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Laser Tracker Calibration
- Testing the Angle Measurement System -[1]

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1 Introduction

Physics experiments at the SLAC National Accelerator Laboratory (SLAC) usually require high accuracy positioning, e. g. 100 µm over a distance of 150 m or 25 µm in a 10 x 10 x 3 meter volume. Laser tracker measurement systems have become one of the most important tools for achieving these accuracies when mapping components. The accuracy of these measurements is related to the manufacturing tolerances of various individual components, the resolutions of measurement systems, the overall precision of the assembly, and how well imperfections can be modeled. As with theodolites and total stations, one can remove the effects of most assembly and calibration errors by measuring targets in both direct and reverse positions and computing the mean to obtain the result. However, this approach does not compensate for errors originating from the encoder system. In order to improve and gain a better understanding of laser tracker angle measurement tolerances we extended our laboratory's capabilities with the addition of a horizontal angle calibration test stand. This setup is based on the use of a high precision rotary table providing an angular accuracy of better than 0.2 arcsec. Presently, our setup permits only tests of the horizontal angle measurement system. A test stand for vertical angle calibration is under construction. Distance measurements[2] (LECOCQ & FUSS, 2000) are compared to an interferometer bench for distances of up to 32 m. Together both tests provide a better understanding of the instrument and how it should be operated. The observations also provide a reasonable estimate of covariance information of the measurements according to their actual performance for network adjustments.

2 Error Sources and Calibration

Most of today's laser trackers are capable of making at least four distinct measurement types (WILKINS, RULAND, 1998). The four primary observables are angles (both horizontal and vertical), relative distances, absolute distances, and tilt measurements. In addition, there are a series of support measurements, such as barometric pressure and dry bulb temperatures, whose information is required in order to make corrections to the primary observables. The accuracy of the measurements is related to the manufacturing tolerances

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[2] The testing of absolute laser tracker distance measurements is analogous to the testing of total station distance measurements. This subject is well understood and will not be discussed in this paper

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of various individual components, the resolutions of measurement systems, the overall precision of the assembly, and how well imperfections can be modeled (i.e. calibrated).

2.1 Angular Measurements

The angular measurements are simply defined as the spatial orientation of the emitted laser beam with respect to the tracker's local coordinate system. This is given by the orientation of the rotating head that emits the beam, hence, anything that affects the head position or its spatial determination will have a negative impact on the measured angles. The main mechanical contributors to this error are the encoders, coupling between the encoders and the rotation shaft, mechanical alignment, and bearing wobble (RULAND, 1993).

The error contribution from the angular encoders themselves can be minimized by using high resolution encoders with a calibration table. The error caused by the coupling of the encoders and the rotation shaft is more difficult to eliminate. The rotation shaft is a precisely machined component that has the encoder attached, but also serves as a carrier for the optics. Any variation in the assembly will manifest itself as a deviation in the encoder reading from the desired "true" value.

An ideal mechanical configuration would have the laser path and the rotational axes of the beam steering assembly one and the same. However, if the beam and the axis are not parallel, the effect is analogous to the collimation error found in a theodolite. As the beam (or telescope) is rotated through 360 degrees, it will trace out a cone. In the case of the tracker, two collimation type errors exist due to the beam path (line of sight), at different locations along its path, having to be parallel to two rotational axes. In addition, if an offset exists between the laser beam and the rotational axis an eccentric error will also exist. As with a theodolite, it should be possible to remove the effects of these errors by measuring targets in both direct and reverse positions and computing the mean to get the result.

The measuring head may be influenced by bearing wobble if the bearings and shaft are not sufficiently aligned or if bearings are substandard or worn. One can understand that if any of these conditions exist, it would have a detrimental impact on the results that would be somewhat inconsistent through the working range of the instrument. This would make it very difficult to model and correct for this effect and makes it imperative that great care be initially taken in the selection and assembly of the shafts and bearings.

