The SLAC Design and Manufacturing Process of Sphere-Mounted Reflectors[*]

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1. INTRODUCTION

Sphere-Mounted Reflectors (SMRs) are used at SLAC for a variety of alignment purposes. They consist of a retroreflective set of mirrors mounted inside a hollowed out sphere. The most significant property of these is that the reflected beam emerging from the SMR is parallel to the incoming beam. The reflector is comprised of three reflective surfaces that are mutually orthogonal forming the geometrical equivalent of the corner of a cube.

Initially a series of 1½ inch (38.10 mm) versions were purchased for $3250 each. These consisted of steel balls that were hollowed out allowing an air-cube to be precisely inserted into the ball so that the apex of the mirror planes would intersect the center of the ball. This is critical so that when the SMR is placed into a "nest" it will always reflect from the same three-dimensional position regardless what orientation it is in. Due to the high cost of manufacturing, a delivery time of several months, and with no assurance that the reflector will pass quality control, we decided to embark on manufacturing these "in-house" hoping for less expensive and equally or possibly even more accurate versions.

2. AIR AND GLASS CUBES

The 1½ inch version of the SMRs has been accepted as standard for much of our work at SLAC. Originally air-cube reflectors were used only with our original laser tracker and the glass or solid-cubes with the TC2002 Total Station or the ME5000 Mekometer. Although the glass-cube retroreflectors are less accurate and do not adapt to changes in temperature as well as air-cubes (Rüeger, 1990), they were less expensive and more durable than the air-cubes. High precision work utilizing the laser tracker required the use of the more accurate air-cubes, but for the ME5000 and the TC2002, a solid cube corner would suffice. Additional concerns were temperature effects where testing revealed that the bought SMRs were susceptible to movement of the mirror apex with respect to the center of the ball (see Section 6). Another concern was that in using the SMRs under challenging field conditions, it was proven inevitable that they would be dropped.

2.1 Constructing a Solid Cube Corner SMR

An SMR containing a solid cube corner has been developed at SLAC. For demonstration, Figure 1 shows the Hewlett-Packard HP 1000-0326 one-inch solid cube corner, normally sold mounted as the HP 10703A retroreflector. The reflector is made of BK-7 optical glass with a refractive index of 1.515. The nodal point therefore lies at a nominal depth of 0.495 inches (12.57 mm) below the front surface. From the inside out, the rear surfaces are coated with silver, copper and epoxy paint.

The housing into which the solid cube corner must be installed is a sphere of 1½ inch diameter. To minimize refraction errors due to misalignment of the ball to the laser beam, the nodal point of the retroreflector should be aligned to the center of the ball so that the ball rotates around the nodal point.
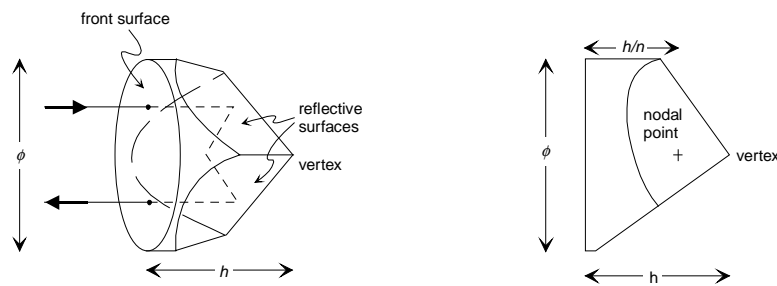
Fig. 1 Solid corner-cube retroreflector

The following features of the solid corner cube reflector are noted:

Vertex: intersection point of the three reflective surfaces.
Height h: normal distance from the front surface to the vertex
Diameter ϕ: aperture of the front surface
Nodal point: image of the vertex as seen from outside the cube, h/n below the front surface, where n is the refractive index of the glass medium.

