Relative range error evaluation of terrestrial laser scanners using a plate, a sphere, and a novel dual-sphere-plate target

Bala Muralikrishnan[1], Prem Rachakonda[1], Vincent Lee[1], Meghan Shilling[1], Daniel Sawyer[1], Geraldine Cheok[2], and Luc Cournoyer[3]

[1]Engineering Physics Division,
[2]Intelligent Systems Division,
National Institute of Standards and Technology,
Gaithersburg MD 20899

[3]Measurement Science and Standards,
National Research Council of Canada,
Ottawa, Canada

Abstract

Terrestrial laser scanners (TLS) are a class of 3D imaging systems that produce a 3D point cloud by measuring the range and two angles to a point. The fundamental measurement of a TLS is range. Relative range error is one component of the overall range error of TLS and its estimation is therefore an important aspect in establishing metrological traceability of measurements performed using these systems. Target geometry is an important aspect to consider when realizing the relative range tests. The recently published ASTM E2938-15 mandates the use of a plate target for the relative range tests. While a plate target may reasonably be expected to produce distortion free data even at far distances, the target itself needs careful alignment at each of the relative range test positions. In this paper, we discuss relative range experiments performed using a plate target and then address the advantages and limitations of using a sphere target. We then present a novel dual-sphere-plate target that draws from the advantages of the sphere and the plate without the associated limitations. The spheres in the dual-sphere-plate target are used simply as fiducials to identify a point on the surface of the plate that is common to both the scanner and the reference instrument, thus overcoming the need to carefully align the target.

Keywords: relative range error, terrestrial laser scanner, sphere target, plate target, dual-sphere-plate target

1. Introduction

Terrestrial laser scanners (TLS) produce a 3D point cloud by measuring the range and two angles (azimuth and elevation) to points on the surfaces of objects in a scene. Establishing metrological traceability of TLS measurements is a challenge [1]. The ASME B89.7.5 [2] provides guidance to demonstrate metrological traceability for industrial dimensional measurements. A key step in the ASME B89.7.5 is the development of an uncertainty budget that describes and quantifies the significant uncertainty contributors. In the case of TLS measurements, the error sources may broadly be classified into instrumental errors, errors related to the form and nature of the object, errors caused by the environment in which the scanning is performed, and methodological errors

[3]. It is a considerable challenge to quantify these error sources and develop detailed uncertainty budgets for TLS measurements.

As a first step towards quantifying instrument errors, the ASTM E57 committee on 3D imaging systems developed a standard – the ASTM E2938-15 [4] - for relative-range error evaluation of 3D imaging systems. TLS systems generally use time-of-flight (TOF) techniques such as pulsed TOF, phase-based TOF, and frequency-modulated continuous wave (FMCW) techniques for range detection. The ranging unit realizes the SI unit of length and is therefore a key component of the system. Characterizing ranging errors is therefore an important aspect in establishing metrological traceability of TLS measurements. Relative range error is one component of the overall ranging error and can be characterized through a relative range error test. The test involves comparing the distance between two target positions along the ranging direction as measured by the TLS against the same distance determined by a reference instrument that offers higher accuracy such as a laser tracker (LT).

The relative range test may be realized in many ways. We have realized it as shown in Fig. 1 with the TLS located at one end of a long tunnel and the LT at the other end of the tunnel. The target is in-line with the TLS and the LT and has accommodations to move nominally in-line with both instruments. The target is first placed at the reference position (close to the TLS) and both the TLS and the LT measure the target position. The target is then moved to the test position, which is farther away from the TLS than the reference position, and both instruments again measure the target position. The relative range error is the difference in the displacement determined by the TLS and the LT between the reference and the test positions. The target is generally moved to different test positions so that the relative range error (with respect to the reference position) may be determined for different displacements.

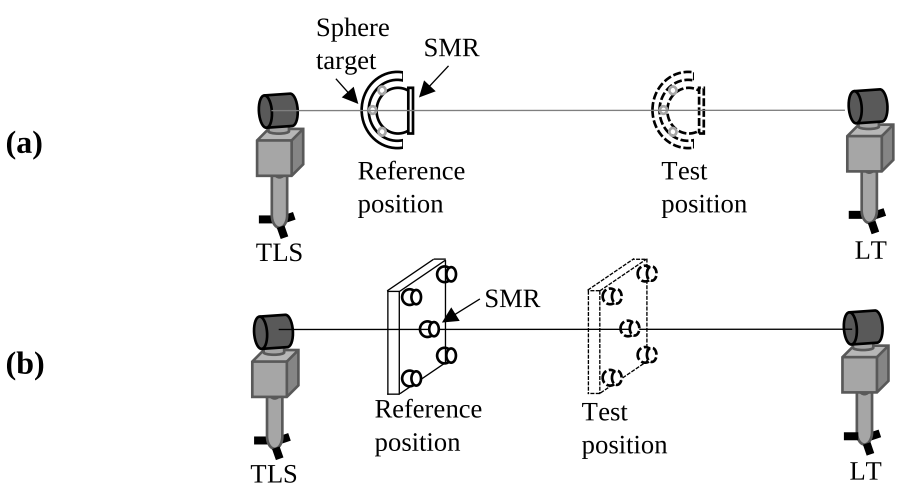


Fig. 1 *Schematic of a relative range test using* **(a)** *a sphere target and* **(b)** *a plate target shown. The reference and test positions are nominally along the line joining the TLS and the LT. Both instruments measure the target at the reference position. The target is then moved to the test position where both instruments measure the target. The relative range error is the difference between the displacement determined by the TLS and that determined by the LT.*