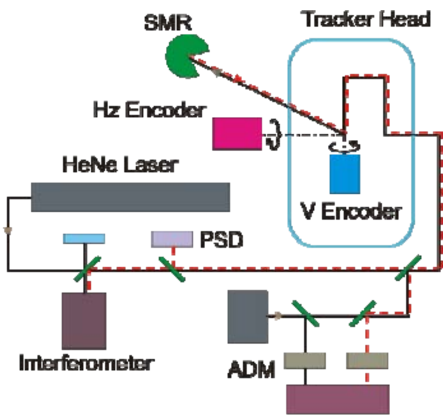

Fig. 1: Laser tracker schematic

There is an additional error affecting the angular measurements that originates from the ability of the tracker electronics to remain on the center of a stationary target. The tracker is a high speed device that receives commands from the servo feed-back loop (fig. 1, Bridges & White, 2008), which is constantly monitoring and correcting for large offsets detected at the Position Sensitive Diode (PSD); once the offset is below a certain threshold, the offset reading is converted into a correction value for the encoder readings. However, even for a stationary target there is a random oscillation of the tracker head about the center of the target. This effect is reduced by taking advantage of its randomness and sampling data over a set time frame, where the final observation result is the mean of many measurements.

2.2 Calibration

The previous section outlined a number of areas where imperfect assembly creates errors in the angular measurement results. In order for the trackers to achieve expected values of a few tens of micrometers, these errors must be reduced. There are already very stringent specifications on the manufacturing and assembly of the units, which are hard to improve upon. Therefore, the desired marginal improvement would be to build an instrument that behaves consistently and hence, can be modeled mathematically allowing corrections to be included for the imperfections.

As mentioned previously, some of the errors can be eliminated by measuring targets in both direct and reverse positions of the instrument. This mode of operation should be used whenever possible, but unfortunately it actually only lends itself to measuring stationary targets where it is easy to redefine the target locations. However, all of the possible corrections must be made “on the fly” when using a tracker for dynamic measurements.

The mathematical model must include parameters that define what was intended to happen with what is actually happening. In essence, the spatial orientation and offsets of the actual beam path with respect to the designed beam path must be included in the model and determined. This creates a minimum of four parameters for each of the two measuring planes as well as a third set of four parameters that describe the collinearity of the laser beam with the optical axis. Additional parameters are included that characterize the location of the PSD, axis non-squareness, and other more complex beam relationships. The actual models used by the manufacturers are considered proprietary so very little information has been published.

Calibration routines are distributed as part of the software package, where the user is guided through a measurement scheme designed to separate and allow estimation of the unknown parameters. They can be full calibrations involving all of the parameters or, as a daily check calibration determining a subset of the most crucial parameters. The routine calibration is fully automated, which allows the operator to make a quick check as to the integrity of this subset of parameters and update as necessary.

It is evident from the above discussions on angular measurements, that any small change in the internal relationship of the various components would require that the calibration parameters be re-determined. Thus the entire system is very sensitive to temperature changes and the determined calibration values are only valid for a small fluctuation from the calibration temperature. The interior temperature is kept constant, but clearly this creates an acclimatization and warm-up period that must be strictly adhered to.

However, these calibration measurements cannot compensate for any errors intrinsic to the angular encoder system. To evaluate the encoder systems, it is necessary to directly compare laser tracker angle readings to a reference normal (INGENSAND, 1986).

3 Encoder System Testing

While earlier generations of laser trackers used encapsulated commercial encoder systems mounted on the horizontal and vertical axes, the miniaturization of today's trackers required the integration of the individual encoder components into the tracker housing. A system calibration approach is necessary to test the performance of the angular encoder systems. This approach has the additional advantage of including any residual errors of the optical path alignment into the calibration.

3.1 Test Set-up Considerations

Referencing a laser tracker's encoder system to a reference normal requires, in principal, the absolute centering of the laser tracker's axes to the reference system's axes. It is important to consider that an error due to an offset of the rotation axis of the laser tracker and the rotary table cannot be distinguished from an error due to an eccentricity of the laser tracker's vertical axis and its encoder. Both errors have the same wavelength, hence, they cannot be separated. Since the required centering accuracy is very hard to achieve, the angle measurement systems are coupled using autocollimation. Autocollimation allows measuring small angles very accurately since a change of the tracker angle $\pm\delta$ produces a signal of $\pm 2\delta$. But most importantly, the tracker doesn't need to be precisely centered. A telescope focused on infinity produces parallel rays which are reflected back onto themselves with mirrors perpendicular to the rays. In this case, the angle α between the two mirrors remains constant (see fig. 2, NEUHIERL, 2005) even if the instrument is shifted by a small amount. Although laser trackers don't use telescopes, the focused laser beam behaves analogously over the tracker's working distances.