For normal incidence (the incoming beam is perpendicular to the front surface), the geometrical path length through the prism is $2h$ and the optical length is $2hn$.
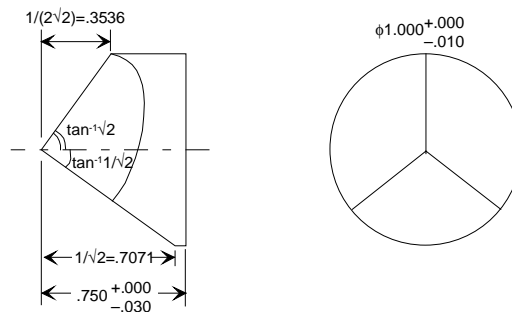
Fig. 2 The HP 1-inch solid corner-cube

The corner-cube retroreflector is installed by holding it kinematically in a hole in the 1½ inch ball using three smaller balls, each ball touching the bottom and the side of the hole and touching one surface of the cube corner (Figures 2 and 3). Since the HP cube corner has an aperture of 1.000 inch (25.40 mm), the diameter of the hole has been set at 1.050 inches (26.67 mm). For the three smaller balls a diameter of 0.375 inches (9.53 mm) has been selected

Fig. 3 Corner-cube installed in 1½ inch ball

Six 1½ inch balls were manufactured by Reed Precision Machining using a Rank Pneumo (Keene, NH) diamond-turning machine. The accuracy of a diamond-turning machine was not necessary for these balls, but it was necessary for the seven 1½ inch balls made at the same time for air-cubes.

The glass cube corner is held in place by a Teflon® gasket and a lock nut, Figure 4, tightened down to 2 inch-pounds of torque (0.22 N·m). A drop of Permalock® was run down into the lock ring threads to seal them. A dab of white epoxy across the thread serves as a tamper-evident seal.
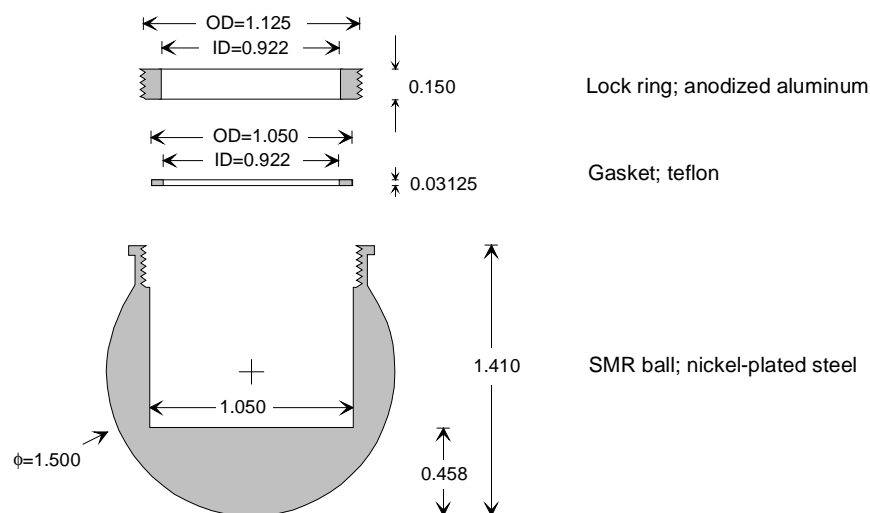

Fig. 4 SMR ball for glass corner-cube

The ball was thus redesigned to remove the collar on the SMR that, in some cases, limited the attitude of the ball in the Hubbs cup or the SLAC nest (Figure 5). Two balls and two retaining rings were manufactured by RPM.
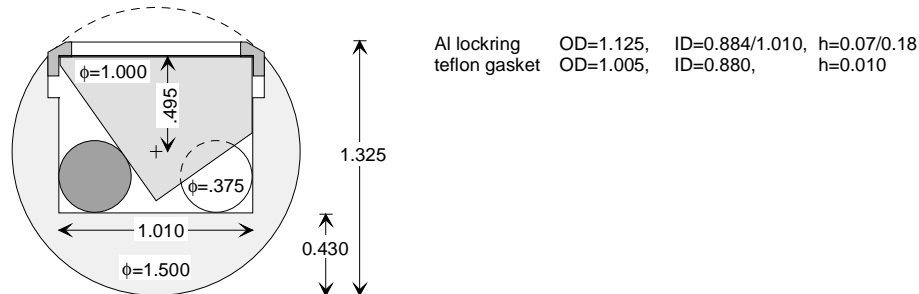

Al lockring   OD=1.125,   ID=0.884/1.010, h=0.07/0.18
teflon gasket OD=1.005,   ID=0.880,   h=0.010

Fig. 5 Glass-cube SMR, second design

The diameter of the hole in the ball is 1.010 inches (25.65 mm), 0.040 inches (1.02 mm) less than on the previous design. The hole is again made 0.002 inches (0.05 mm) deeper than the ideal value of 0.318 inches (8.08 mm) below center.