The choice of target geometry [5-7] is an important factor in the realization of these tests. The recently published ASTM 2938-15 [4] describes a relative range test for 3D imaging systems using planar targets. The clear advantage of planar targets is that the laser beam strikes the target at incidence angle of nominally zero degrees, hence 3D imaging systems can produce 3D point clouds of these targets even at far distances. However, identifying the point on the plane measured by the TLS that coincides with the point measured by the LT is a challenge. If there is an offset between the two points, small misalignment angles in the orientation of the plate can result in Abbe errors that reflect as a range error.

A sphere target offers the advantage of allowing the determination of a unique derived point, its geometric center. If both the LT and TLS can determine the true geometric center of the sphere, alignment of the target along the line joining the LT and the TLS is not an issue. Some TLS systems, however, may have difficulty in obtaining enough data from the surface of spheres at far distances to reliably determine the sphere center. It is therefore possible that the center determined from such data may result in larger errors in determining the geometric center, which would result in the incorrect determination of the relative range error. Also, large spheres with small form error that are suitable at far distances (50 m or greater) can be expensive.

In this paper, we explore the advantages and limitations of the plate and the sphere target, and propose a novel dual-sphere-plate target that overcomes the limitations of the plate and the sphere target. The spheres in the dual-sphere-plate target are only used as fiducials to identify a point on the surface of the plate (i.e., finding the center of the plate from the TLS data), thus minimizing the errors induced by target misalignments.

2. Reference measurement uncertainty

Reference measurements for the relative range experiment are performed using a LT in absolute distance meter (ADM) mode. For this particular LT, the manufacturer-specified maximum permissible error (MPE) in range is 10 µm. This has been verified in our laboratory by comparing the ADM against our reference interferometer. Using the manufacturer-specified MPE as the upper bound for a rectangular distribution, the standard uncertainty in range measurement for any target position is $10/\sqrt{3}$ = 6 µm. The uncertainty in displacement is therefore $6\sqrt{2}$ = 8 µm. The k = 2 expanded uncertainty due to the LT is therefore 16 µm, which is at least a factor of 10 smaller than the observed errors of the TLS under study.

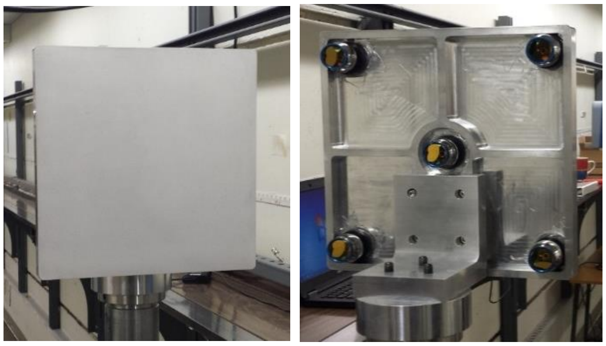
3. TLS settings

All TLS data are acquired at 92 points per degree along both the vertical and the horizontal angle direction. Four scans are acquired at each position of the target. The data is then reduced to the derived point (the center of the plate or the sphere) and results from four scans averaged to attenuate the influence of random effects.

4. Relative range measurements using a plate target

4.1 Plate target

The plate target is fabricated out of aluminum and is shown in Fig. 2. It is 304.8 mm x 304.8 mm (12 in x 12 in) on the front and has a thickness of 25.4 mm (1 in). The front surface is sand-blasted to produce a scanner friendly dull gray matte finish. Five 38.1 mm (1.5 in) spherically mounted retroreflector (SMR) nests are glued onto the backside of the plate. One of the five SMR nests is located centrally on the plate and is used for reference measurements with the tracker. The other four SMRs are located on each of the four corners (≈250 mm apart) and are used to align the plate.



(a) **(b)**

Fig. 2 **(a)** *Front view of the plate artifact* **(b)** *back view showing the SMRs*

4.2 Plate alignment and measurement procedure

When performing relative range measurements, it is important that the center of the plate as determined by the TLS coincides with that determined by the LT to avoid Abbe errors. That is, however, often not possible. In our design of the plate, the center of the SMR (O_1 at the reference position and O_2 at the test position) is in fact offset from the front face of the plate by about d = 30 mm, see Fig. 3. When the artifact is moved from the reference to the test position, the displacement recorded by the LT is O_1O_2. If the plate suffers from a pitch angle α at the test position and the TLS measurements result in A_1 and A_2 as the centers of the plate at the reference and test positions, respectively, then the displacement determined by the TLS is larger than the reference displacement O_1O_2 by approximately $d(1\text{-}\cos\alpha)$. For an offset d of 30 mm and a pitch angle α of 5º, the error is approximately 0.11 mm, which is a significant fraction (≈ 30 %) of the ranging error of the TLS under study.