The collinearity of the laser tracker axes and the test stand's axes is achieved by precisely leveling both systems. A small difference (<0.08 degree) in the leveling of the two instruments has only negligible effects on the calibration results (<0.1 arcsec). The collinearity is checked with the internal laser tracker measurement systems. By measuring the zenith angle with the laser tracker to the mirror at different orientations of the rotary table, the parallelism of the two rotation axes can be determined. The axial displacement of the rotation axes can be found by checking the distances. To avoid any cross-talk of residual set-up errors, the horizontal and vertical encoder systems are tested sequentially. Presently, only the horizontal encoder test stand is ready for production measurements, the vertical comparator is still under construction.

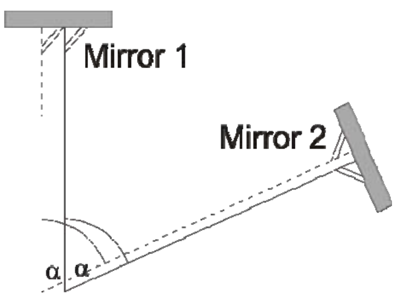

Fig. 2: Autocollimation and centering

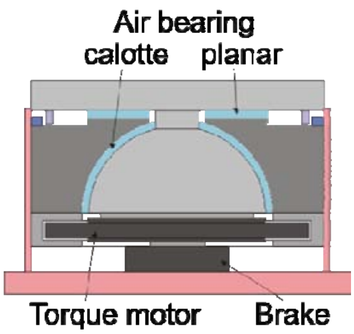

Fig. 3: Cross-section of rotary table

3.2 Horizontal Rotary Table

The rotary table RT264TB was built by Kugler GmbH, Salem, Germany. It holds a circular mounting platform with a diameter of 280 mm. The platform sits on two different kinds of air bearings (see Fig. 3, KUGLER, 2006). A planar air bearing is located directly below the face plate providing the lifting capacity for the platform and the load. The second air bearing, a calotte type spherical bearing, counters the planar bearing and provides lateral stability due to its shape. The angular position encoder consists of a Renishaw Signum RESM angle encoder system with a 200 mm diameter stainless steel ring with 20 µm graduations and four symmetrically positioned read heads (Renishaw SR). The system is specified with 1 arcsec graduation accuracy and 0.01 arcsec resolution. The use of four read heads eliminates the angular reading errors caused by the eccentricity of the measurement system relative to the rotary axis of the table and provides some redundancy.

3.2 Rotary Table Encoder System Calibration

Calibration of the angular readings of the rotary table is based on the principle of the rosette technique (SCHREIBER, 1886, NOCH & STEINER, 1966, COOK, 1954). The rosette technique is used to calibrate precision polygon prisms. Step 1 of the calibration process (see fig. 4), is to measure the difference of the angle between two adjacent faces from that of two autocollimators. Step 2 is to rotate the polygon prism by the angle between two faces without changing the autocollimators and measuring the difference of the angle between the next two adjacent faces from that of the two autocollimators. This step is repeated for the n sides of the polygon until every angle difference is measured. The sum of the angles measured must result in 360 degrees. With this information the angle between the two autocollimators can be determined and the deviations of the readings can be attributed to deviations of the individual angles from the nominal.

