A 170 mm hollow corner cube retro-reflector on Chang'e 4 lunar relay satellite

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Abstract

We are developing a hollow corner cube retro-reflector (CCR) with an aperture of 170 mm, which will be carried by Chang'e 4 relay satellite. There are two objectives: (1) making performance verification of CCR for the next generation of lunar laser ranging and (2) doing the satellite laser ranging (SLR) experiment for a larger distance than the earth-moon distance. This satellite is about 450,000 km far from the earth and will operate around the second Lagrange point of earth-moon system with a radius of 12,000 km. The CCR is made of three ULE glass panels using the Hydroxide Catalysis Bonding (HCB) technique. The dihedral angles aim for ≤ 0.6 arc-second and have been achieved 2.8, 2.9 and 7.8 arc-second for the current prototype. To test the space-qualified performance, a thermal circulation test ranging from -15 ℃ to +50 ℃ has been operated successfully for 8 periods (totally 32 hours) continuously.

1. Introduction

Lunar Laser Ranging (LLR) has made great contributions to the investigations of the Equivalence Principle, the time variation of Newton's gravitational constant, the lunar rotation, tide and interior structure. However, because of the lunar libration, the precision of ranging measurement is now limited to several millimeters by the corner-cube retro-reflectors array structure on the moon, which were made with small aperture (38 mm) CCRs. In order to solve this problem, the CCR for the next generation of LLR is proposed to be a single CCR with a large aperture so that 1-mm precision can be achieved. [Currie et al., 2011; Turyshev et al., 2013]

We are developing a large aperture and hollow CCR, which will be carried on Chang'e 4 relay satellite that will be launched in June 2018) as a first step to test the performance of single and large-aperture CCR in the space. This satellite will operate around the second Lagrange point of Earth-Moon system with Halo orbit of 12000-km radius. The averaged distance of this relay satellite is about 450000 km far from the Earth. The CCR has an aperture of 170 mm and is formed by three pieces of ULE glass using the Hydroxide Catalysis Bonding technique. Each dihedral angles aim for $\leq$ 0.6 arc second to ensure a concentrated far-field diffraction pattern. According to the theoretical analysis, its effective reflection efficiency is the same as that of the Apollo 15 CCR array on the moon. To ensure the compatibility of space environment, the CCR needs to be tested by a series of experiments, such as acceleration, vibration, impact, thermal vacuum, ultraviolet radiation and charged particle radiation testings.

2. Chang'e 4 relay satellite

The Chang'e 3 mission has been successful in 2013. As a backup, Chang'e 4 will change its original task to unprecedentedly land at the far side of the moon in 2019. However, it also brings some new challenges such as the communication relay between the lunar lander and the control station on the ground.

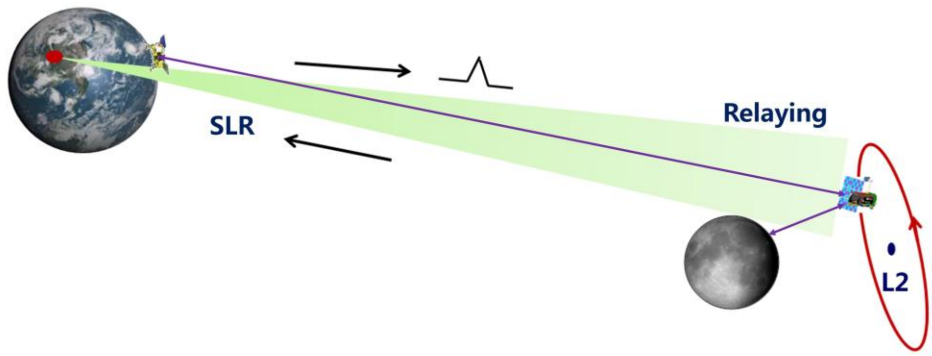

Figure 1 The Chang'e 4 relay satellite

As seen in Figure 1, this relay satellite will operate around the second Lagrange point (L2) of the Earth-Moon system with a Halo orbit. To test the performance of our large aperture and hollow CCR, we will install a CCR with an aperture of 170 mm on the relay satellite and try to do satellite laser ranging (SLR) for the relay satellite. It is more difficult to successfully receive the ranging signal as the distance is even ~70,000 km larger than LLR. Therefore, in the first phase of ranging experiment, we plan to employ a pulse laser with 10 ns width which has a pulse energy of ~3J. The ranging precision of 0.75 m is expected. In this case, it properly ensures that the laser ranging station can receive the ranging signal from the relay satellite safely. Afterwards, in the second phase, we will upgrade a laser with ~100ps pulse width to improve the ranging precision to several millimeters for each normal point.