We do note that this offset d is of concern because the SMRs in our measurement are mounted on the backside of the plate. It is possible to obtain LT reference measurements by manually probing the sides of the plate with the SMR. This will reduce or eliminate the offset d but increase significantly the amount of time and effort to obtain reference measurements.

The problem due to the offset d is further compounded by the fact that the TLS may in fact not record A_1 and A_2 as the centers of the plate. If the data are not uniformly distributed, it is quite possible for the TLS to record points B_1 and B_2 as the center of the plate at the reference and test positions, respectively. Then the displacement determined by the TLS is B_1B_2, which is larger than the reference by an amount $e\sin\alpha + d(1\text{-}\cos\alpha)$, where e is the offset A_2B_2 (Fig. 3(b)). For an offset e of 1 mm, an offset d of 30 mm, and a pitch angle α of 5º, the overall error is 0.2 mm (the contribution due to offset e is 0.09 mm), which is a significant fraction (≈ 60 %) of the ranging error of the TLS under study. Alignment is therefore critical in performing the relative range tests using a plate target. It should be noted that although Fig. 3(b) shows the effect of pitch angle only, the same discussion applies to yaw angle as well; an offset out of the plane of the paper in Fig. 3(b) in conjunction with a yaw angle will produce similar effect as a pitch angle. We also note that because there are no fiducials on the plane, the point recorded by the TLS may not necessarily intersect the line joining the TLS and the LT. It is therefore quite possible that some finite offset *e* will exist in relative range measurements made with planes. Alignment is therefore necessary to reduce or eliminate the effect of the offset.

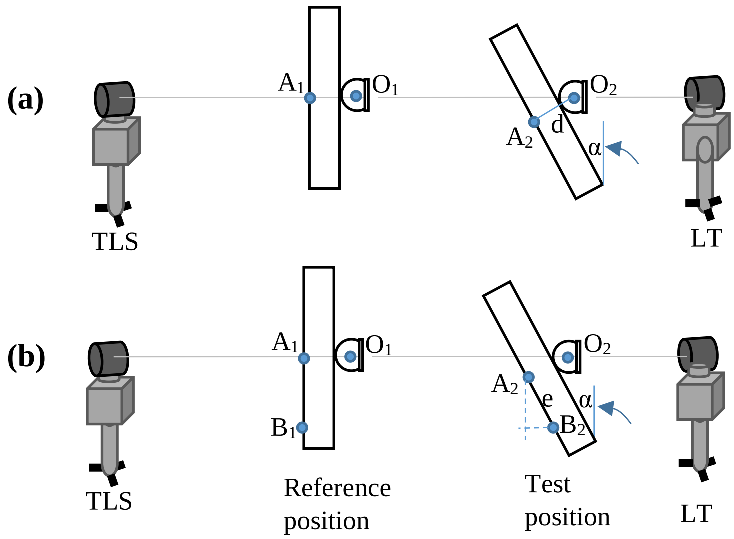


Fig. 3 *Effect of plate misalignment on relative range tests* **(a)** *showing the effect of offset d along the ranging direction* **(b)** *showing the effect of offset e perpendicular to the ranging direction*

To mitigate the errors discussed above, the following alignment and measurement procedure is adopted. The TLS and the LT are placed about 23 m apart in our tape tunnel facility. The laser beam of the LT is directed to the center of the rotating prism mirror of the TLS (by placing an SMR very close to the TLS) and the azimuth and elevation angles are recorded. This establishes the reference line, i.e., the approximate line joining the LT and the TLS. The plate is then placed at the reference position (≈2 m from the TLS) such that the center of the plate (as determined by the central SMR) is on the reference line to within about 0.1° along the azimuth and elevation axis directions from the reference line.

The four corner SMRs are then measured to calculate the yaw and pitch angles. During the alignment, the objective is to align the plate until the range as measured by the LT to each of the four SMRs are within about ± 25 µm of each other while maintaining the azimuth and elevation angles of the central SMR to within 0.1° of the reference line. Because the four corner SMRs are located on a square of side length ≈250 mm, the pitch and yaw angles are then at most $\tan^{-1}(0.025/250)$ = 0.006°. With the plate carefully aligned as described above, a 30 mm offset *d* will have negligible influence on the measurement. However, because we only align the central SMR to within 0.1° of the reference line, that plate may remain misaligned by as much as 0.1° even if the range values to all four corner SMRs are equal. A 1 mm offset *e* will then result in an error of 1sin(0.1) = 0.002 mm while a 50 mm offset *e* will result in an error of 0.087 mm.

Because our measurements resulted in a uniform distribution of points on the surface of the plate, alignment of the central SMR to within 0.1° was sufficient in our case. If the offset error e is anticipated to be large, a tighter tolerance may be required in the alignment of the central SMR to the reference line.

4.3 Relative range errors

The relative range measurements on the plate target are performed by moving the target in steps of 3 m starting from a reference distance that is 2 m from the TLS. The plate was carefully aligned at each of the positions as described earlier. This was a time consuming process, taking more than three hours to complete the measurements at the seven positions.

