

The Influence Of The Tooling Ball Reflector On The Accuracy Of Laser Tracker Measurements: Theory And Practical Tests

by
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1. Abstract

Since summer 1996 Leica offers a retroreflective target for their SMART310, LT500 and LTD500 laser tracking systems which incorporates a small glass prism in a ½ inch spherical housing called Tooling Ball Reflector. This has been the first time the air path corner cube as it was common for most spherically mounted retroreflectors (SMR) till then has been replaced by a glass prism.

The use of a glass prism is not without problems for the user of a laser tracker, since accuracy dependencies in respect to the entry angle of the laser beam can be observed. Furthermore these systematic errors can exceed the accuracy specifications of the laser tracker by a multitude. This means special attention has to be paid by the user when such tooling ball reflectors are in use. Even if it can be assumed that all measurements have been made correctly it leaves often some inadmissible uncertainties on the reliability of the measurement results.

The paper explains the physical fundamentals causing these effects. The characteristics and magnitude of the error for static measurements is illustrated in theory and as results from practical tests. An outlook on possible alternatives to the currently available glass prism type tooling ball reflector is also given.

2. Introduction

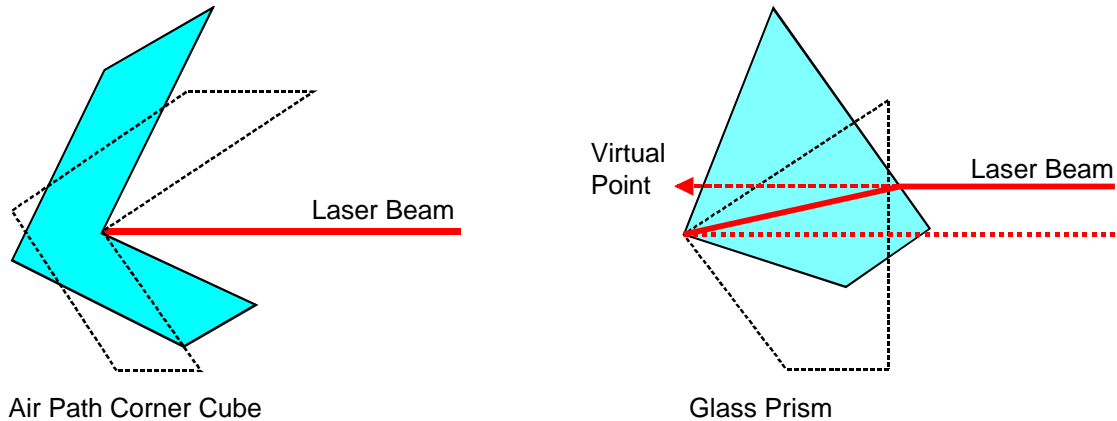
For a long time only two different kinds of retroreflective targets have been used with laser trackers: cateyes and air path corner cubes. Since the cateye is relatively big and heavy the corner cube is the kind of retroreflector preferred by most users. Thus corner cubes are available in a variety of housings mainly in balls of different sizes, starting from 3 ½" down to ½" in diameter. These SMRs are manufactured respectively sold by several companies.

Glass prisms, as they are very common in other applications like in the linear interferometry, are usually not suited for measurements with laser trackers due to the effects on the lateral and distance accuracy caused by the often uncontrollable entry angle at the retroreflector.

The only SMR made for laser trackers carrying a glass prism is the TBR (Tooling Ball Reflector) from Leica. This became feasible because only a very small glass prism is mounted inside the ½" ball, which limits the maximal possible errors, but can also not eliminate the errors entirely. The advantages of a glass prism are its robustness against breakage when dropped and the cost effectiveness. Furthermore it is much easier kept clean and it returns more light to the tracker than an air path corner cube, which is especially advantageous on long measuring distances.

3. Optical Effects Caused by Glass Prisms

The major difference between an air path corner cube and a glass prism is the change of the medium the laser beam travels through. Whereas the laser beam always stays in air while being reflected at the three plane mirrors of an air path corner cube, it has to travel through partly glass while going through a glass prism.