Two coated solid corner cubes were ordered from Edmund Scientific. These BK-7 reflectors are the same size as the HP reflectors: $\phi = 25.4 +0 -0.1$ mm; $h = 19.05 \pm 0.25$ mm. They are available coated or uncoated. Whereas the HP unmounted reflectors are a special order item, these are a standard product. Figure 6 is an example of the final assembly.

Fig. 6 SLAC glass-cube assembly

2.2 Geometry of the Corner-cube Reflector

The hollow or air-cube reflector is made of three front surfaced mirrors; the beam is transmitted entirely through air. As mentioned, a solid glass retroreflector is made of a single piece of optical glass with three mutually orthogonal surfaces (Figure 7). The beam is transmitted through the glass medium. The hollow corner cube is just a special case of the solid reflector with a refractive index $n = 1$.
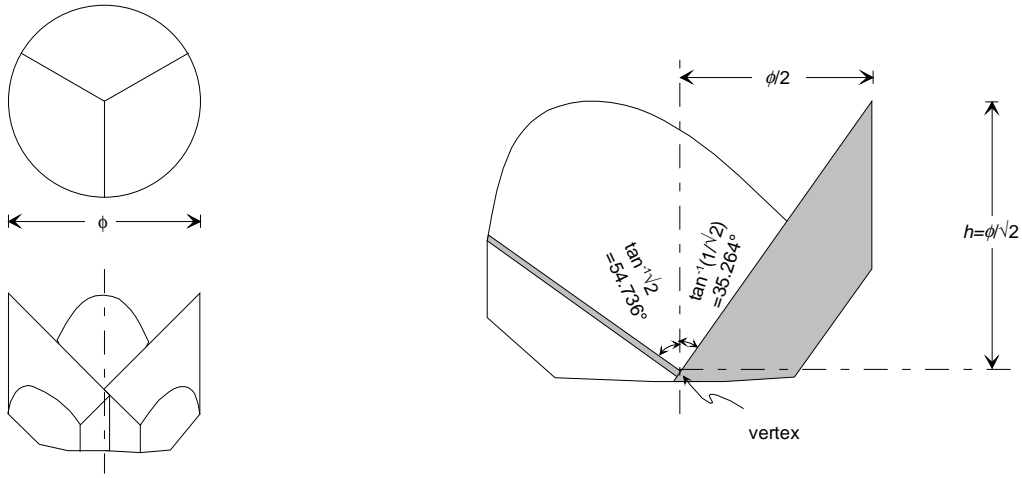
Fig. 7 Hollow corner-cube retroreflector

Figure 8a shows a cube corner in which the three reflective surfaces lie in the XY, YZ and ZX planes of the coordinate system. The vertex lies at the origin O. The front surface is XYZ, where X, Y and Z each lie 1 unit from O. Each side of the plane XYZ is therefore √2. P is the pedal point at the foot of the normal dropped from O to the plane XYZ. A is the midpoint of XY and the point where the projection of ZP meets XY. Since XY=√2, XA=OA=1/√2.
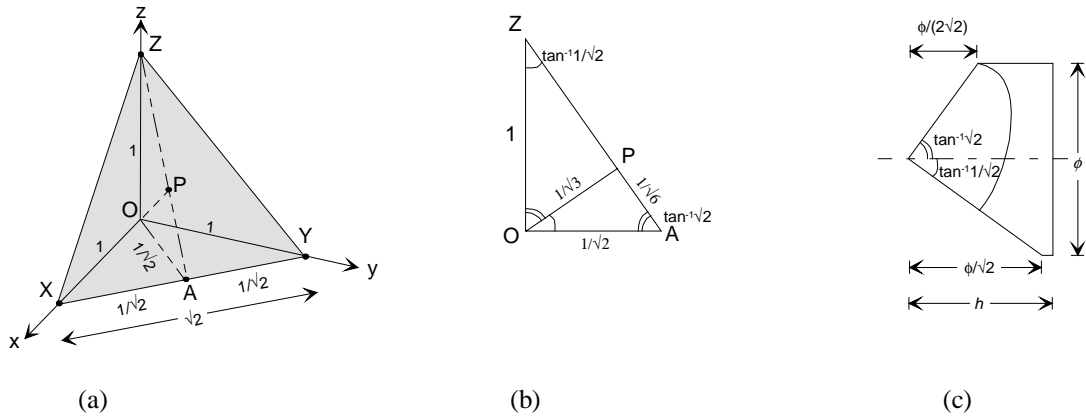