3. CCR design and technique requirement

The CCR was designed with single 170 mm aperture as well as hollow structure, as shown in Figure 2. There are four advantages of a larger-aperture and hollow CCR, listed as below. Firstly, compared with the solid CCR, a hollow CCR has a smaller weight (<1.6 kg) that is less than half of a solid one with same aperture. Secondly, as the laser light is reflected from the front surface by reflecting coating film without the propagation paths inside the CCR glass medium, therefore, the variation in optical path length caused by the thermal deformation of a solid CCR can be avoided. [Araki et al., 2016]. Thirdly, the systematic uncertainty of laser ranging due to the array structure of CCR can be eliminated as a single CCR with only one reflecting center, hence it is proposed to be the CCR for next generation of LLR [Currie et al., 2011, 2013]. Finally, the larger the aperture of CCR, the smaller the divergence angle of reflecting light, so that a more concentrated far-field diffraction pattern can be obtained, meaning more returned photons can be received on the ground [Otsubo et al., 2011].

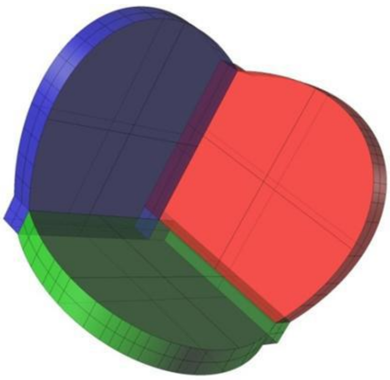

Figure 2 A 170-mm aperture single and hollow retro-reflector

A larger aperture results in a larger reflection cross-section as well as a smaller divergence angle. As shown in the following estimation, for a hollow CCR with a reflectance of 0.6 (compared with a solid CCR with a reflectance of 0.9), the received light power reflected by a 170mm-aperture single CCR is almost the same as that reflected by the Apollo 15 CCR array [Otsubo et al, 2010].

area Reflectance

$$\frac{I_{Apollo15}}{I_{170mm}} = \frac{300}{1} \cdot \left(\frac{3.8}{17}\right)^2 \cdot \left(\frac{3.8}{17}\right)^2 \cdot \frac{0.9}{0.6} = 1.12$$

CCR number divergence angle

The technical specifications t of CCR is shown in Table 1. Corning ULE 7972 is employed because of its extremely low thermal expansion coefficient (CTE) of

~1×10^{-7}/K and relatively small mass density of 2.2g/cm^3 (compared with glass ceramics). The weight of the CCR is about 1.6 kg and the total mass of remained accessories, including CCR, glass window, housing, vibration attenuation structure, is less than 3.5 kg. The thickness of each glass panel is 15mm. Based on the calculation of laser ranging equation, the divergence angle must be ≤ 2 arc-second to ensure that enough photons are received by ranging station (~0.74 per laser pulse). This number is calculated based on the technical specifications of the laser ranging system at Kunming station in China. The reflection coating is protected silver with the central wavelength of 532nm. The planned life time for relay satellite is 5 years as well as the CCR, and the reliability is probably degraded over time due to the aging effect of the silver coating film operating in space.

Table 1 CCR technique parameter.

	Item	**Parameter**
CCR	Aperture	Φ170 mm
	Weight	≤ 1.6 kg
	Dihedral angle	< 0.6 arc second
	Divergence angle	≤ 2 arc second
	Material	Corning ULE 7972
	Central wavelength	532nm
Spacecraft payload	Weight	≤ 3.5 kg
	Reflectance	> 0.6
	Life time	5 years

4. Experimental results

We use the Hydroxide Catalysis Bonding technique to bond three ULE glass panels to form a hollow CCR [Preston and Merkowitz, 2013, 2014]. The HCB technique was originally developed by the research team at Stanford University. Because of its high bonding strength and low CTE, it had been applied in two space missions: Gravity Probe B and LISA pathfinder. Furthermore, its bond layer (~100nm) is extremely thinner compared with most of the commonly-used bonding interface layers (~10μm). Consequently, HCB is the best choice to meet the requirement of sub-arc-second dihedral angle as we need.

The challenge in manufacture is how to fabricate three glass panels together to form a hollow retro-reflector with an extremely high precision. We utilized a high-precision solid corner cube as the corner template which was based on the method from Preston and Merkowitz [2014]. .

