A Laser Tracker Calibration System

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Abstract - We describe a laser tracker calibration system developed for frameless coordinate metrology systems. The system employs a laser rail to provide an *in-situ* calibrated length standard that is used to test a tracker in several different configurations. The system is in service at the National Institute of Standards and Technology (NIST) and at the Naval Surface Warfare Center, Corona Division (NSWC, Corona Division). The system description, calibration procedure, and uncertainty budget are presented.

Introduction

Laser trackers are becoming 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 increasingly 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. 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.

This paper describes the design of the NIST Laser Rail Calibration System (Larcs) which is deployed at the NSWC, Corona Division. The system was developed to provide users with an easy to use and easy to maintain tool for performing length measurement tests for characterizing the

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Commercial equipment and materials are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

performance of laser tracker measurement systems [1]. The system employs a laser interferometer with environmental sensors, a rail system and support structure that can be configured to generate a long reference length, typically four meters, in any arbitrary orientation in the tracker measurement volume. The detailed design of the Larcs and the advantages of its use for performing length measurement testing are discussed in this paper.

Background

Fixed length artifacts, such as calibrated scale bars, having target nests at each end are frequently used to perform length measurement testing. Alternatively, rigid structures, such as tripods, which hold a single target nest fixed relative to another fixed nest may also be employed. The latter construction is called a virtual length since there is no material standard between the nests and the metrology loop is connected through the tripods and the floor. Limitations exists for both practices which may make them either impractical or, more seriously, incapable of assessing the manufacturer's stated measurement specifications. What follows is a discussion of both the physical and virtual length methodologies for establishing a calibrated length artifact as well as a brief description of the advantages of the Larcs design.

In practice, the ranging system of the laser tracker is used to perform an *in-situ* calibration of physical length artifacts used during testing [2]. This is carried out by aligning the interferometer of the tracker directly along the length of the artifact such that only the interferometer is employed in the measurement and not the angular encoders (which are less accurate) of the laser tracker. In order to satisfy the requirement for traceability [3], if the tracker is used to calibrate the artifact's length, the laser tracker interferometer system itself must be independently calibrated. This usually necessitates a back-to-back comparison of the tracker's interferometer with a second calibrated interferometer.

Once this requirement has been met, the newly calibrated artifact is then used to determine the measurement errors for lengths that are particularly sensitive to errors in the tracker's angular encoders and optical and mechanical geometrical alignment. Due to time and economic constraints, re-calibration of the scale bar during the extensive performance tests is not typically performed. As a result, any drift in the artifact dimensions due to a change in its temperature may mask or exaggerate tracker measurement errors. For artifact materials such as steel and aluminum, the thermal drift due to temperature change is typically 10 to 25 micrometers per meter per degree Celsius.

Even if the temperature of the artifact is accurately known and compensation for the thermal expansion applied, the uncertainty in the artifact's coefficient of thermal expansion may degrade the accuracy of the performance evaluation. For example, the uncertainty in the nominal coefficient of thermal expansion for common artifact materials is estimated at one to two micrometers per meter per degree Celsius. For a four meter artifact that changes temperature by two degrees during measurement, the uncertainty in the calibrated length due to the uncertainty in the coefficient of thermal expansion is approximately 16 micrometers for just this single source of uncertainty. For some measurement tasks this uncertainty may be unacceptably large.

To support physical artifacts during measurement, operators frequently clamp them to a single tripod or rigid stand. The position of the target is then recorded in each of the target nests. Because of the long cantilevered lengths, the weight of the spherically mounted retroreflector targets (SMRs) can substantially bend the tripod or support structure. The change in static loading when the SMR is placed in each of the nests results in movement of the target between measurements. The effect is that the origin of the reference length shifts during the measurement which leads to an apparent length error. To compensate for this behavior, operators frequently use two SMRs. One is used as the measurement target while the other is simply placed in the opposite target nest and used as a dummy static load during the measurement process. The coordinate of the target SMR is recorded in one nest and then the measurement and dummy load SMRs are switched. Using this technique, the static loading on the support structure, during the measurement, remains unchanged at the cost of additional operator work and consequently lower efficiency. Although this procedure effectively eliminates the problem caused by non-symmetric loading of the support structure, increased manual intervention provides opportunity for the creation of operator blunders. In particular, the magnets which typically hold the SMR in the target nests are quite strong, making removing and replacing the SMRs without moving the test setup quite difficult. Increasing the number of times the operator removes and replaces the SMR creates the opportunity for inadvertently bumping or moving the reference length, resulting in an erroneous performance evaluation.