| (a) | (b) | (c) |

Fig. 8 Geometry of the corner-cube

The following properties about the angles of the cube corner can be deduced (Figure 8b):

$$\tan POA = \frac{1}{\sqrt{2}}, \quad POA = 35.2644° \tag{1}$$

$$\tan PAO = \sqrt{2}, \quad PAO = 54.7356° \tag{2}$$

$$\sin POA = \cos PAO = \frac{1}{\sqrt{3}} \tag{3}$$

$$\cos POA = \sin PAO = \frac{\sqrt{2}}{\sqrt{3}} \tag{4}$$

Each of the three reflective surfaces of a hollow or solid cube corner is an elliptical segment (Figure 9).
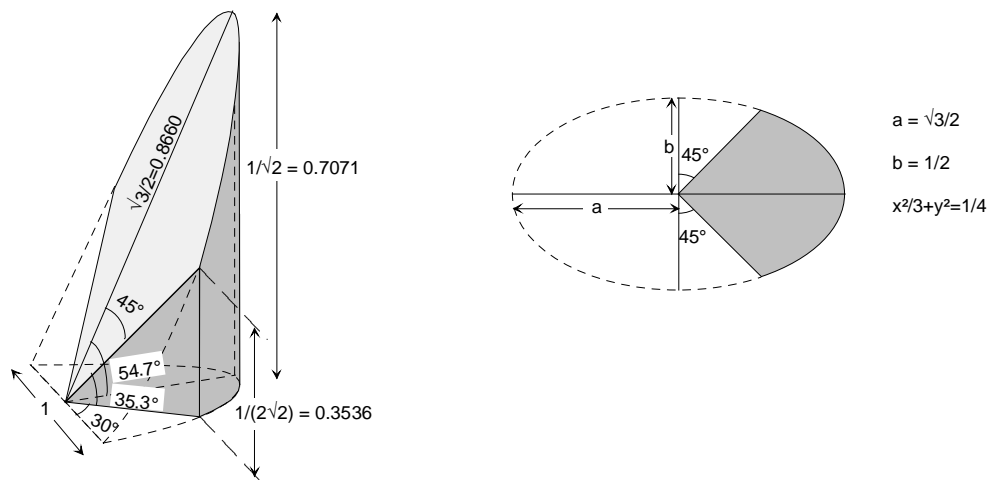

Fig. 9 The reflective surface of a corner-cube segment

For a cube corner of 1-inch aperture, the ellipse has the following geometry. The semi-major and semi-minor axes are

$$a = \frac{\sqrt{3}}{2}, \qquad b = \frac{1}{2} \tag{5}$$

The eccentricity e is

$$e^2 = \frac{a^2 - b^2}{a^2}, \qquad e = \frac{\sqrt{2}}{\sqrt{3}} \tag{6}$$

The equation of the ellipse is

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$
$$y^2 = \frac{1}{4} - \frac{x^2}{3} \tag{7}$$

Figures 10 and 11 show final assembled versions of the air-cube.

Fig. 10 Air-cube with Teflon® collar

Fig.11 Air-cube with Rulon® collar

3. MANUFACTURE OF SPHERICAL HOUSING

One major consideration in manufacturing the hollowed out sphere into which the retroreflector will be placed is in keeping the sphere's form. Tight tolerances on the diameter and the sphericity of the ball are vital to ensure the same three-dimensional point that the SMR apex represents will occur at all positions of the ball in the target nest (Section 2.1). Any bumps or valleys on the surface of the ball that touch the nest will misalign the ball enough to negate the very accurate range and angle readings necessary for a high final accuracy.

Early in this project, the balls that were diamond-turned by Reed Precision Machine (Section 2.1) formed accuracy of about 0.0004 inches (0.01 mm). The stainless-steel balls were purchased in bulk and hollowed out where eventually the tolerance of the hole was around 0.001 inches (0.03 mm). Due to the nature of the mounting of the balls for diamond-turning, a 0.001 inch (0.03 mm) size bump was left on the back of the ball. Although attempts to shave this down did eventually succeed, this additional cost became a concern.