Fig. 4 shows the relative range errors for the TLS under study at the 5 m, 8 m, 11 m, 14 m, 17 m, and 20 m range values (this corresponds to displacements of 3 m, 6 m, 9 m, 13 m, 15 m, and 18 m, respectively, from the reference position). The relative range error is largest at the 5 m distance (3 m from the reference position) and decreases at larger distances.

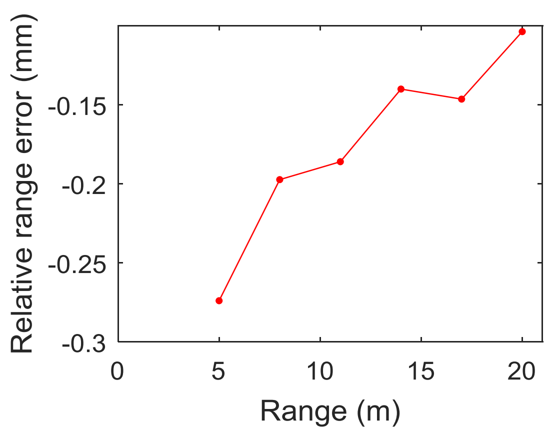


Fig. 4 *Relative range errors using a plate artifact*

4.4 Plate target summary

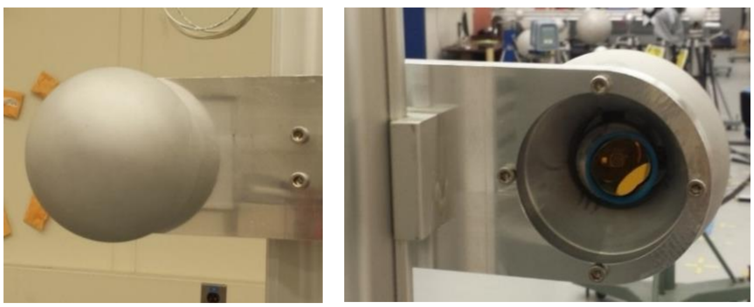
A clear advantage of planar targets is that the TLS can produce 3D point clouds of planar targets at far distances without introducing any artifacts (i.e., the data is nominally representative of a plane without any systematic errors) in the data. However, identifying the point on the plane measured by the TLS that coincides with the point measured by the LT is a challenge. In our design of the plate, the LT measures a point that is offset from the plate. It is therefore important that the TLS data be reduced to a point that lies on the line joining the LT and the TLS. If that cannot be achieved, the plate has to be carefully aligned at each of the test positions to reduce the effect of Abbe errors. This can be a challenging and time consuming task.

5. Relative range measurements using a sphere target

5.1 Sphere target

Any sphere with scanner friendly characteristics such as matte finish, high diffuse reflectance factor, non-volumetric diffusion surface, large diameter, and small form error in comparison to the ranging error, may be suitable as a target. While solid spheres can be inexpensive, obtaining reference measurements using a LT is a challenge. Rachakonda *et al.* [8] discuss a LT based SMR-walking method to obtain reference measurements using solid (or hollow) sphere targets. In this method, the sphere surface is probed using an SMR, while being tracked by an LT to obtain the reference measurements. This method involves considerable manual labor, is time consuming, and very dependent on the skill of the operator.

In this study, we use commercial targets called 'integration spheres,' depicted in Fig. 5. These are partial spheres made of aluminum with a satin finish that is suitable for 3D imaging systems. The inside of the sphere is machined out and a kinematic nest is located centrally to seat a 38.1 mm (1.5 in) SMR as shown in Fig. 5(b). The SMR is held in place by magnetic preload. The concentricity between the outer surface of the scanning sphere and the center of the SMR is measured on a coordinate measuring machine (CMM) and determined to be less than 10 µm. The form error of the outer surface is also determined to be less than 10 µm. The concentricity and form error are at least an order of magnitude smaller than the ranging errors of the TLS under study.



(a) **(b)**

Fig. 5 (a) *Front view of the integration sphere,* **(b)** *back view showing a centrally located 38.1 mm (1.5 in) SMR*

5.2 Determining center of sphere target

It is important that the center of the sphere as determined by the TLS coincides with that determined by the LT to avoid Abbe errors. In the case of the integration sphere, the center of the SMR is in fact concentric with the outer surface to within 10 µm. However, it is still possible that the TLS point cloud obtained from the surface of the sphere is not a correct representation of the sphere geometry, but is somehow distorted by the material in the immediate vicinity of the target (because of secondary reflections) or by local averaging on the sphere surface. The diameter of the laser spot for the TLS under study is about 3 mm at exit and increases at the rate of about 3 mm for every 10 mm. The spot size is thus fairly substantial on a 100 mm diameter sphere and local averaging is therefore conceivable. This distortion often results in the sphere appearing to be squished or flared, i.e., the unconstrained radius of the sphere calculated from the sphere data could be smaller or larger than the calibrated diameter of the sphere, giving a center location that is influenced by the target rather than just TLS ranging errors.