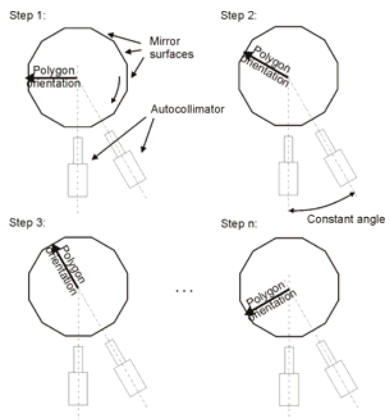

Fig. 4: Polygon prism calibration

This technique is designed to calibrate a polygon prism which limits its use for the calibration of a rotary table to the n sides of the polygon prism. The approach used for calibrating the SLAC rotary table is slightly different. Two autocollimators are again used with a constant angle between them (see fig. 5). Instead of using a polygon a fixture with only two mirrors is used (GASSNER & RULAND, 2008), where the angle between the mirrors is also constant. The technique applied can be described in the following steps. The first step

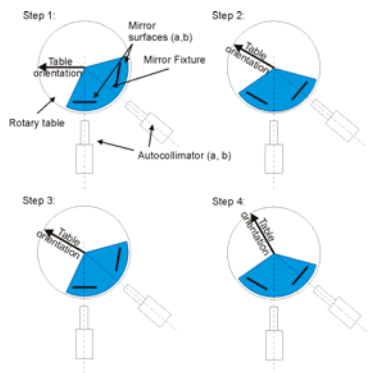

Fig. 5: Calibration steps

is to set the fixture with the mirrors in a manner that mirror ‘a’ is positioned in line with autocollimator ‘a’ (see fig. 5, Step 1). Step 2 is to rotate the table together with the fixture until mirror ‘b’ is in line with autocollimator ‘b’, thereby rotating the table by an angle x (x needs to be evenly dividable into 360). Step 3 consists of holding the rotary table in position while placing the fixture back into the position with mirror ‘a’ in line with autocollimator ‘a’ (see Fig. 5, Step 3). Step 4 is a repetition of step 2, the table is again rotated by an angle x. The steps are repeated until a full circle is completed. A prerequisite for this method is that the internal positioning system of the rotary table can determine the zero position with high accuracy identifying when the full circle is completed. By counting the steps needed to complete the circle, angle x can be calculated and the angles measured by the rotary table at every step can be compared to multiples of x. Angle x can be set to any angle evenly dividable into 360 by changing the position of one autocollimator. The advantage of using a small angle x for a higher resolution is counteracted by the fact that the described technique tends to experience drift in the measurements due to the longer test duration and the larger number of mirror resets.

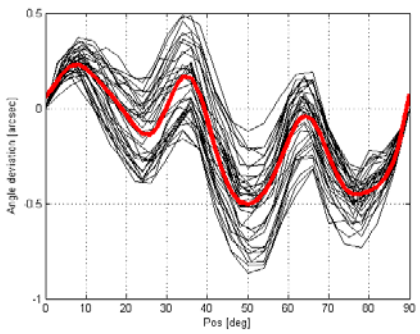

Fig. 6: Results of the rotary table calibration. (Single calibration run – black lines; estimated calibration result – red line)

The Kugler rotary table has a total of four angle encoder read heads spaced 90 degrees from each other. By analyzing the results of the calibration runs it becomes evident that the deviations repeat themselves every 90 degrees. Therefore the deviations can be attributed to the graduation ring and the errors of the read heads can be neglected. The results of multiple calibration runs are depicted in fig. 6. Hence, the absolute value of an angle between two positions of the rotary table can be determined with ±0.2 arcsec accuracy after applying the calibration data to the internal positioning system.

4 Laser Tracker Testing

The calibration of the laser tracker (see fig 7, 8) is performed by using the rotary table torque motor to turn the platform, along with the laser tracker. During this motion, the laser trackers remains locked on to the target mirror. Hence, while the tracker head remains stationary, the tracker’s body moves with the platform. This results into a new horizontal angle reading which is compared to the rotary table encoder reading.

4.1 Retroreflector vs Mirror

In the above setup a mirror is used as the target to eliminate the effects of an offset between the rotation axes. Almost all field measurements are made with a spherically mounted retroreflector (SMR) instead of a mirror. To confirm the assumption that measurements to a mirror are affected by the same deviations as measurements to a retroreflector, the two setups were compared (see Fig. 9). The measurements to the SMR are corrected for the axial offset between the rotary table and tracker. Only small deviations were found which could have been caused by the slightly different test set up. Further investigations have to be performed to eliminate the discrepancies or to explain the differences.