The lateral error at the prism is caused by the refraction at the front surface, where the beam enters the glass. The error in the distance measurement is due to the variation in the length of the beam's path inside the prism. There is also a change in the length of the path the beam stays in air, which has taken into account, too. Since these effects are unrecognized by the laser tracker, it delivers the coordinates of a virtual point (at the end of the arrow) instead of the prism's corner point.

The amount of the lateral and distance error is a function of the entry angle. The dimension, e.g. height of the glass prism and the refractive index of the glass used have a proportional influence on the errors and are important, when designing a retroreflector.

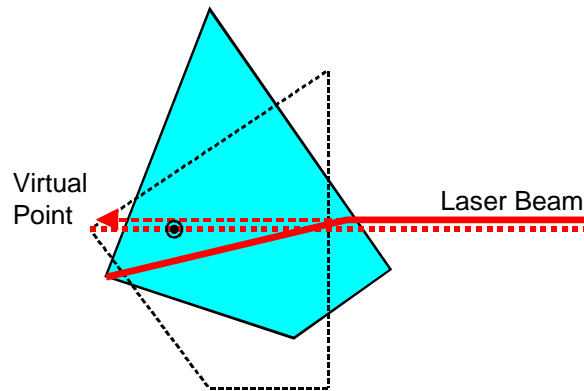
The following example gives an idea of the magnitude of these effects:

If the air path corner cube of a 1.5" SMR would be replaced by a glass prism of the same dimensions (height of the prism = $\frac{3}{4}$ ", refractive index of the glass = 1.5) the following errors would occur:

Entry angle	Lateral error	Distance error
0°	0.0000"	0.0000"
10°	0.0441"	0.0038"
20°	0.0915"	0.0156"

It is possible to compensate for these errors by moving the pivot point away from the prism's corner point.

However, it is not possible to compensate entirely the relatively complex error pattern caused by the refraction with the simple circular movement of the prism's corner point around the pivot point. By optimizing the location of the pivot point a good compromise between a certain limited range of the entry angle and the maximal allowable errors may be found in many cases. The best results are usually obtained with the pivot point approx. $\frac{2}{3}$ of the prism's height behind the front surface.



⊙ Pivot point

Error compensation through relocated pivot point

Leica's TBR has a prism with a height of 6 mm (0.2362") integrated. The distance between the front surface and the ball's center (pivot point) is 3.86 mm (0.1520"). The refractive index of the glass is 1.5151 (BK7). This design results in lateral and distance errors as shown below.

Table 1

Entry Angle	Lateral Error	Distance Error
	in 0.001"	
-42.5°	-15.91	2.38
-37.5°	-10.28	1.24
-32.5°	-6.09	0.54
-27.5°	-3.12	0.14
-22.5°	-1.19	-0.04
-17.5°	-0.08	-0.09
-12.5°	0.39	-0.07
-7.5°	0.42	-0.03
-2.5°	0.17	0.00
0.0°	0.00	0.00
2.5°	-0.17	0.00
7.5°	-0.42	-0.03
12.5°	-0.39	-0.07
17.5°	0.08	-0.09
22.5°	1.19	-0.04
27.5°	3.12	0.14
32.5°	6.09	0.54
37.5°	10.28	1.24
42.5°	15.91	2.38