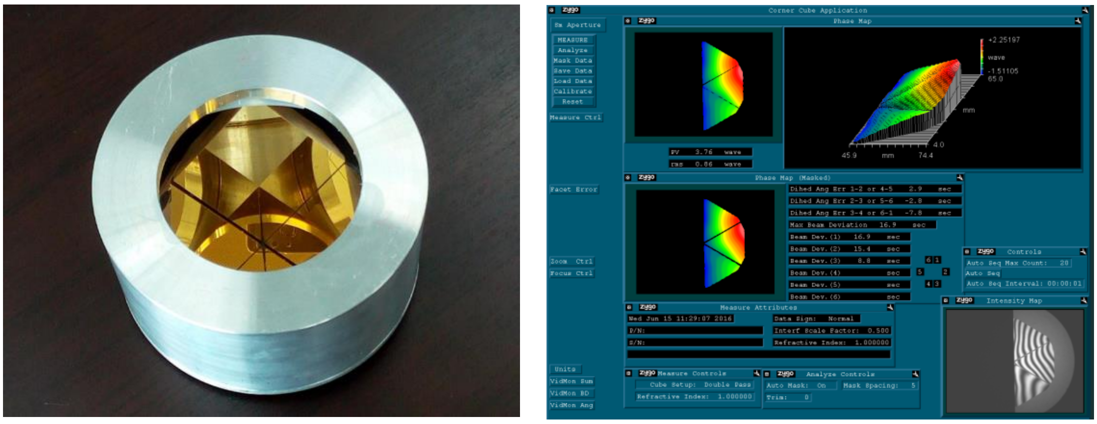

Figure 3 Prototype of Φ70mm hollow CCR (left) with gold coating and measurement result obtained using ZYGO interferometer (right).

Figure 3 shows a prototype of hollow CCR with aperture of 70mm. The dihedral angles measured using ZYGO interferometer are 2.8, 2.9 and 7.8 arc-second, respectively, which are needed to be improved further to reach the aim of 0.6 arc-second.

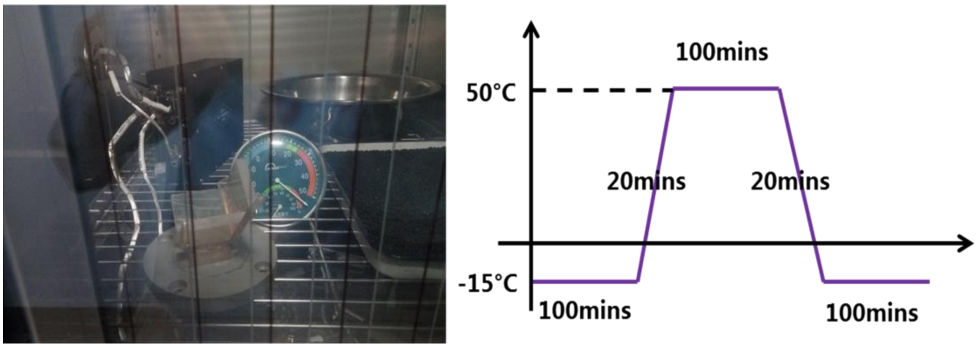

Figure 4 Thermal circulation experiment.

To ensure the space qualification for operating in space environment, the CCR must be tested by a series of experiments, such as acceleration, vibration, impact, thermal vacuum, ultraviolet radiation and charged particle radiation experiment. We have made a preliminary thermal test to verify the viability of silicate bonding. The test conditions are shown in figure 4. The temperature interval is ranging from -15 to +50 ℃, and the heating and cooling phase are lasting for 20 minutes, respectively. Both maximum and minimum temperatures are maintained for 100 minutes during every period. Finally, we tested the hollow CCR for 8 periods continuously (32 hours). The CCR survived with no damage and more strict thermal cycle testings and other compulsory testings are performed in progress.

5. Conclusion

We present the recent progress of developing a 170mm-aperture hollow CCR. The CCR will be carried by the Chang’e 4 relay satellite which is about 450,000 km far from the Earth. This is an ambitious attempt to do the SLR experiment over a distance farther than the Earth-Moon distance. Meanwhile, the performance of the large-aperature and hollow CCR will be also tested for the next generation of LLR. A thermal circulation test ranging from -15℃ to +50℃ was done for 32 hours continuously and the result indicated the validity of HCB technique for manufacturing large-aterture and hollow CCR. To meet the requirements, there are still many testings needed to be performed during the very limited remained time period before the lunching of Chang'e 4 relay satellite.

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