Another way of creating a reference length is to fix a single target nest to a rigid structure such as a tripod or stand. Two of these structures are then positioned relative to one another to create a virtual length. Again, the tracker's interferometer is typically used to measure the separation of the targets, thereby establishing a virtual artifact. If the environment is not thermally stable, as is often the case for large work volumes, the tripods thermally distort causing relative motion between the two target nests. During the measurement process, this motion may be incorrectly interpreted as laser tracker measurement error. Even if the operator correctly identifies this error source, characterizing or compensating for this behavior can be quite difficult. The difficulty arises because the material between the two tripods (often a cement floor) does not lend itself easily to thermal compensation.

The Larcs was developed to overcome some of the limitations associated with traditional methods for realizing a calibrated length. The Larcs, which is an adaptation of an instrument which was developed by NIST for evaluating large coordinate measuring machines [4], uses an independent reference laser interferometer, along with environmental sensors, to provide an *in-situ* calibrated or reference length for all length measurements performed. The advantage of using an independently calibrated interferometer system is that all measured lengths are traceable to the SI unit of length, *i.e.*, the meter. Consequently, no independent calibration of the tracker interferometer system is required.

Mechanically, the Larcs is designed to be easily configured to support a reference length in any orientation within the tracker work volume. The effects of operator blunders are minimized by using custom software, developed by NIST, that provides step by step automated measurement procedures. (Currently the software only interfaces with Leica laser trackers. This is because the Leica AXYZ software is a common software program used by both NSWC, Corona Division and NIST. However, the Larcs hardware can be used independently of the software to characterize any laser tracker.) The results of the scripted measurement tasks provide a fairly complete characterization of the laser tracker measurement system capability. The software is designed to provide careful checks to guarantee that the measurement procedures are consistent for all measurements and that operator influence quantities are minimized. Although at the time of this writing the draft standard *"B89.4.19 Performance Evaluation of Laser Based Spherical Coordinate Measurement Systems"* [5] is not yet complete, it is believed that these tests will be consistent with the evaluation procedures of the standard.

System Description

The design of the system was driven, in large part, by the functional requirement of the measurement tasks. In order to characterize the point-to-point length measurement capability of laser trackers, a reference length must be measured in enough orientations to examine a significant portion of the angular encoders' range. Measuring a reference length in a vertical, horizontal and two diagonal orientations at several distances from the tracker meets this requirement. Figure 1 shows a schematic of the Larcs configured to perform a horizontal measurement test. A reference laser interferometer and movable target carriage are mounted on an optical rail. The rail is then supported on tripods in the requisite orientations. The carriage, which holds two retroreflector targets, is manually positioned along the rail in the specified positions. Figure 2 shows an operator positioning the target carriage during the measurement process. Two SMRs are required. One is directed towards the reference interferometer and is used to establish the reference length. The other is directed

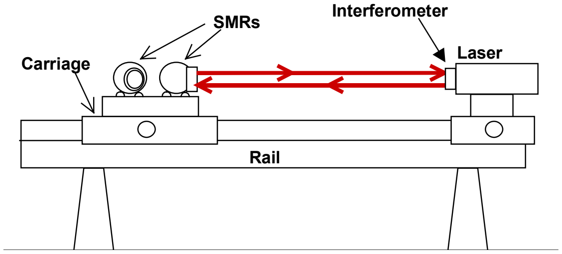

Figure 1. Schematic of Larcs system shown assembled in the horizontal length measurement configuration

towards the laser tracker and serves as the tracker target. The dashed lines shown in the picture depict the path of the measurement beams.

