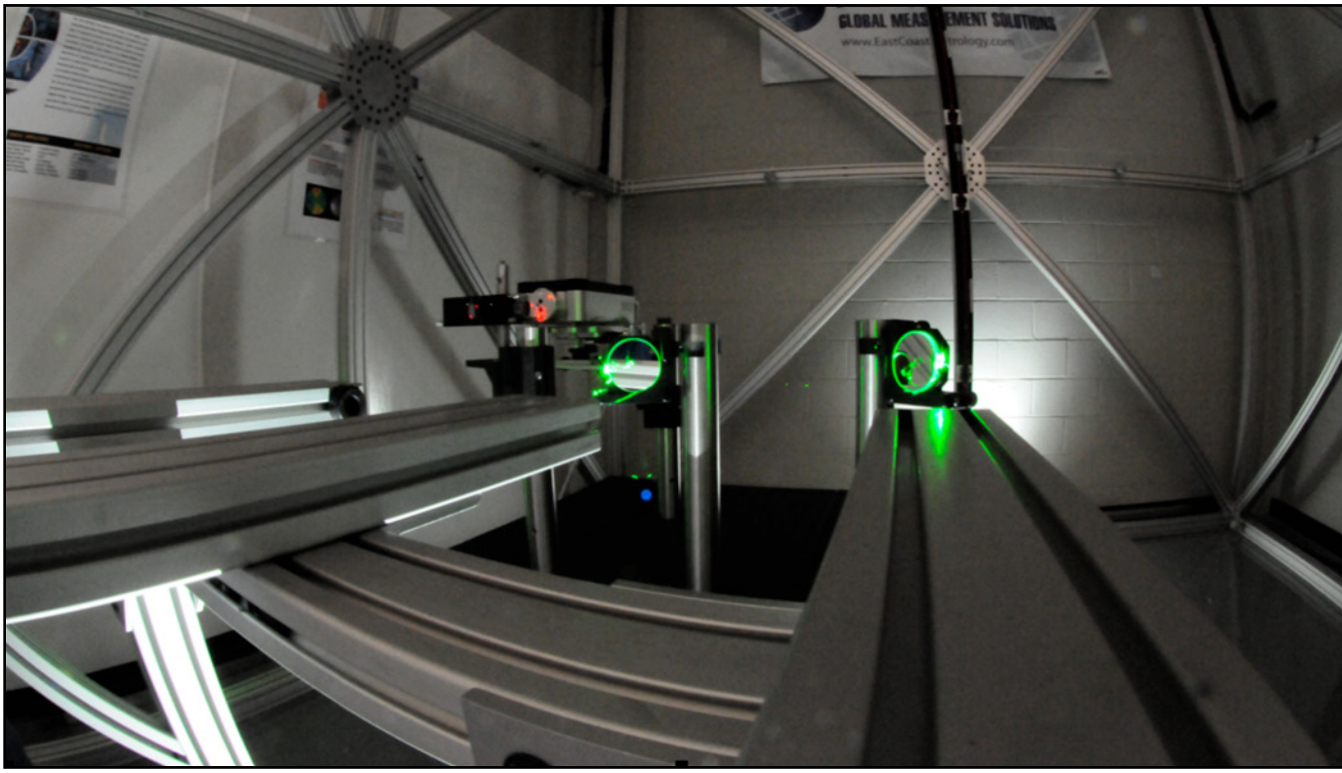

Linear Laser Performance: How Distance, Environment, and Setup Affect a Laser Tracker's Linear Accuracy

by Mateusz Turolski and Lukasz Turolski, ECM Global

Calibration of laser trackers using precision rails and a reference interferometer (one with no angular encoders) is the most precise way of evaluating linear performance, yet only a handful of institutions and companies use such equipment. In addition, little research has been conducted examining the added benefits and capabilities of precision rails when evaluating the linear performance of laser trackers.[1] A wide array of calibration procedures exist, many of which do an adequate job of testing tracker performance. However, no procedure is perfect, and uncertainties are an inherent obstacle during every calibration. In this article, we will highlight the capabilities of calibration rails when conducting in-line distance measurement testing; in particular, examining in-line measurement as a function of distance. Linear accuracy of laser trackers is determined by calculations that hold true in ideal environments, but how about the real world? Will a 3-meter-length standard measured 1 meter away yield the same result as if it were measured 30 meters away, even in a clean and stable setting? This article will put forth data from a controlled study that will shed light on this issue and attempt to constrain the uncertainties of real-world factors that could affect laser tracker linear accuracy using calibration rails.

INTRODUCTION

Manufacturer specifications of laser trackers are determined under ideal conditions. This can make accurate calibration of equipment in typical environments problematic. Although trackers are equipped to compensate for environmental conditions, readings can deviate considerably due to instrument error. Additionally, the tracker setup can cause uncertainties relating to stability, angular encoder error, and error of the reference standard.[2] This article will test the capabilities of precision rails in evaluating the linear performance of laser trackers. Uncertainties due to the factors listed above are inherent in all laser tracker calibrations. The reduction of these uncertainties allows more precise evaluation of the linear performance of laser trackers.

