Hollow Retroreflectors for Lunar Laser Ranging at Goddard Space Flight Center

Alix Preston, Stephen Merkowitz

Laser ranging to the retroreflector arrays placed on the lunar surface by the Apollo astronauts and the Soviet Luna missions have dramatically increased our understanding of gravitational physics along with Earth and Moon geophysics, geodesy, and dynamics. Although the precision of the range measurements has historically been limited by the ground station capabilities, advances in the APOLLO instrument at the Apache Point facility in New Mexico is beginning to be limited by errors associated with the lunar arrays. At Goddard Space Flight Center, we have developed a facility where we can design, build, and test next-generation hollow retroreflectors for Lunar Laser Ranging. Here we will describe this facility as well as report on the bonding techniques used to assemble the retroreflectors. Results from investigations into different high reflectivity mirror coatings, as well as dust mitigation coatings will also be presented.

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Introduction

Laser ranging to the retroreflector arrays placed on the lunar surface by the Apollo astronauts and Soviet Luna missions have dramatically increased our understanding of gravitational physics along with Earth and Moon geophysics, geodesy, and dynamics [1]. Although the precision of the range measurements has historically been limited by the ground station capabilities, advances in the APOLLO instrument at the Apache Point facility in New Mexico is beginning to be limited by errors associated with the lunar arrays [2]. Over the past two years, a facility at Goddard Space Flight Center (GSFC) was developed for the design, fabrication, and testing of open cube corners for use in next generation retroreflectors. This facility consists of both a far-field diffraction pattern (FFDP) test-bed and a retroreflector assembly area. For this paper, only the retroreflector aspect of the facility will be focused on. In order to fabricate the hollow corner cubes, a Zygo interferometer is used to do the cube alignment in real-time. Software specifically designed for corner cube applications was used to measure the dihedral angles, beam deviations, wavefront error, and several other features of the corner cubes. The Zygo is mounted vertically on a 10 cm thick granite table that sits on the concrete foundation of the building. This is done in order to reduce measurement errors caused by vibrations.

There are two different retroreflector designs that have been studied at GSFC. The first consists of a base in which the two other mirrors are bonded on top. One mirror forms an “L” shape with the base, while the third mirror fits against the L-shape to complete the retroreflector. These corner cubes have an aperture of approximately 7 cm, are made of fused silica, use high-reflectivity dielectric coatings at 532 nm, and are bonded together using hydroxide-catalysis bonding (HCB). The second design has each mirror sitting on top of the next such; analogous to the petals of a flower. For this “flower” design, only a small amount of bond area is used (typically 1-2 mm thick along the entire bonding length). The mirrors have a protective aluminum coating for the reflective surfaces and are made out of a Pyrex equivalent borosilicate glass. Both epoxy and HCB bonding methods are used to assemble the corner cubes for this design.

Epoxy Bonded Retroreflectors

Using a 50/50 mixture of Epon 828 and Versamid 142, we were able to bond corner cubes using the flower design with dihedral angles of better than 1 arcsecond while achieving a wavefront flatness of better than 1 wave. Using this tehchnique we were able to produce several corner cubes with similar characteristics.

Thermal Testing

A modified vacuum chamber was used to thermally cycle an epoxy-bonded corner cube. The same Zygo used to make the cubes was used to test them as the corner cubes were being cooled. A 15 cm diameter aluminum coated mirror was used to reflect the light from the Zygo into the thermal chamber. A temperature sensor was placed on the corner cube, and another on the cold plate that is cooled using liquid nitrogen. Although we were able to get the cold plate to temperatures just above 100 K, the temperature of the corner cube did not go below 250 K. This was due to a large heat flux from the front of the vacuum chamber causing a large temperature gradient through the chamber and fixture the corner cube rested on. Thermal shielding is currently being made to reduce this effect. Using this thermal chamber, we hope to be able to thermally cycle the corner cubes from -180 C to 120 C. This is the expected temperature range the retroreflectors will encounter on the Moon.