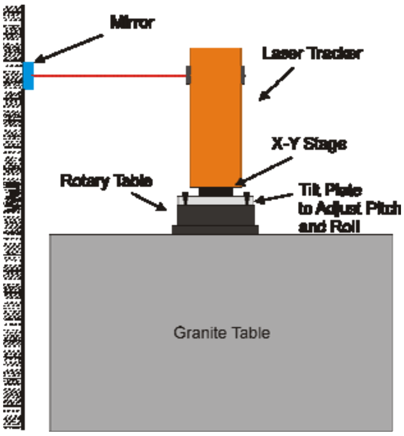

Fig 7: Schematic of setup

Fig 8: Faro laser tracker test setup

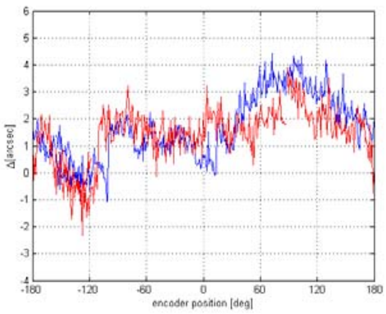

Fig 9: Mirror target vs SMR

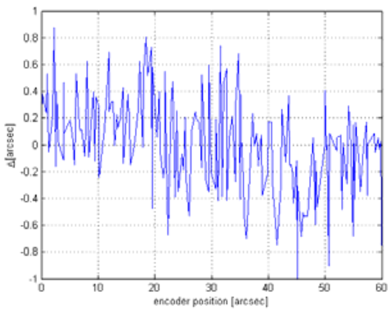

Fig. 10: Angle measurement resolution

4.2 Encoder Resolution

To determine the angle measurement resolution, a test was performed with the rotary table moving in 1 arcsec steps over a range of 1 arcmin. The results (fig. 10) show neither a systematic trend nor a step pattern with the step height being the finest resolution. This was expected since the laser tracker measured angle is the sum of the encoder reading plus a correction derived from the PSD reading.

4.3 Laser Tracker Stability

As discussed earlier, improving the tracker performance by applying corrections derived from calibration measurements requires the tracker to be stable over the time frame between calibrations. To test the stability, the tracker was removed from the rotary table and transported from the laboratory to the office and back, a distance of about 4 km. The calibration measurements were repeated the next day. The measurements (see fig 11, 12) show essentially the same trend, however, the amplitudes seem to differ slightly. Further investigations on the stability of the calibration parameters are still necessary.

4.4 Horizontal Angle Measurement System Mapping

Finally, the angle measurements of the SLAC trackers were mapped. Again, as previously discussed, the angle measurement accuracy is improved by applying an error map as part of the factory calibration process. Fig 13 shows the horizontal angle errors of on older model tracker with the encoder map correction turned off. Fig. 15 shows the same tracker with correction turned on. It is evident that the angle errors could be significantly improved with a better correction map.

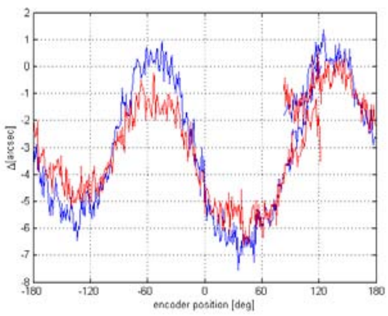

Fig. 11: Angle calibration results before and after transportation (older model)

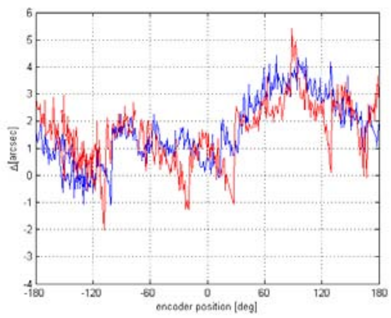

Fig 12: Angle calibration results before and after transportation (newer model)