As an example, Fig. 6 shows the unconstrained best-fit radius of a nominal 75 mm radius sphere scanned at different point densities from 6 points per degree through 57 points per degree (equal sampling intervals along both the vertical and horizontal axis directions). The unconstrained radius changes by at least 3 mm indicating that surface averaging might be a problem for some scanners. We note that the points-per-degree specification is with respect to the TLS; that is, 6 points per degree at a distance of 5 mm will result in a sampling interval of (1/6 x π/180) x 5000 = 14.5 mm while a 57 points per degree specification will result in a sampling interval of 1.5 mm. The spot size at the 5 m distance is about 4.5 mm; thus, data acquisition at 57 points per degree will result in the spot overlapping on the surface from one point to the next.

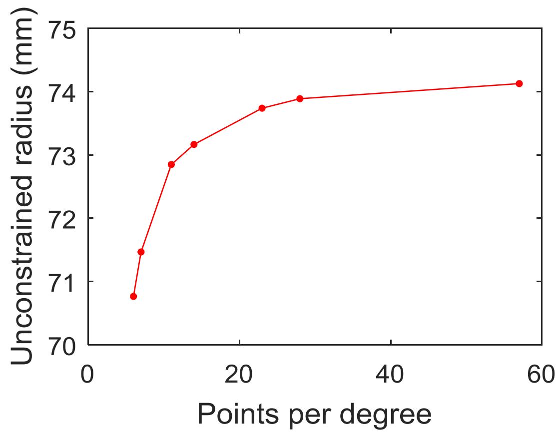


Fig. 6 *Unconstrained radius as a function of point density*

In other situations, mounting of the sphere (i.e., material in the immediate vicinity) has a considerable influence on the measured radius. As an example, a sphere of nominal 50 mm radius was mounted at the center of a square aluminum plate (each side measuring 457.2 mm as shown in Fig. 9). The sphere was scanned with the TLS from about 16 m and the unconstrained radius was determined to be 44 mm. When a 38.1 mm (1.5 in) wide ring of absorbing black flock paper was added around the sphere, the radius increased to 48 mm. When the sphere was mounted with 100 mm standoffs (i.e., not mounted directly on the plate but offset by 100 mm), the radius increased further to 49 mm. This indicates that the mounting of the sphere and the scanned surfaces close to it has considerable influence on the measured data, affecting the unconstrained radius, and therefore the sphere center location of a constrained or unconstrained fit. In the next section, we discuss the effect of squishing/flaring on sphere center and relative range error.

5.3 Effect of sphere squishing/flaring on sphere center and relative range error

The schematic in Fig. 7 illustrates profiles of a real sphere surface (solid gray line) and the point cloud (solid black line) of that sphere as measured by a TLS system. The measured surface in this illustration appears more ellipsoidal than spherical, with the long axis oriented along the ranging direction. The data are segmented so that data within a cone opening angle of 120° is retained. As can be seen in the figure, a constrained fit based on the calibrated radius of the sphere produces a center O_1 that is farther away from the TLS than the true center O. An unconstrained fit produces a center O_2 that is closer to the TLS than the true center O.

To evaluate the effect of sphere squishing/flaring, the quantity of interest is the error in the center O_1O. If the center error O_1O is constant, that is, its value is the same at the reference and the test positions, the center error will not affect the relative range measurement. However, if the center error O_1O is different at the reference and the test positions, the relative range error will appear to be larger or smaller than the true relative range error. It is difficult to quantify the center error O_1O because the true center O is an unknown quantity. However, the measured data does provide another potentially useful quantity, the unconstrained radius, from which we can estimate the error in the center O_1O through a simple simulation.

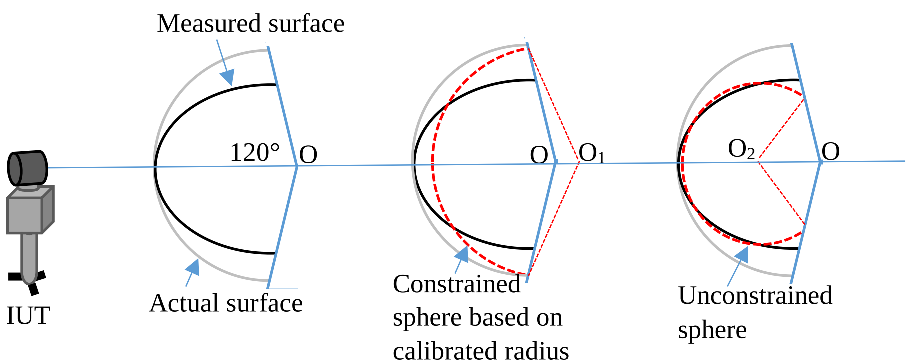


Fig. 7 *Error in the center coordinate because of apparent squishing of sphere*

For this purpose, we first perform an unconstrained orthogonal least-squares fit on the measured data to determine the unconstrained radius r_{uc}. This provides an estimate of the extent of squishing or flaring of the sphere for this TLS/target combination under these measurement conditions. We then numerically generate a sphere data set with a radius r_{uc}, centered at a distance r-r_{uc} from the origin where r is the calibrated radius of the sphere, and truncated over a cone opening angle of 120°. The data is generated at the same sampling interval as that of the measured data. We then perform a constrained orthogonal least-squares fit with a radius equal to the calibrated radius of the sphere target. The distance of the constrained center from the origin of the sphere is an estimate of center error O_1O. In Fig. 8, we plot the center error as a function of the unconstrained radius for a nominal 50 mm radius sphere. Simulations characterizing center errors are reported by Shilling et al [9] for several cases.