Another difficulty in manufacturing these balls was found to occur after the hole had been made. The edges of the ball around the opening would flare out about 0.1 inches (2.5 mm). This occurred due to the method of manufacture used to create the balls—leaving a hardened surface with a relatively soft interior. Through various trials it was determined that the best strategy was to first anneal the balls at 500°F (260°C) for two hours. This relieved internal stresses thus minimizing the effect of hollowing out the sphere.

Fig. 12 Grinding spherical housing

Another local company (Groundim XI) and later an offshoot known as Ontime Machining helped design a fixture to mount and grind the balls to a sphericity tolerance of about 0.0001 inches (0.003 mm). Essentially the fixture has two axes of rotation allowing the entire surface including the very bottom (where the bump was) to be ground precisely (Figure 12). This was less expensive due to not using a diamond-turning process and actually resulted in a smoother surface without any bumps. The balls were nickel-plated providing a slightly softer surface to grind than the bare annealed stainless steel yet would still withstand the stresses of actual use.

Fig. 13 Supplied air-cube

4. GRINDING THE AIR-CUBE

Air-cubes are purchased with a stated parallelism between the incoming and outgoing light rays of one arcsecond. These high accuracy retroreflectors are made from fused silica and installed into a metal protective housing that for our purposes must be removed (Figure 13). Next

the surface that will be glued to the inside of the stainless-steel ball must be ground flat. The bottom of the air-cube is not a precision surface. The three tiny flats on the base are not coplanar, and the distance of these flats from the vertex varies in the range 0.02-0.05 inches (0.51-1.27 mm). Ontime mounted the air-cube on a vacuum chuck, and ground the back surface so that, when assembled, the 'glue-line' was only 0.0005–0.001 inches (0.01-0.025 mm). The amount of grinding was controlled by regularly measuring the thickness of the base.

A 1 inch glass corner cube was made into a vacuum chuck for the hollow corner cube reflectors allowing circular grinding by running vacuum to what would have been the three reflective surfaces (glass cubes can be purchased without silvering). Holes were drilled through the center of each reflective surface, and orthogonal to that surface. The holes met on the center-line inside the prism. A fourth hole was drilled in the center of the front face to meet the other three holes (Figure 14).

Fig. 14 Grinding Fixture

After grinding, the air-cube is measured precisely in SLAC's QC room, by measuring the height of a precision ball inside the air-cube above the surface plate on which the air-cube rests. The depth of the hole in the ball has already been precisely measured. We can therefore calculate the depth of the glue-line to an accuracy of ≈0.0001 inches (0.003 mm).

5. THE ALIGNMENT FIXTURE

5.1 The Concept

The heart of our first assembly fixture was a glass-cube retroreflector and three micrometers. The glass cube forms a kinematic mount for the air cube. The fixture is placed on the Leitz CMM; the three surfaces of the glass cube are measured and the location of the vertex point is calculated. The air-cube is placed on the glass-cube followed by the 1½ inch ball. The location of the center of the ball is determined. The three micrometers, which act orthogonally, are used to move the ball around until its center is coincident with the vertex point above the small spheres.

Using a jeweler's diamond drill a hole is drilled into each of the four faces of the glass-cube. A vacuum line transforms the glass-cube into a vacuum chuck. It has been found necessary to lubricate the faces with a small amount of alcohol to ensure the air-cube seats correctly onto the glass cube.

5.2 Assembling the SMR: The Fixtures

The prototype assembly fixture was built of brass at SLAC (Figure 15). To complete the fixture, the glass-cube used to hold the air-cube was fixed to the post. After drilling the vacuum holes, the glass-cube was epoxied to the brass post with 5-minute epoxy. A length of brass or aluminum tubing (as used for model airplanes) was run up through the center of the post to feed the vacuum.

To align the ball over the air-cube, the three exposed faces of the vacuum chuck were measured, and a coordinate system defined center on the vertex.

The adjusters were Newport DS-4 High Precision Adjusters with a coarse travel of 4 mm and a fine travel of 0.3 mm. One division on the fine adjustment drum equals 1 µm; one complete turn equals 50 µm. Using these adjusters, the 1½ inch ball was maneuvered until the CMM measurements indicated that its center lied at the origin of the coordinate system. When the ball was properly located, the adjusters meet the ball at a radius of 0.612 inches (ϕ=1.225 inch) from the centerline of the fixture. The top of the micrometer holder (4) would lie at $z = -0.429$ inches in the coordinate system defined by the vacuum chuck.