Chart 1

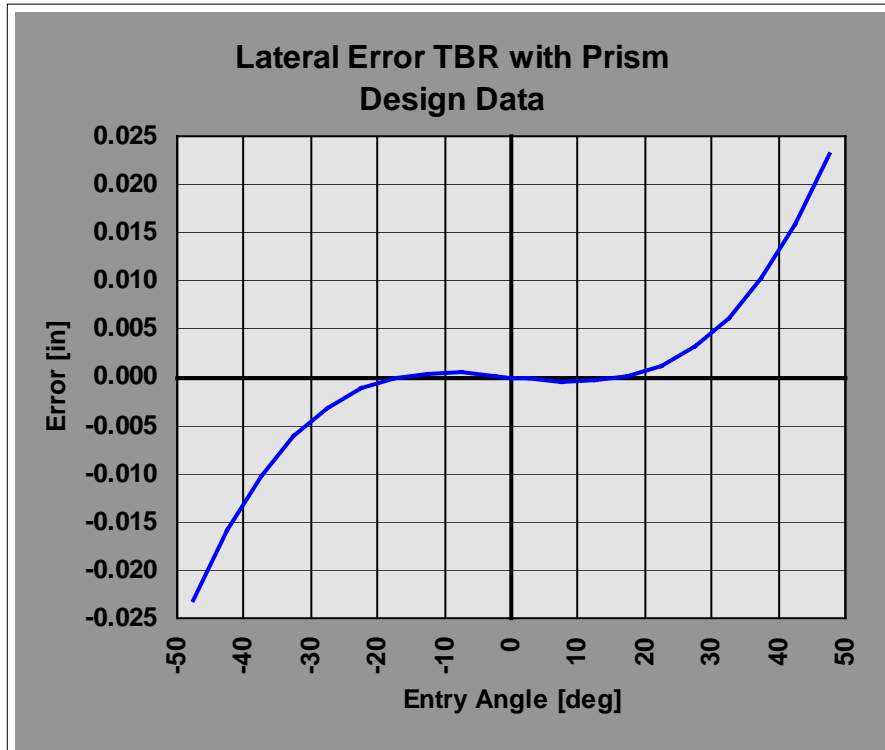
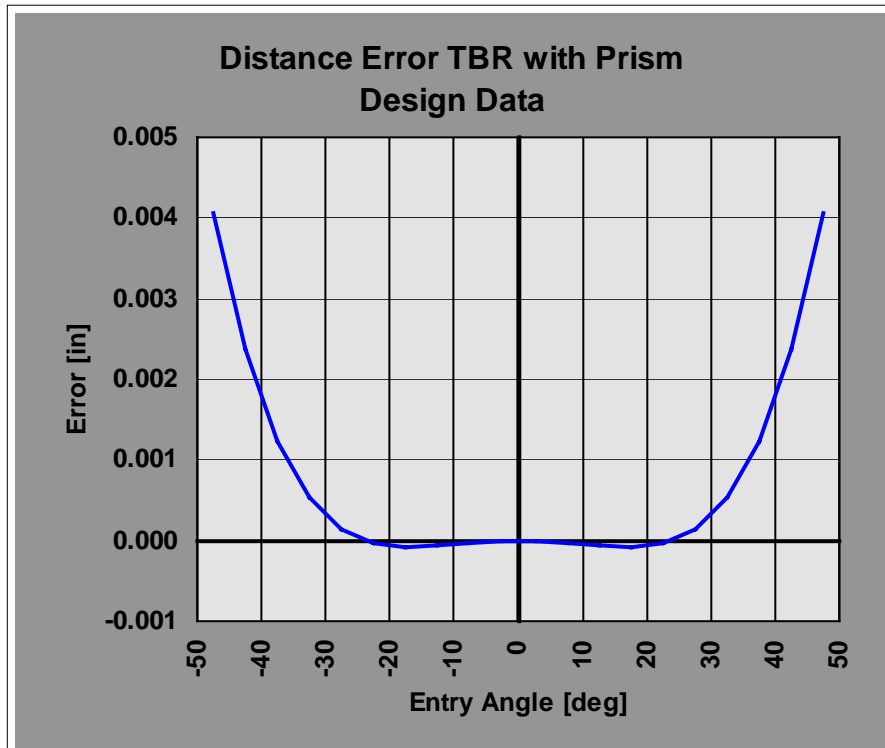