Although the rail system is easily configured to perform each of the remaining measurement tasks, the Larcs at the NSWC, Corona Division consists of three individual setups. Because the rail and support components of the system are relatively inexpensive, it is not cost prohibitive to use three independent setups. In fact, using independent setups saves valuable time by eliminating the necessity to reconfigure the Larcs for each required orientation. For measuring the vertical and left and right diagonal lengths, the rails are positioned and supported as shown in Figure 3. The left and right diagonal measurements are obtained by measuring the reference length with the tracker placed on opposite sides of the inclined rail. The system employs a single reference linear interferometer (the most expensive component) that is moved to each measurement setup. Figure 3 shows the reference interferometer attached to the inclined rail. In order to measure a vertical length, the reference interferometer is simply moved and attached atop the vertical rail as shown in Figure 4.

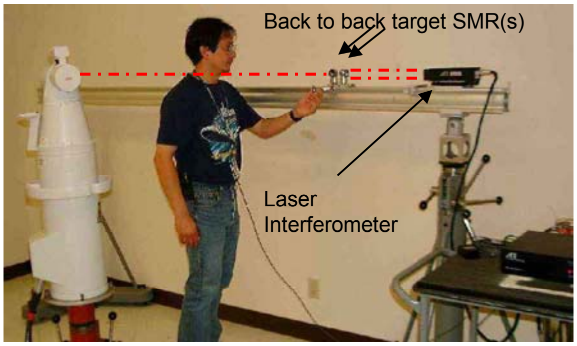

Figure 2. Larcs at NSWC, Corona Division configured to measure a horizontal length.

The reference laser interferometer is attached to each rail via a mounting plate. The mounting plate has a knurled friction knob that clamps the laser and interferometer tightly to the rail. An additional mounting plate is placed on the vertical rail to provide a safety stop in the event the laser mount is not sufficiently tight (see Figure 4).

The Larcs target carriage includes two kinematic nests that are used to position and hold the two SMRs. Each target seat consists of a three ball nest that captures the SMR and holds it magnetically. The seats are comprised of three four-millimeter carbide spheres. (See Figure 5.) The magnet is located in the center of the carbide sphere nest and has sufficient force to hold the SMR in place even if the carriage is fully inverted. This is an important requirement as the nests must secure the SMR in the vertical orientation during measurement. The seats are mounted on posts which can be raised or lowered to adjust the vertical height, relative to the laser beam, of each SMR. The posts are mounted on an adjustable plate that is translated and rotated in the plane of the carriage to align the horizontal position and orientation of the SMRs relative to the measurement path. This alignment is critical to reduce Abbe offset and is discussed in the uncertainty budget section of this paper. The design of the adjustable plate allows reasonably inexpensive optical rails to be used, as the requirement for very straight optical rails is reduced by using the aforementioned available adjustments. This helps to lower the economic barrier for implementation of this type of system.

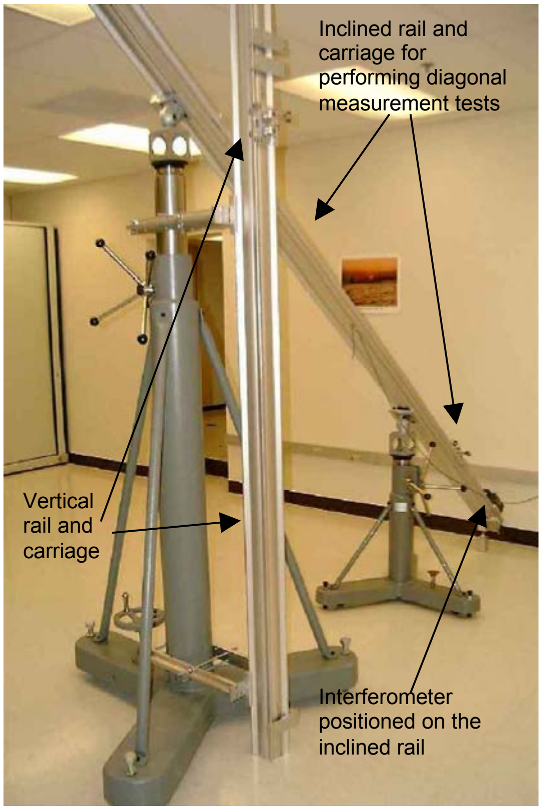

Figure 3. The Larcs rail system configured for measuring the vertical and diagonal lengths.