The ball was removed and the air-cube placed on the fixture. After placing a small amount of 5-minute epoxy in the bottom of the hole, the ball was placed on top of the air-cube and held down by a spring fixture. Minor micrometer adjustments on the order of 0.0001 inches (0.003 mm) were usually necessary to compensate for mechanical slop in response to the spring.
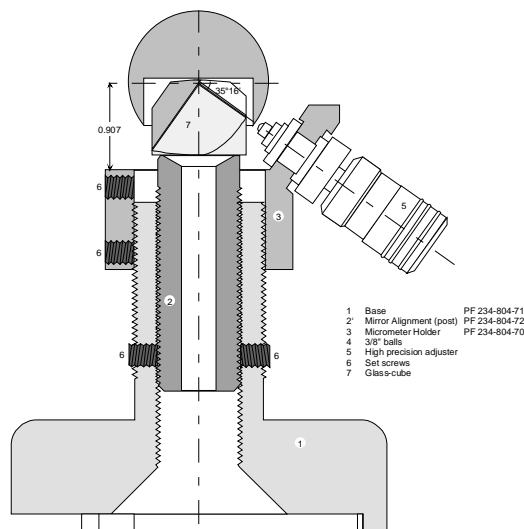
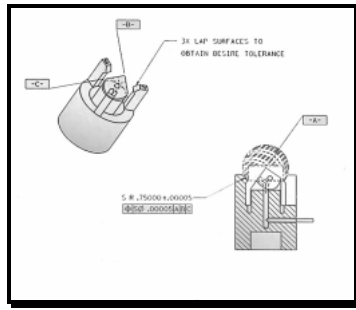Fig. 15 The first assembly fixture for the air-cube SMR
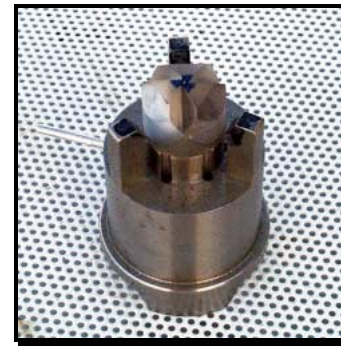
Fig. 16 Schematic of new
SMR fixture

Fig. 17 Completed version
of new SMR fixture

Through testing it was found that a new fixture would accomplish the alignment of the mirrors and the ball without having to adjust the micrometers (Figures 16 through 19). The same fixture used to align the ball over the retroreflector is used to vacuum-hold the reflector on the chuck while being ground for depth. Again the philosophy is to grind the retroreflector to a depth such that a thin layer of glue can be placed on the back and the ball, and subsequently placed over, thus resting on the three posts. The posts are durable being reinforced with carbide inserts. The fixture itself is solid "Super-Invar 32-5 Alloy" making it highly stable thermally.

Fig. 18 Glass-cube with
vacuum holes

Fig. 19 Sphere on
fixture

Initial machining by Ontime involved milling the fixture. The perpendicular distance from each post to the apex of the glass-cube prism was initially 0.742 inches (18.85 mm). After grinding this was 0.750 inches (19.05 mm). After initial machining the glass prism was attached to the central post using 5-minute epoxy. A Teflon® sleeve was used to ensure centering of the prism. The fixture was then measured using SLAC's CMM where one of the most critical measurements was to compute the position of the posts relative to the apex of the prism.

Using these results the fixture was returned to Ontime with a calculated amount to remove for each post. A conservative layer of material was removed from each and once again the fixture was measured at SLAC. This process was repeated four times until the exact center of the ball resting on these posts would coincide with the apex of the glass-cube prism

One problem encountered in assembling the SMRs was mirror surface degradation. After testing it was found that this occurred due to glue seeping through the air-cube; primarily through the apex where the material is very thin. This was rectified by slightly redesigning the ball making it deeper, thus allowing less material to be ground off the back of the air-cube.

In actual assembly a very fine touch is necessary in placing the ball over the air-cube. Conservative amounts of glue are applied to the ground back of the air-cube, then the ball is placed over it resting on the three pillars. One must ensure through inspection of the ball's placement that it rests on these pillars and that it is laying flat. Instead of a spring (used to apply force down on the ball) as with the first fixture, carefully placed weights are applied to the back of the ball. This was found to be more stable than the spring assembly and allowed more force to be applied.