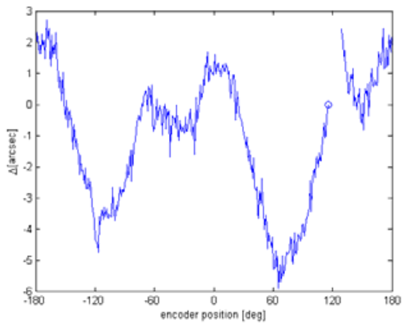

Fig. 13: Older tracker without encoder map correction

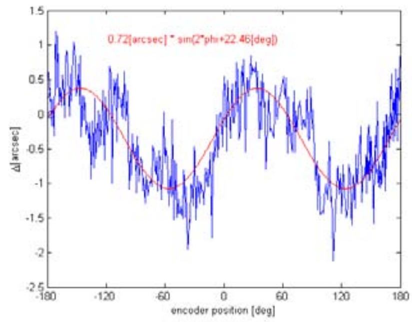

Fig. 14: Same tracker with correction enabled

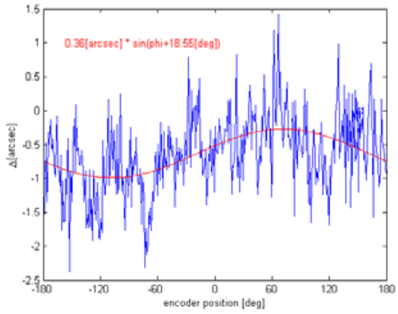

Fig. 15: Newer tracker model horizontal angle errors

The mapping results of a newer model tracker are shown in fig. 15. While the residual errors are significantly smaller than those of the older model, the map still shows a systematic component which could be corrected for by an improved correction map.

5 Conclusion and Outlook

The calibration of the rotary table resulted in an absolute angle accuracy of better than 0.2 arcsec. With the presented setup it is possible to test any horizontal angle measurement instrument as long as it can be mounted to the faceplate of the rotary table with the rotation axes being collinear and additionally supporting autocollimation. The testing of our laser trackers so far indicated that the deviations of their angle measurement systems are stable and can be corrected. Presently, a procedure is under development to derive encoder correction maps from our test results. With these improved correction maps we expect angle accuracies of better than 1 arcsec. A test stand to calibrate vertical angles is under construction; first results are expected in early 2009.

References

Bridges, B. & D. White (1998): Laser Trackers – A new breed of CMM, in: Quality Digest Magazine, 2/1998

Cook, A. H. (1954): The calibration of circular scales and precision polygons, British Journal of Applied Physics, pp. 367-371

Gassner, G & R. Ruland (2008): Laser Tracker Test Facility at SLAC – Progress Report, in: Proceedings of 10th International Workshop on Accelerator Alignment, Tsukuba, SLAC-Pub-13129

Grillmayer, E (2003): Untersuchung systematischer Fehlereinflüsse bei Messungen mit dem Kreisel DMT Gyromat 2000, Shaker Verlag, p 189

Ingensand, H. (1988): TPM – Ein neues Gerät zur vollautomatischen Prüfung von Teilkreisen in elektronischen Theodoliten, in: Schnädelbach, K. & H. Ebner (Hrsg), Ingenieurvermessung 88, Dümmlerbuch 7808, Bonn

Kugler GmbH (2006): Operating Instructions – air bearing rotary table RT264TB

LeCocq, C. & B. Fuss (2000): Analysis of Laser Tracker and Total Station Surveys, SLAC-TN-2000-1

Neuhierl, T. (2005): Eine neue Methode zur Richtungsübertragung durch Koppelung von Inertialmesstechnik und Autokollimation, Dissertation, Technical University Munich

Noch, R. & O. Steiner (1966): Die Bestimmung von Kreisteilungsfehlern nach einem Rosettenverfahren, Zeitschrift für Instrumentenkunde 74, Heft 10

Ruland, R. (1993): The Chesapeake Laser Tracker in Industrial Metrology, in: XX International FIG Congress, Melbourne, Australia, 1994, SLAC-PUB-6286

Schreiber, O. (1886): Untersuchung von Kreistheilungen mit zwei und vier Mikroskopen, Zeitschrift für Instrumentenkunde 6

Wilkins, R. & R. Ruland (1998): New Generation Laser Trackers, internal report