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Development of the Retroreflector on the Moon for the Future Lunar Laser Ranging

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Abstract. *Lunar Laser Ranging (LLR) data are important for the investigations of the lunar rotation, tide, and lunar deep interior structure. The range accuracy of LLR has been less than 2 cm for the last 20 years due to the progress of laser transmit/receive system on the ground stations and the atmospheric signal delay model, however, one order or more accurate ranging than 2cm is needed for better understanding of the lunar deep interior. We are developing 'single aperture and hollow' retroreflector (Corner Cube Mirror; CCM) to be aboard future lunar landing missions. The aperture of CCM is 20cm because the reflection efficiency of that size is found to be higher than that of Apollo 11 array CCP (Corner Cube Prism). For the CCM ultra low expansion glass-ceramic (ClearCeram*®Z-EX, *OHARA Inc.; hereafter CCZ-EX)' or 'single crystal Si' is selected for candidate material of CCM taking into account small |CTE|/K (Thermal expansion coefficient over thermal diffusivity) and large specific Young modulus. The optical performance of CCM deformed by lunar gravity or solar illumination in the holder model is presented for some cases.*

Introduction

Since the first ranging by McDonald Observatory to the lunar retroreflector array put in the Mare Tranquillitatis in July 1969, the lunar laser ranging (LLR) has provided unique and valuable data which constrain modern numerical or semi-analytical lunar ephemerides. Furthermore, research field relating to LLR now covers the lunar ephemerides, gravitational physics, geodynamics, seleno-dynamics, and the celestial reference system (Chapront and Francou, 2006). Accurate LLR data has been unique and quite important to investigate lunar deep internal structure (Yoder, 1981; Williams *et al.*, 2001). However, for further investigation of the liquid core such as ellipsoidal figure parameters or its bulk composition and the existence of solid inner core, improvement of the measurement accuracy is strongly desired. For that purpose we are investigating new type lunar retroreflector with no degradation on returned pulses for future lunar landing missions. In this article status and current results of our investigation are reported briefly.

Design Concepts of New Lunar Retroreflector

<u>Position of new retroreflector on the Moon</u>: Five lunar retroreflectors are deployed around central region of lunar disk. This situation is not approprite for precise observation of the lunar physical libration (perturbation of lunar spin motion). New reflector on the lunar high latitude region is expected to enhance the sensitivity for the lunar physical libration. Furthermore, the new reflector

would be more efficient if deployed as far as from A15 site to detect lunar physical libration because about 3/4 of lunar returns are from large A15 reflector.

Configuration of new retroreflectors: The accuracy of LLR reaches 1.9cm or less in weighted rms for the past 4 years (Williams *et al*., 2013), however, existent lunar retroreflectors have an serious problem that reflected laser pulses suffer from time width broadening and height decrease, leading to degradation of range precision and detection probability, respectively. This is caused by oblique laser incidence to the plate type lunar retroreflector composed of prism array. This problem would be recovered by averaging many timing data of photo-electrons for making one normal point (APOLLO web site; http://physics.ucsd.edu/~tmurphy/apollo/apollo.html). But more general resolution is to deploy new single-device retroreflector (corner cube) on the Moon because it has no optical path difference for any incidence direction (Fig.1).