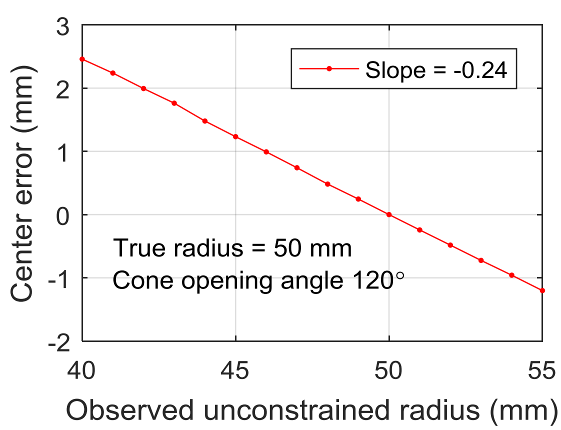


Fig. 8 *Center error along the TLS ranging direction as a function of unconstrained radius*

As an example on how this plot may be used, let the unconstrained radius of a nominal 50 mm radius sphere at the reference position be measured to be 48 mm. The error in the center at the reference position can be determined as -0.24 x (48-50) = 0.48 mm. At the test position, let the unconstrained radius be determined as 44 mm. The error in the center at the test position is -0.24 x (44-50) = 1.44 mm. The difference, 0.96 mm, is therefore the magnitude of the error introduced into the relative range measurement because of the increased distortion of the sphere at the far distance.

The plot in Fig. 8 may be assumed to be linear for all practical purposes, although in reality it is not. The slope of the graph is -0.24 for a cone opening angle of 120°. Table 1 shows the slope for other cone opening angles ranging from 60° through 160°. While Fig. 8 and Table 1 are based on a nominal 50 mm radius target placed 10 m away and sampled at 92 points per degree, we have performed such simulations for different target sizes, different sampling densities, and different target distances which have all resulted in the same slope of -0.24.

Table 1 *Slope as a function of cone angle*

Cone opening angle (degrees)	**Slope**
60	-0.07
80	-0.13
100	-0.19
120	-0.24
140	-0.28
160	-0.30

5.4 Verifying the simulation through an experiment

In order to experimentally validate the above simulation, we mounted a nominal 50 mm radius sphere on a 457.2 mm x 457.2 mm (18 in x 18 in) plate as shown in Fig. 9. We refer to this artifact as the single-sphere-plate target. The front surface of the plate is sand-blasted to a matte gray finish. The idea is to determine the orthogonal distance between the sphere-center and the plate at different distances from the TLS; if the center of the constrained fit does move along the ranging direction because of the increased squishing or flaring of the sphere, the sphere-center to plate distance is also expected to change. Thus, by monitoring the sphere-center to plate distance, we can infer the movement of the center of the sphere. The sphere-center to plate distance was calibrated on a contact probe CMM and determined to be 0.02 mm.

The artifact is scanned at distances of 2 m through 20 m in steps of 3 m. The unconstrained radius of the sphere is shown in Fig. 10 (a). It is clear that there is considerable squishing at the 20 m distance compared to the 2 m distance, with an unconstrained radius of 46.9 mm at 20 m and 49.7 mm at 2 m. From the simulations in the previous section, we anticipate the center to have moved by -0.24 x (46.9-49.7) = 0.672 mm. The experimentally determined change of the sphere-center to plate distance is 0.66 mm, which is in excellent agreement with the simulations. Fig. 10 (b) shows the change in the sphere-center to plate distance with respect to that at the reference position (2 m distance) obtained experimentally at the different ranges along with the simulation predictions based on unconstrained radius. This experiment validates the simulation and clearly confirms the movement of the constrained fit center because of sphere squishing/flaring.

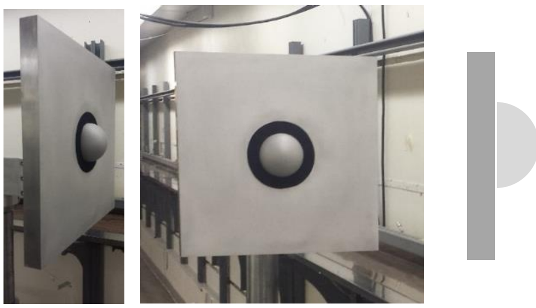


Fig. 9 *Different views of the artifact designed to determine if the constrained fit sphere moves because of sphere squishing/flaring*

(a)

(b)