6. ANALYSIS AND RESULTS

The first indication that a new SMR reflects is to simply see if the laser tracker will actually track it. Since the assembly of the glass-cube SMRs was less harsh on the reflecting surfaces, the tracker had no problem following them as was expected (Table 1). Glue seepage and surface contact made the first couple of attempts at tracking the air-cube SMRs fail. Once compensating for this problem, they tracked without too much trouble.

Table 1 Repeatability of two SLAC air-cubes

SMR	Nest Readings (mm)	Far Target Readings (deg or mm)	
SLAC 02 (white)	180.5414	Azimuth	245.8697
		Elevation	97.5312
		Distance	10357.4533
Return SLAC 02 to tracker nest and then move to same far target.	180.5414	Azimuth	245.8695
		Elevation	97.5310
		Distance	10357.4533
SLAC 03 (red)	180.5412	Azimuth	245.8698
		Elevation	97.5305
		Distance	10357.4530
Return SLAC 03 to tracker nest and then move to same far target	180.5412	Azimuth	245.8698
		Elevation	97.5306
		Distance	10357.4530

The position of the air-cube within the ball was tested using our CMM. Figure 22 (next page) is indicative of the accuracy of placement of the air-cube and also shows how well the diameter of the ball has been kept constant. Typical accuracies of about 0.0001 inch (0.003 mm) are now expected using the new SMR fixture.

Thermal stability was of some concern and Figures 20 and 21 compare our SMR to
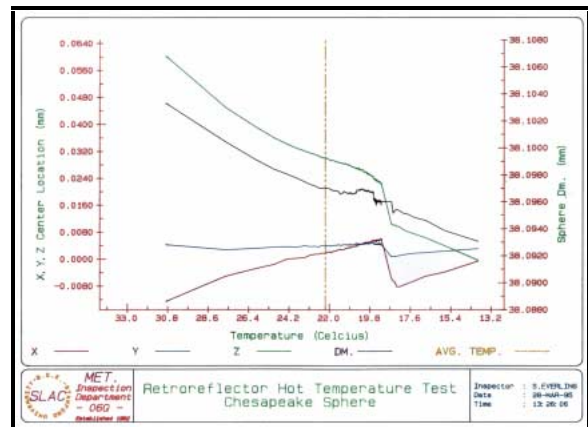

Fig. 20 Hot temperature test of supplied SMR

one that was supplied with the laser tracker. The positions of the apex (X,Y, and Z) are considerably more stable in the SLAC SMR. Although the diameter does change by what may be considered a significant amount in both test cases, it is fairly uniform and thus can be easily modeled. Final costs per unit are now about $980 dollars.
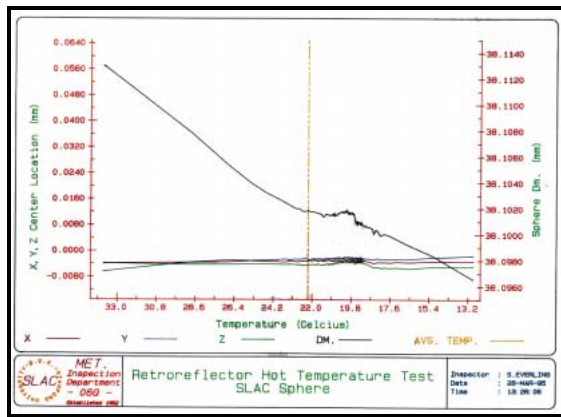

Fig. 21 Hot temperature test of SLAC SMR

Fig 22 Sample CMM results for final air-cube assembly

7. CONCLUSION

The manufacture and assembly of both glass and air-cubes at SLAC has been successful. Considering the inevitable mishaps that occur when using these reflectors, it is important to have a supply and the ability to manufacture more both quickly and accurately. Our SMRs are presently being used successfully under field conditions. To promote durability, a new generation of all metal SMRs is under consideration. As a preliminary step, Figure 23 an all-metal retroreflector constructed by Opticon of Massachusetts that will be placed inside a steel ball. Eventually it will be desirable to have the ball and mirror assembly constructed using only one piece of metal.

Fig. 23 All-metal retroreflector

8. ACKNOWLEDGMENTS

9. REFERENCES

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[2]   G. Bowden, SLAC Internal Memo, June 25 1993.

[3]   J.M. Rüeger, *Electronic Distance Measurement, 3rd Ed.*, Springer-Verlag, 1990, pages 148 - 164.