In addition to examining the capabilities of calibration rails, this experiment will also test whether in-line distance measurement specifications of trackers (at 3-meter lengths) hold true, even when measured over a range of distances. Theoretically, laser trackers should measure known distances with the same accuracy, regardless of how far away they are from the laser tracker. Therefore, 3-meter lengths measured 10 meters away should be just as accurate at the maximum range of the rail setup (i.e., 30 meters). The experiment's rail setup offers a unique opportunity to test these specifications for commonly used laser trackers in industry. By isolating uncontrollable uncertainties and minimizing controllable uncertainties, more precise evaluation of laser trackers can be performed, which can potentially identify inaccuracy trends as a function of distance.

EXPERIMENTAL SETUP

The experiment took place in a clean, stable, temperature-controlled lab. A calibration rail precisely aligned to within ± 0.254 mm was used to slide a fixture holding two collinear reflectors. A mirror array was used to extend the range of three individual rails standing side-by-side from 10 meters to 30 meters. This setup reduces environmental uncertainty by shortening the distance between instruments, resulting in a more favorable approach than a pure linear setup where environmental conditions could vary significantly on opposite ends. Environmental conditions, especially temperature, can contribute a significant amount of uncertainty if not properly monitored and compensated.

Three setup configurations, one for each rail, were chosen so that data could be recorded at 3-meter intervals. The interferometer, once aligned, was kept stationary throughout the experiment, and the trackers were placed in three positions, depending on the setup (see figure 1). Four laser trackers were chosen (labeled A, B, C, and D), including trackers from two major manufacturers. Trackers B and C are the same make and model, whereas Trackers A and D are from the same manufacturer but different models. This approach was chosen to expand sample diversity while still observing repeatability within manufacturer.

An important aspect of testing linear performance is eliminating the use of angular encoders. The tracker head must be set in line with the path of the reflector to eliminate encoder error and achieve the highest possible accuracy. Thus, each tracker was aligned prior to testing to minimize the use of angular encoders. Although perfect alignment is difficult to achieve, each tracker was aligned so that uncertainty due to encoder error was relatively insignificant. In the worst-case scenario, angular encoder error in this setup accounted for a total of 0.07 μm.

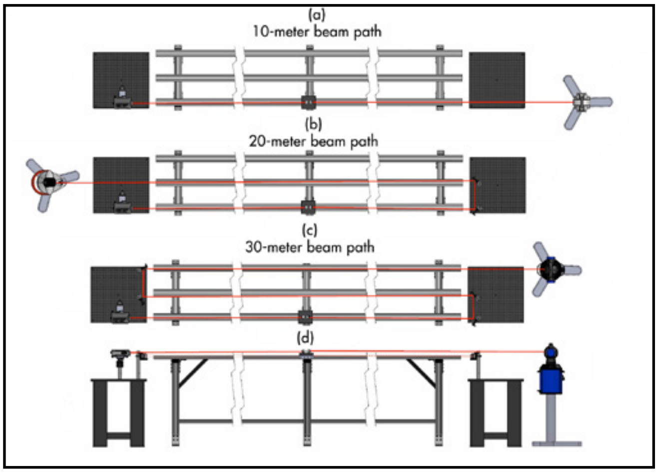

Figure 1. Experiment schematic, showing the tracker positions in relation to the reference interferometer and rail, showing the tracker positions for the10-meter (a), 20-meter (b), and 30-meter (c) max beam path ranges, in addition to a side-view display (d)

Once set up and aligned, standard 3-meter lengths were measured simultaneously by both the laser tracker and the interferometer. Environmental conditions such as temperature, pressure, and relative humidity as measured by both instruments were also noted for comparison. Measurement data was collected at 3-meter intervals consisting of five samples at each interval.

UNCERTAINTIES

Constraining and quantifying experimental uncertainties are crucial when analyzing and interpreting results, especially when dealing with high-precision measurement data. The first obstacle is creating a setup that contributes minimal influence on the experiment results. Depending on the level and straightness of the rail, the offset between the collinear reflectors could contribute error due to the pitch and yaw of the fixture. In this study, the total uncertainty due to pitch, yaw, and stability of the rail combine for a total of 1.3 μm. The pitch and yaw were determined along the 10-meter length of rail that held the cart. Stability was measured over a 5-second time span on the rail, corresponding to the sampling time of the laser trackers.

Perhaps the most important factor to take into consideration in this experiment is environmental uncertainty. Using an independent and calibrated temperature probe, temperature data across the length of the rail remained relatively constant, displaying a minimal temperature gradient (± 0.056° C). However, temperature readings between the interferometer and trackers deviated by as much as ± 0.833° C. These significant temperature deviations can be attributed to temperature probe error of certain trackers, and can be considered as uncontrollable factors. This is important because the trackers and interferometers compensate measurements based on environmental readings, most importantly temperature. Differences in environmental conditions affect the wavelength of the laser by changing the index of refraction of the median it travels through. Using the maximum deviations in temperature, pressure, and humidity to compute an index of refraction, an uncertainty estimate of 1.37 μm was determined for measurements over a 3-meter distance.[3]