Figure 4. The laser interferometer attached to the vertical rail.

The carriage contains a brake mechanism which must be released by the operator before the carriage can be repositioned. The operator simply squeezes the hand lever to disengage the brake (see Figure 5). The brake re-engages automatically upon release of the hand lever. This prevents the carriage from sliding unintentionally along the inclined or vertical rails and damaging the SMRs.

The system is supported on four tripods; two hold a rail horizontally (Figure 1) and two hold a rail in an inclined orientation. The final rail, which is required for performing the vertical length measurement tests, is attached to the tall tripod which is also used to hold the inclined rail. Because it is only necessary to measure the vertical lengths from one side of the rail, this fixturing does not impose any limitations on the measurement process and allows for significant space savings. (See Figure 3.)

Systems Tests

The following section describes the tests that are required as part of the Larcs measurement software. Although the hardware can be used independently of the Larcs software to perform point-to-point length measurement tests, the result of the automated measurement routine can be used to characterize the performance of laser tracker measurement systems. The tests are sensitive to the major error sources of the tracker and consequently provide valuable information about the tracker system measurement capability. The software requires that a minimum of 99 length and 108 two-face measurements be performed. The physical location and orientation of the tracker, relative to the rail and target positions for these measurements, are fully specified. If three independent setups are used, the performance evaluation tests can be completed in typically five hours. This section will provide a detailed description of the positions and orientations for each required measurement. Although the Larcs software provides a scripted program for performing the two-face tests and analyzes the data, these measurements do not require the use of the Larcs hardware.

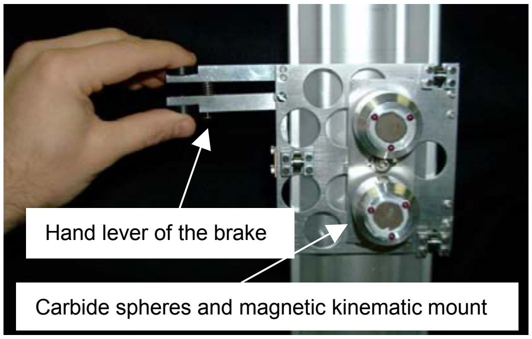

Figure 5. A hand lever is used to disengage brake mechanism before repositioning the carriage.

A minimum of nine distinct horizontal length measurements with the tracker placed at three different distances from the rail are required. The position of the tracker relative to the rail is depicted in the schematic of Figure 6. (Note: for the remainder of this discussion the letter “D” will refer to the distance between the rail and the tracker as depicted in the corresponding figures.) An initial horizontal measurement is performed with the tracker as near to the rail as possible (D < 1 m). Three repeated measurements of a length along the rail of approximately 2.3 meters are performed. This measurement position is selected because it forces the operator to measure over a large range of the horizontal encoder.

The tracker is then moved approximately D = 3 meters from the rail. The same length is measured three additional times. The tracker is then indexed (rotated) 90 degrees about the standing axis and the measurement repeated. The tracker is indexed two additional times, each by 90 degrees so that all quadrants of the horizontal encoder are examined. The measurement is repeated three times in each position so that 12 total measurements are obtained. This procedure is also repeated with the tracker positioned at D = 5 meters from the rail. The estimated error (tracker measured length minus the reference linear interferometer displacement measurement) is recorded for each measurement.