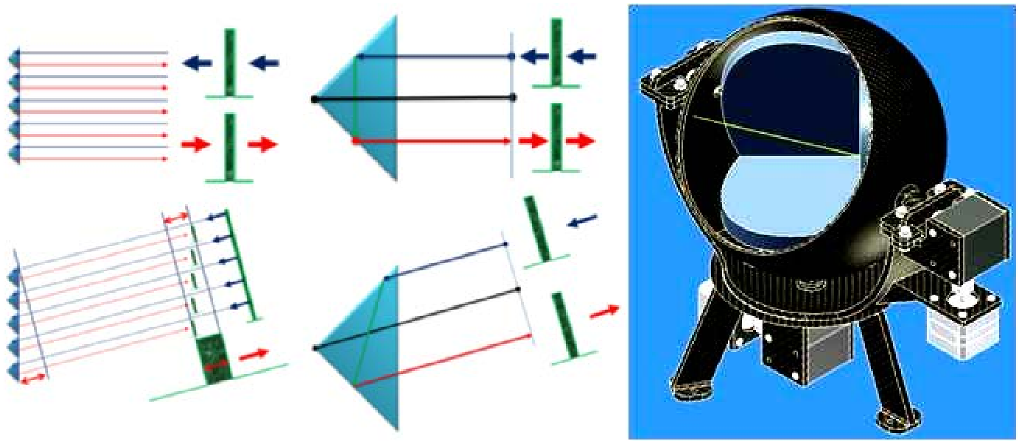

Figure 1. Left; Comparison of return pulse modulation between prism array reflector and single-device retroreflector: Right; Conceptual model of single-device retroreflector (Dome Co. Ltd.).

Size of new single-device reflector: The aperture of the single-device reflector is obtained by using optical cross section formula as follows (Degnan, 1993).

$$\sigma_{cc} = \frac{4\pi\rho D_{cc}^{n}}{\lambda^2}$$

, where σ_{cc} is optical cross section, ρ is reflectivity, D_{cc} is aperture diameter, λ is wavelength, and n is 4 for the case that retroreflector is at rest with respect to laser station, here we assumed n as 3 taking into account relative velocity between Earth and Moon with dihedral angle offset for new retroreflector (Otsubo *et al*., 2011). By equating total cross section of the array type reflector with that of single-device retroreflector, equivalent aperture diameter is obtained. Derived value is 17.6 cm for the reflector at A11 site and 25.4 cm at A15 site. Based on these estimations, we aim to develop single-device lunar retroreflector whose diameter is 20cm.

Advantage of hollow type reflector: An example of large hollow type reflector whose diameter is 50cm carried by MIDORI is shown in figure 2 with prism type reflector whose diameter is 10cm (http://www-lidar.nies.go.jp/RIS/index0-e.htm; Sugimoto and Minato, 1996; Currie *et al*., 2011). The prism reflector is indeed more rigid than hollow type one, however, its diameter is limited up to about 10cm due to the problem of material homogeneity and/or weight budget. Thus hollow type reflector is considered to be better than prism one for larger aperture and high accuracy. Hereafter, we call the hollow reflector as Corner Cube Mirror (CCM).

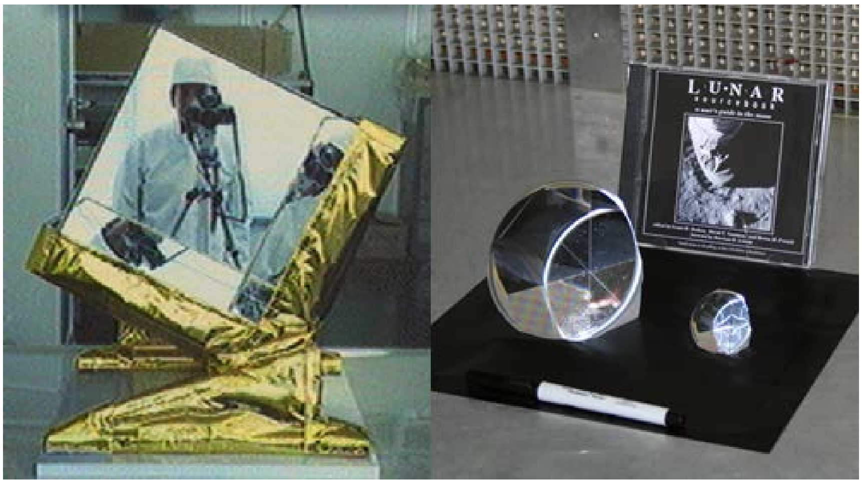

Figure 2. Left; Hollow type retroreflector whose diameter is 50cm on board MIDORI:
Right; Prism type retroreflector whose diameter is 10cm.