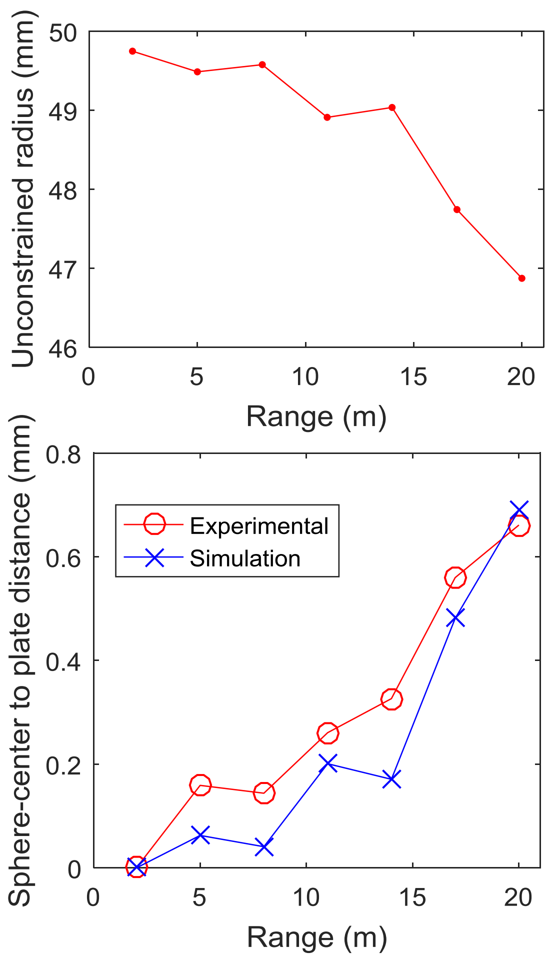


Fig. 10 (a) *Unconstrained radius as a function of distance* **(b)** *Sphere-center to plate distance*

5.5 Relative range error using sphere target

Fig. 11 shows the relative range errors using the sphere target for the TLS under study at the 5 m, 8 m, 11 m, 14 m, 17 m, and 20 m range values (this corresponds to displacements of 3 m, 6 m, 9 m, 13 m, 15 m, and 18 m, respectively). The center is determined using constrained radius fitting. The relative range error is considerably larger than that determined using the plate (shown in Fig. 4 and also shown in Fig. 11 for comparison) because the increased squishing of the sphere at far distances has moved the center of sphere resulting in an apparent range error.

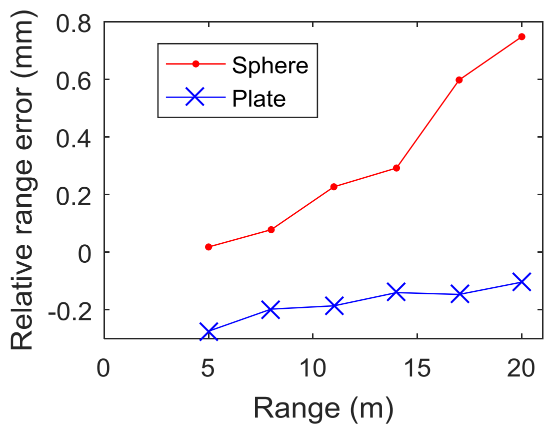


Fig. 11 *Relative range errors using the sphere target and the plate target*

5.6 Sphere target summary

A sphere target, particularly the integration sphere target, offers users a convenient way to realize relative range tests. However, material in the immediate vicinity of the sphere and local surface averaging may cause the sphere to appear squished or flared resulting in an apparent range error. The range error caused by the target geometry cannot be separated from that caused by TLS ranging errors. A sphere target may be used for relative range tests if sphere squishing/flaring induced effects can be minimized or if it can be proven to be very low by comparing the unconstrained radius with the calibrated radius. A sphere target may also be used if sphere squishing/flaring induced effects can be tolerated because of large manufacturer provided range error specifications.

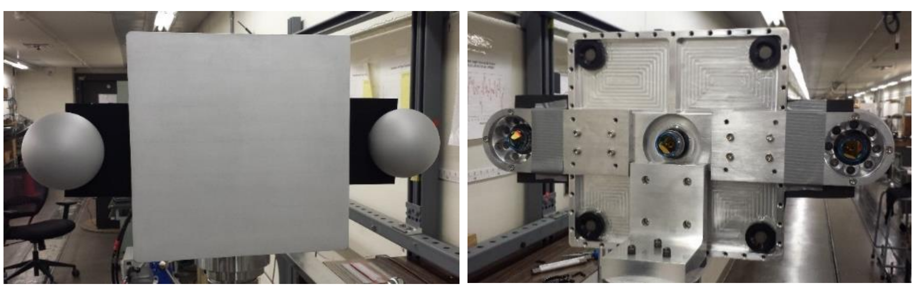
In this context, it is worth highlighting again the difference between the ranging error of the range measurement technology and an apparent ranging error introduced by the incorrect determination of the center of the sphere. If the TLS can correctly reduce the 3D point cloud data to a derived point that coincides with the geometric center of the sphere but the range measurement technology incorrectly records a longer range (i.e., every point appears farther away), then the sphere appears farther away than it really is; such an error would be regarded as a true range error of the TLS. On the other hand, if a TLS possesses a perfect range measurement technology (with no ranging errors whatsoever), but the TLS 3D point cloud cannot be reduced to a center that coincides with the geometric center of the sphere, the result will be an apparent ranging error. It is important that this spherical geometry induced error not be confused as an error source of the underlying range measurement technology.