The vertical and left and right diagonal measurements are performed in much the same way. The vertical and diagonal length measurements are performed with the tracker at approximately D = 3 and 5 meters from the rail (see Figure 7). The vertical test examines a significant range of the vertical encoder while the diagonal tests examines errors that occur when both rotational axes are employed. Again, the tracker is indexed a total of three times at each distance from the rail. This gives a total of 24 measurements for each diagonal and vertical setup.

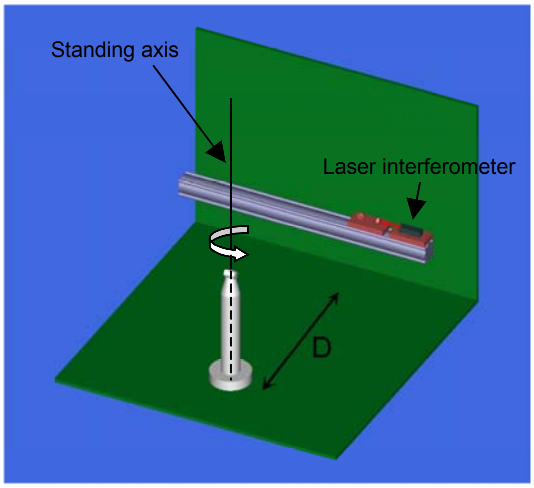

Figure 6. Schematic of the position of the laser tracker relative to the Larcs rail for horizontal measurements. For clarity, the tripods that support the rail in this orientation are not shown.

The two-face measurements are performed by first measuring the position of a fixed target in face one. The tracker head is then rotated into face two and the measurement repeated. The apparent position shifts in the vertical and horizontal directions are recorded. Two-face measurements are required because they accentuate the reversible errors in the physical positioning of the optical components of the laser tracker. The vertical rail of the Larcs along with a single target nest can be used to perform these tests. As the measurement does not require comparing the measured results to a reference length, the linear interferometer is not required.

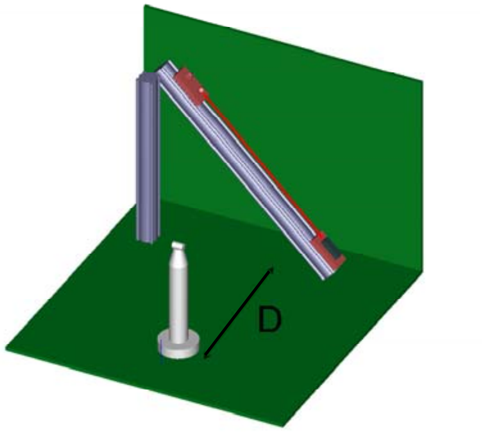

Figure 7. The laser tracker is positioned for measuring the left diagonal length. The right diagonal length measurement is performed by positioning the tracker on the opposite side of the inclined rail.

The target for the two-face tests is measured at three heights relative to the tracker: as near to the floor as possible, at approximately tracker height above the floor and at approximately twice the tracker height above the floor. Measurements are performed with the tracker at three different distances from the vertical rail (approximately two, four and six meters). At each distance the tracker measures the target location three times at each height above the floor. The tracker is indexed three times for a total of 36 measurements at each distance. For the three distances that is a total of 108 two-face measurements. The horizontal and vertical transverse deviations are reported.

Uncertainty Budget

The Larcs is designed to evaluate the point-to-point length measuring ability of laser trackers via a series of performance tests. The magnitude of the estimated errors reported by the Larcs performance tests depends on the metrological quality of the particular tracker under evaluation. Like all test equipment, the Larcs is not perfect, *i.e.,* even a perfect tracker will yield an imperfect performance test result due to small uncertainty sources in the Larcs. This section describes each of the major uncertainty sources of the Larcs. A quantitative description of each source and its contribution to the overall system measurement uncertainty is included. (Note: geometry errors in the construction of the SMR employed by a user during tracker measurements can lead to direct errors in the measured coordinates. The extent of the imperfection in the SMR must be assessed by the user and included as a potential measurement error.)