Chart 2



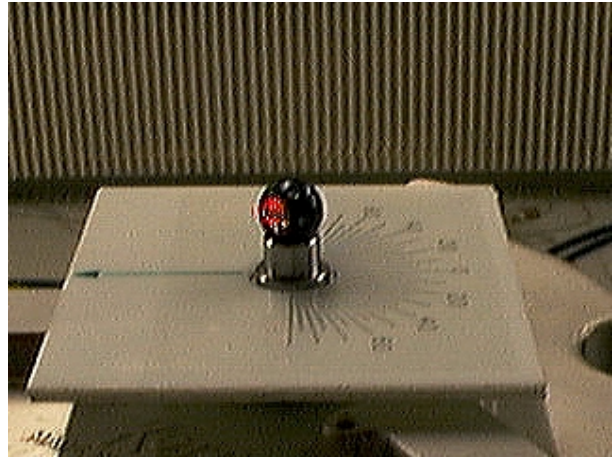
Though the TBR allows entry angles close to $\pm 50^\circ$ the error are becoming unacceptable large beyond $\pm 25^\circ$, which is about the entry angle an air path corner cube usually cuts off the laser beam.

4. Test Results

To verify the design data several TBRs were measured. The measurements were made with several LTD500s. A tool was mounted on a industrial stand, which allowed to rotate the TBRs in steps of 5° .



Test setup



Tool (the bold can be rotated around the vertical axis and has an index mark on the rear)

The test results are agreeing with the design data very well. They also proof, that it is easily possible to take measurements with entry angles up to $\pm 45^\circ$, which, of course, leads to errors exceeding the accuracy of the laser tracker by a multitude.

The results of one of these many measurements are shown in the table and charts below.

Table 2

Entry Angle	Design Data		Test Results	
	Lateral Error	Distance Error	Lateral Error	Distance Error
	in 0.001"			
-42.5°	-15.91	2.38	-16.61	2.38
-37.5°	-10.28	1.24	-10.16	1.24
-32.5°	-6.09	0.54	-6.26	0.61
-27.5°	-3.12	0.14	-2.83	0.18
-22.5°	-1.19	-0.04	-0.63	-0.10
-17.5°	-0.08	-0.09	0.24	-0.14
-12.5°	0.39	-0.07	0.71	-0.14
-7.5°	0.42	-0.03	0.51	-0.10
-2.5°	0.17	0.00	0.18	0.02
2.5°	-0.17	0.00	-0.24	-0.02
7.5°	-0.42	-0.03	-0.55	-0.10
12.5°	-0.39	-0.07	-0.39	-0.14
17.5°	0.08	-0.09	0.47	-0.14
22.5°	1.19	-0.04	1.26	-0.14
27.5°	3.12	0.14	3.54	0.18
32.5°	6.09	0.54	6.69	0.41
37.5°	10.28	1.24	10.98	1.20
42.5°	15.91	2.38	16.93	2.34