6. Dual-sphere-plate target

4.1 Description

The dual-sphere-plate target consists of two 100 mm integration spheres mounted to the sides of the plate target described in Section 2.1. Two views of the target are shown in Fig. 12. The spheres are designed to be mounted in such a manner that the center of the spheres are on the plane defined by the front surface of the plate. Although Fig. 12 shows the five SMR/nests previously used with the plate target, they are no longer necessary and are not used here.
The central idea of the dual-sphere-plate target is that the spheres are used as fiducials to identify a common point on the plane that is measured by both the TLS and the LT. By ensuring that the two instruments measure the same point, careful alignment of the plate is no longer necessary. At each position of the target, the LT measures the centers of both spheres. The average of the two measured coordinates is considered as the reference value for the center of the plate. The TLS scans both the plate and the two spheres. The sphere centers are extracted, averaged, and projected onto the plane determined from point cloud data of the plate. The coordinate so determined is considered to be the measured center of the plate at that position of the target.

Because the TLS measurement results in a point on the best-fit plane, to ensure that both instrument measure the same point, it is important that the LT also determine the range to a point that lies on the same plane. It is for this reason that the dual-sphere-plate artifact is designed so that the center of the spheres lies on the front surface of the plate. However, offset along the ranging direction (into and out of the plane of the plate) will not significantly affect measurements. If the spheres are away from the plane by 0.1 mm, in presence of a 5° pitch, the error in the range is only 0.1(1-cos(5°)) = 0.0004 mm. The offset was measured using a CMM and determined to be less than 0.1 mm.



(a) (b)

Fig. 12 (a) *Front view of the dual-sphere-plate target* **(b)** *back view of the target showing the SMRs mounted inside the integration spheres.*

We note here that the artifact shown in Fig. 9 may also be used as a dual-sphere-plate target. The only disadvantage with that artifact is that the central region of the plate is not available because it is occluded by the sphere. The design shown in Fig. 12 overcomes that problem by placing the fiducial spheres outside the central region.

6.2 Relative range error measurement

Fig. 13 shows the relative range errors using the dual-sphere-plate target for the TLS under study at the 5 m, 8 m, 11 m, 14 m, 17 m, and 20 m range values (this corresponds to displacements of

3 m, 6 m, 9 m, 13 m, 15 m, and 18 m, respectively). The target was only visually aligned at each position. For comparison purposes, we also show the relative errors obtained using the plate target (the plot in Fig. 4). It is clear that the relative errors obtained using the dual-sphere-plate target are practically identical to that obtained using the plate target indicating that the dual-sphere-plate target is suitable for relative range error evaluation, but requiring lower alignment effort than using the plate target

Because four scans were obtained at each position of the targets, we are able to determine the one standard deviation repeatability at each target position along the ranging direction of the TLS. These are as small as 5 µm at the reference position and as large as 40 µm at the 20 m distance. The repeatability of the mean of the four scans is therefore 2.5 µm and 20 µm at the reference and 20 m distance, respectively. The repeatability in the displacement between the test position and the reference position can therefore be calculated as the root sum square, and is about 20 µm for the 20 m distance. We note that this is not the overall uncertainty in the TLS measurements, but simply the one standard deviation repeatability in the lengths.

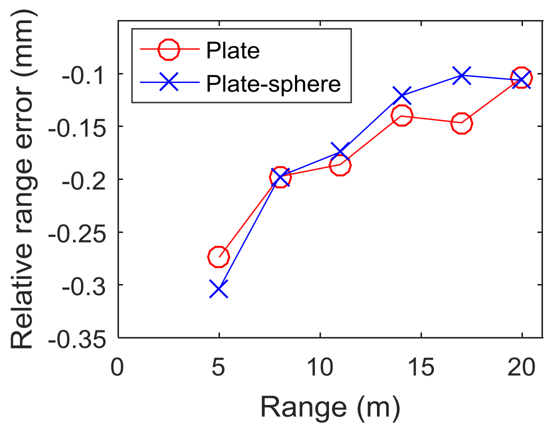


Fig. 13 *Relative range errors using the dual-sphere-plate target and the plate target*

6.3 Dual-sphere-plate target summary

The proposed dual-sphere-plate target offers a quick and convenient way of realizing relative range error tests. It draws from the advantages of the plate target and the sphere target without the associated limitations. The spheres in the dual-sphere-plate target are only used as fiducials to identify a point on the plane that coincides with that determined by the LT. The radial direction movement of the sphere center due to squishing/flaring is no longer an issue because the spheres centers are projected onto the plane defined by the TLS point cloud data of the plate.

7. Conclusions

Relative range error measurement is a critical aspect in the performance evaluation of TLS and target geometry is an important aspect in the realization of these tests. In this paper, we describe relative range tests performed on a TLS using a plate target, a sphere target, and a novel dual-sphere-plate target. The plate target provides relatively distortion-free data even at far distances but the plate itself needs careful alignment which can be time consuming. The sphere target offers a unique derived point, the center, that in principle may be determined using both the LT and the TLS. However, many TLS systems produce point cloud data that results in the center being away from the true center of the sphere, resulting in target induced errors in the measurement. In this context, we propose a novel dual-sphere-plate target that draws from the advantages of the plate and the sphere target without the associated limitations. We experimentally demonstrate that the dual-sphere-plate target produces nearly identical relative range errors as a plate target, but the measurement may be performed without having to align the plate at each test position saving the user considerable time and expense in realizing the tests.

Disclaimer

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