The manufacturer's specification for the linear interferometer system used with the Larcs, which includes the environmental compensation, is 1.0 part per million (1.0 micrometers per meter). The interferometer, along with the environmental system included with the Larcs, was evaluated at NIST and was determined to perform within this specification over a temperature range of 18 to 22 degrees Celsius, yielding a standard uncertainty of 0.6 micrometers per meter per degree Celsius.

The position of the retro-reflectors relative to the reference laser interferometer measurement path can produce an Abbe error. Figure 8 depicts the Abbe offset which produces this error when the carriage is rotated about the apex of the reference retro-reflector. A similar error is caused by rotation of the carriage about an axis perpendicular to the top surface of the carriage. The pitch and yaw of the carriage along the rail was measured using angular optics. The largest magnitude of the angular motion is 600 arc-seconds (≈3 milliradians). Although this is a rather large angular motion, a result of using inexpensive rails, the effects of this error can be greatly reduced. As discussed earlier, the position of the retro-reflectors relative to the reference interferometer measurement path can be adjusted using the extendable mounting posts and the two degree of freedom adjustable plate. The position of each retro-reflector is adjusted by placing an SMR in one of the target nests and viewing the return beam from the reference interferometer on a target over the return aperture. This process is repeated for the remaining SMR nest. Using this technique, the target nests can be adjusted to within 0.5 millimeter of the reference interferometer measurement path. The uncertainty in the Abbe offset combined with the angular motion of the carriage leads to a standard uncertainty due to this error source of approximately 1.5 micrometers.

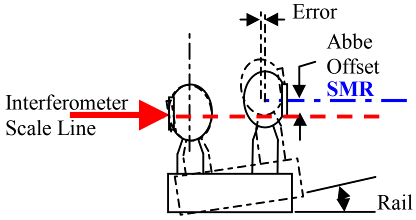

Figure 8. Error from rail pitch and Abbe offset

Relative motion between the rail system and the laser tracker can lead to apparent length measurement errors. This is because the reference interferometer coordinate frame is attached to the rail, while the laser tracker frame is usually attached to ground. If the rail undergoes a small translation during a measurement, the laser tracker correctly measures a position change of the tracker SMR. The reference interferometer measures no apparent position change because the reference interferometer, for rigid body motion, stays fixed relative to the reference SMR. This uncertainty source is characterized in [4]; however, since there are no forces exerted on the carriage, unlike the CMM probing case, the standard uncertainty is significantly smaller and is due to operator interactions with the carriage as described below.

A preliminary design of the retro-reflector carriage used a knurled locking nut to hold the carriage fixed in position. Tightening and loosening of the carriage created forces that caused motion of the rail relative to the tracker, leading to large measurement errors (between 15 to 20 μm). This uncertainty source was significantly reduced by redesigning the carriage so that the operator no longer tightens and releases a locking nut. With the addition of the brake mechanism, the operator imparts only a small force between the forefinger and thumb to release the carriage (see Figure 5). The preliminary carriage design also contained

Teflon bearing surfaces. Friction between the rail and the moving carriage was sufficient to cause relative motion of the rail. The new design replaced the Teflon bearing with roller bearings. The roller bearings provide much lower friction between the two components, significantly reducing the relative motion between the frames. Because it is difficult and impractical to measure the independent contributions of the addition of the brake mechanism and the roller bearings to the Larcs displacement measurement uncertainty, the effects of these modifications are characterized jointly. This is done using a second interferometer referenced to ground to detect relative motion of the rail. This also assesses uncertainty sources such as vibrations, and air turbulence that contribute to non-repeatability. The standard uncertainty due to these error sources was determined to be 0.7 micrometers.

The weight of the carriage can cause motion of the reference interferometer relative to the laser tracker. The reference interferometer may move along the direction of the measurement path due to bending of the rail. This bending is caused by a change in static loading of the rail when the target carriage is repositioned, similar to the aforementioned problem with cantilevered scale bars. To reduce the magnitude of this error source, the new carriage design was made much lighter by removing excess material. Additionally, the reference laser interferometer was moved and mounted over one of the tripods, to provide a more stable mount. To reduce the loading on the rail, the target carriage is located, in each of the two positions which comprise a single measured length, as close as possible to a tripod. This reduces the elastic deformation of the rail during the measurement. After these modifications, the standard uncertainty due to these uncertainty sources was reduced to 0.3 micrometers.