Chart 3

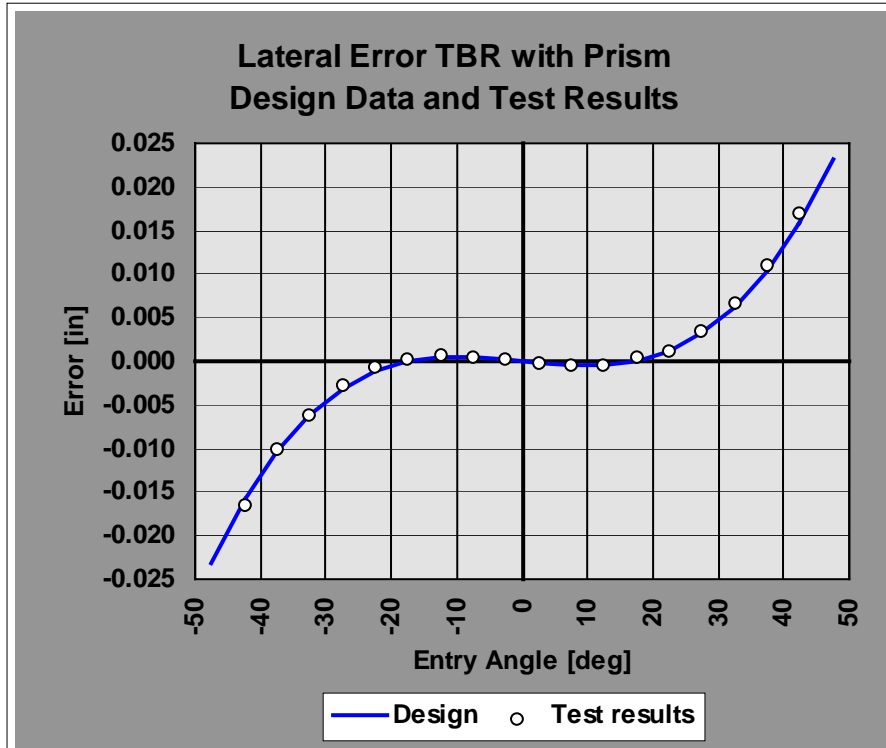
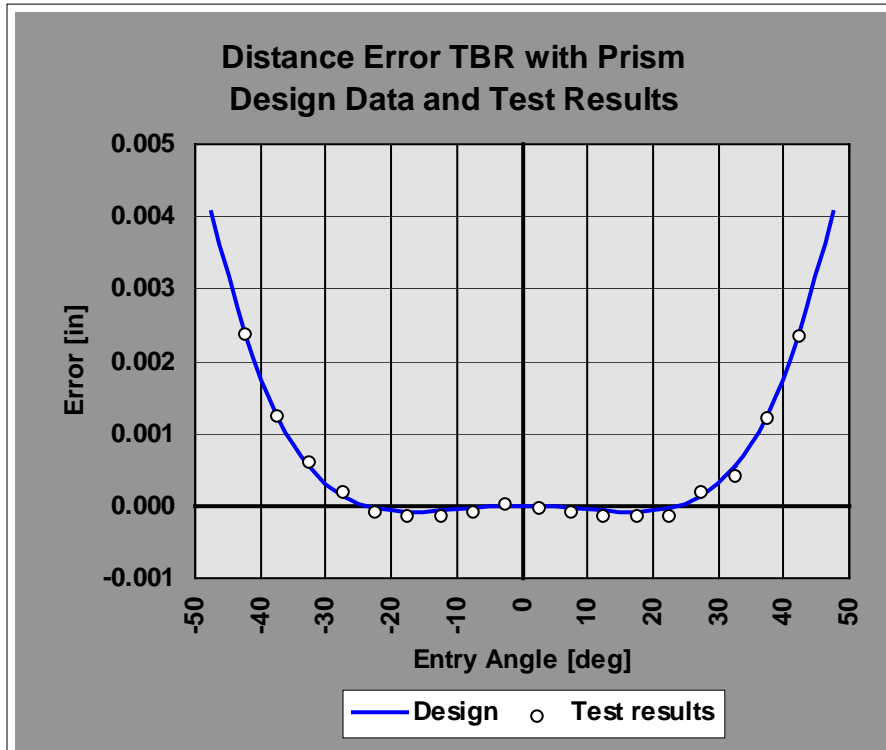


Chart 4



5. Conclusion

The use of a small glass prism as a retroreflector for tracker measurements can be a cost effective, robust, nearly unbreakable alternative to an air path corner cube, especially in small sized reflectors like the TBR. However, a sufficient accuracy is only guaranteed as long as operated within an entry angle range which is equivalent to the one provided by the air path corner cube. The extended range of the acceptance angle can be used only for tracking when no measurements are taken.

With the current version of the Leica-made TBR there is no control, whether the maximal permissible entry angle has been exceeded during the measurement or not. Integrating an air path corner cube, which is free of entry angle related effects, also in TBR-sized SMRs is a possible solution to add more confidence to the measurement results. Another answer to the problem, which would maintain the advantages of the prism, is to limit the maximal possible entry angle by a ring-shaped diaphragm as shown in the picture of a first prototype below. This modification of the TBR is currently under evaluation at Leica and first test have already proofed the effectiveness of this new design.



Modified Tooling Ball Reflector (prototype)