Despite not putting the corner cube through the same thermal conditions that it would experience on the Moon, promising results were still obtained. When at room temperature, the flatness of the wavefront is approximately 1 wave. As the corner cube was cooled, the wavefront distorted dramitically and at its lowest temperature, the wavefront had bent to almost 13 waves into a “taco” shape. After the corner cube returned to room temperature, the wavefront returned to what it originally started at, and the dihedral angles changed by only a few tenths of an arcsecond. This means that the epoxy bonded cubes were able to survive almost 12 waves of distortion in the wavefront and still returned to almost the exact shape. To determine if the bending of the cube was due to the bonding process of the corner cube, or from a temperature gradient caused from thermally cycling the corner cube, the corner cube was rotated such that it was sitting on the holding fixture with a different mirror than was originally used for the first thermal test. The corner cube was then cooled in the same manner and the same bending of the wavefront was observed. Because the same behavior occurred when the corner cube was in a different position, this can only mean that the bending of the wavefront, and hence the cube, was caused by a temperature gradient through the cube, and not from the bonding process.

HCB Bonded Retroreflectors

The HCB method was used for both corner cube designs. When the HCB method was used on the flower design, almost all of the cubes would “flower open.” This means that the dihedral angles would increase by a significant amount, and in many cases, they increased beyond the range of the Zygo. The exact cause of this is unknown, but we conjecture it is from either the small amount of bond area, the rough bonding surface, or a combination of both. Although most of the corner cubes were not measureable after using the HCB process, a few cubes were good enough that they will be able to be used to compare to the epoxy-bonded corner cubes.

Significantly better results were achieved using the HCB method on the first design. This was most likely due to the mirrors in this design having flatter and smoother bonding surfaces. Most of the corner cubes made with this design and bonding technique had dihedral angles to better than 15 arcseconds of perpendicularity. The large dihedral angle offsets are most likely due to the non-perpendicualrity of the mirrors. In order to get dihedral angles closer to 90º, the mirrors need to be polished closer to perpendicular.

When using HCB to bond the mirrors of the first design, either two or three of the mirror interfaces could be bonded. It was noticed that when all three of the bonding interfaces were bonded, significant stresses in the corner cube could be seen from the interferogram. The exact cause of this is not known, but it is speculated that the non-perpendicularity of the mirrors was the cause. Since the HCB process tends to pull the bonding surfaces together, if there is a gap between the bonding surfaces, the HCB process will try to pull it together. This will then cause the mirrors to bend that will induce stresses within the corner cube.

Conclusion

Using the facility developed at GSFC, we are able to bond hollow retroreflectors using different designs, reflective coatings, and bonding techniques. We produced corner cubes with dihedral angles perpendicular to better than 1 arcsecond and have a wavefront better than 1 wave using epoxy bonding methods. Although we were not able to produce corner cubes with sub-arcsecond dihedral angles using HCB, we were still able to produce a few that will be used to compare their performance against the epoxy-bonded cubes. A single epoxy bonded cube was thermally cycled to 250 K in a thermal chamber showed that it was capable of withstanding large stresses and still return to its original shape. It was also shown that the bending of the wavefront was due to a thermal gradient, and not due to the bonding process.

In addition to making corner cubes using epoxy, several corner cubes were made using the non-flower design. Although the dihedral angles of these cubes are not as good as those made using epoxy, they have shown that to make a hollow corner cube using HCB, the bonding surfaces need to be flat, smooth, and as perpendicular as possible to the mirrored surface. Once modifications to the thermal chamber and corner cube holder have been made, thermal tests will resume on both the epoxy and HCB corner cubes.

[1] S. M. Merkowitz, Living Rev. Relativity, **13**, (2010)
[2] T. W. Murphy Jr. et. Al., Class Quant. Grav., **29**, 184005, (2012)