Thermal cycling of the environment can cause low frequency movement of the entire Larcs apparatus. If the elapsed time between the two measurement positions which comprise a single length measurement is short, the effect of drift in the rail system can be significantly reduced. Over the course of a few hours the setup can drift several micrometers. The Larcs software requires that the time between the two measurement points not exceed 30 seconds. If the time between the two points exceeds this threshold the software will not record or display the measured result. Using this approach, the standard uncertainty due to thermal drift is limited to less than 0.2 micrometers in an environment with a short term thermal drift rate of less than 2 degrees Celsius per hour.

The last major contributor is the uncertainty that arises when the system is setup on a compliant surface. (At the micrometer level almost all surfaces are compliant.) The tripods rotate slightly when the floor around any one of the support feet is compressed. The source of compression may be simply an operator standing near one of the support feet of the tripod. The error is magnified by the tall tripod because of the long lever arm. The error was measured and recorded. On a concrete floor, a 95 kilogram (210 lbs) person can move the rail structure and SMR approximately 8.0 micrometers. The motion of the tripod is primarily elastic and the remaining hysteretic behavior is less than 0.1 micrometers. Consequently, as long as the operator moves away from the tripod before recording a measurement point, a major portion of this uncertainty source can be removed. The Larcs automated software is used to effectively remove the elastic component of this uncertainty source. The system provides a visual prompt and an audible beep to remind the operator to step back from the setup before each measurement is recorded. (If the Larcs is used on a surface other than a concrete floor, the effect of the inelastic component of the rail motion due to surface deformation during measurement must be included in the uncertainty budget.)

Assuming theses uncertainties are uncorrelated, the individual components can be combined via the root sum of squares. This gives a combined standard uncertainty of (1.7 μm + 0.6 μm/m × L) micrometers, where L is in meters. The expanded uncertainty (*k* = 2) [7] is then (3.4 μm + 1.2 μm/m × L) micrometers. For the 2.3 meter length described in the draft standard, the expanded uncertainty is 6.2 micrometers. The uncertainty budget is summarized in Table 1.

Table 1

Uncertainty Source	Standard Uncertainty
Laser interferometer	0.6 μm/m
Abbe errors	1.5 μm
Rail Translation	0.7 μm
Thermal Drift	0.2 μm
Floor Compliance	0.1 μm
Combined Std. Unc.	1.7 μm + 0.6 μm/m × L
Expanded Unc. (*k* =2)	3.4 μm + 1.2 μm/m × L

The uncertainty statement was tested by comparing the Larcs to a second interferometer referenced to ground. A back-to-back displacement measurement comparison was performed measuring six lengths, each 2.3 meters long. The magnitude of the largest difference between the two systems was 5.1 micrometers and the magnitude of the average difference was 4.4 micrometers, both well within the 6.2 micrometer expanded uncertainty statement.

Summary

We have described the development and utility of the NIST Laser Rail Calibration System (Larcs). The system calibrates the point-to-point length measuring capability of a laser tracker. The Larcs has a length measurement uncertainty of 3.4 μm + 1.2 μm/m × L when employed under normal metrology conditions (18 °C to 22°C). A typical laser tracker yields a performance evaluation result (the largest observed error) of 35 μm on a 2.3 meter length when performing a length measurement calibration using the Larcs, hence the manufacturer's specification for these instruments can be approximated by this value. This infers a (tracker) specification to (Larcs) uncertainty ratio [6] of approximately 6:1, notably better than the usual 4:1 required in many quality systems. The automated procedures, which are provided as part of the instrument, are fully specified and its ease of use makes the system a valuable and convenient tool for evaluating the point-to-point length measurement capability of laser tracker measuring instruments.

Acknowledgements

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