Taking into account all other uncertainties, we computed an overall uncertainty budget of 3.37 μm (as seen in the table in figure 3). The maximum permissible error (MPE) allowed for

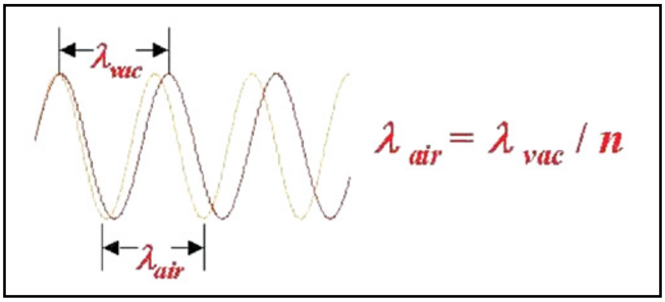

Figure 2. Example of how laser wavelength (λ) is affected by the index of refraction (n) of the air it travels through (Image courtesy of NIST)

Experiment Uncertainty Budget						
	Source of uncertainty	**Controllable**	**Estimate**	**Probability distribution**	**Divisor**	**Standard uncertainty**
1	XL-80 interferometer and XC-80 compensator	No	0.73 μm	Normal	1	0.73 μm
2	Resolution	No	0.25 μm	Rectangular	$2\sqrt{3}$	0.07 μm
3	Rail misalignment error @ ± 0.5 mm	Yes	0.05 μm	Rectangular	$\sqrt{3}$	0.03 μm
4	Error due to pitch of cart [0.1° and 0.25-mm offset]	Yes	0.74 μm	Rectangular	$\sqrt{3}$	0.43 μm
5	Error due to yaw of cart [0.1° and 0.25-mm offset]	Yes	0.74 μm	Rectangular	$\sqrt{3}$	0.43 μm
6	Stability (interferometer in relation to rail) @ 5 sec.	Yes	0.22 μm	Normal	1	0.22 μm
7	Temp difference between instrument readings	No	2.38 μm	Rectangular	$\sqrt{3}$	1.37 μm
8	Angular encoder error	Yes	0.12 μm	Rectangular	$\sqrt{3}$	0.07 μm
				Combined uncertainty	@$k = 1$	1.68 μm
				Expanded uncertainty	@$k = 2$	3.37 μm

Figure 3. *Table of the uncertainty budget, showing the various factors that influence the results of the experiment*

the trackers measured (Tracker D) was 11 μm, contributing a max uncertainty/MPE ratio of 0.306.

EXPERIMENTAL RESULTS AND DISCUSSION

The results for all four trackers show that in-line distance measurement accuracy is not a function of distance. The data show no clear trends that linear accuracy diminishes with distance. The deviations of trackers A and D (same manufacturer, different model) seem to fall within the uncertainty budget laid out for this experiment. Conversely, while in-line measurements for trackers B and C (same manufacturer and model) fall within the MPE threshold throughout the length of the rail, deviations vary considerably. The deviations for trackers B and C exceed the uncertainty budget, perhaps due to the error associated with the trackers. However, because the deviations of trackers A and D fall within the uncertainty budget, there is no way to discern whether the deviations are due to tracker error or experiment setup.

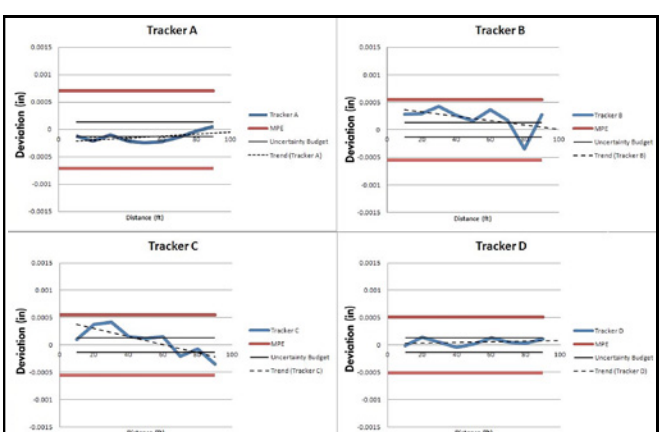

Figure 4. *Results of the distance in-line measurement experiment for all four laser trackers*

By reducing controllable experiment uncertainties and isolating the uncontrollable, more precise evaluation of laser trackers can be performed. In this case, the controllable error stems from pitch and yaw of the cart, angular encoders, as well as stability and misalignment of the rail. Under initial experiment conditions, the uncertainty/MPE ratio was 0.306. However, if controllable uncertainties were eliminated entirely, the uncertainty budget decreases to 1.55 μm, resulting in a max experiment uncertainty/MPE ratio of 0.141. This is significant because less than a quarter of the permissible error of tracker D could be accounted for, thus constraining any remaining error outside of the uncertainty budget to tracker inaccuracy. By reducing the uncertainty budget, more precise estimates for tracker linear inaccuracy can be determined. Based on these results, calibration rails prove to be an ideal solution for reducing calibration uncertainties. Although no setup can entirely eliminate all uncertainty, calibration rails show the most potential for minimizing and isolating these uncertainties.

ACKNOWLEDGEMENTS

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