Material search for new lunar retroreflector: It is considered that materials suitable for CCM should have following properties, (1) [thermal deformation coefficient / thermal diffusivity] is low and (2) [Young Modulus / density] is high. Silicon (Si) and ClearCeram®Z-EX (CCZ-EX; glass ceramics, OHARA Co. Ltd.) are selected as candidtae materials for CCM among several materials plotted in figure 3.

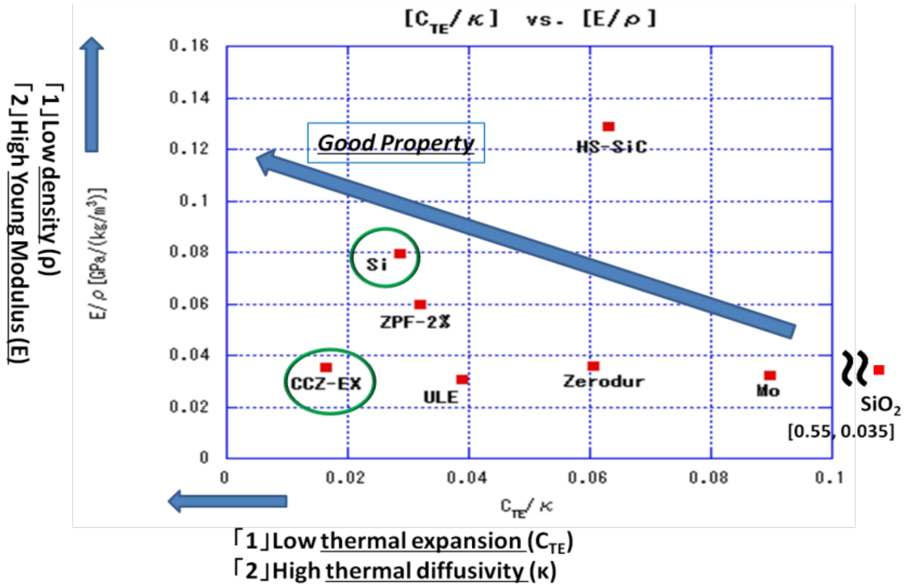

Figure 3. Thermal / Mechanical property map for several materials.

Summary: Our concepts of new lunar retroreflector (CCM) are summarised as follows;

- [1] Placed on high latitude and far from A15 site of the Moon,
- [2] Single-device and hollow type reflector,
- [3] More than 20cm aperture diameter.

Further evaluation and selection process for CCM material is described in the next chapter.

Optical Evaluation of CCM

Evaluation process to select CCM material is as follows;

- [1] Simulate temperature distribution of CCM by Thermal Desktop® software

- [2] Simulate surface deformation of CCM by ANSYS® software taking into account lunar gravity and temperature distribution data obtained at [1]
- [3] Evaluate optical performance of CCM by CodeV® software using surface deformation data obtained at [2]
- [4] Repeat the evaluation process above for Si and CCZ-EX, respectively

The simulation settings are as follows:

- [1] Aperture figure of CCM is hexiagonal and diameter of the inscribed circle is 20cm.
- [2] The coating material is silver with high reflectance and low emissivity against severe thermal condition.
- [3] CCM is set inside of lunar Tycho crater located on lat. 43 degree on hot condition at noon, taking into account self-shadowing in the holder model (Fig. 4).
- [4] The optical axis of CCM is toward the mean Earth direction.
- [5] Two fixation types are employed for our simulation (Fig. 4). The first one is simple fixing at 3 points on the back side of CCM to the holder (Type [0,0,0]). The second is combination of the simple fixing at the corner point and fixing with 1 degree of freedom at 2 other points (Type [0,1,1]).
- [6] Thermo-physical data of Si are quoted from the following sources; White and Minges (1964) for thermal expansion, Glassbrenner and Slack (1964) for thermal conductivity, NIST-JANAF Thermo chemical Tables 4th ed. (http://kinetics.nist.gov/janaf/) for the specific heat. As for CCZ-EX, measured data by Agune Co. Ltd. or Niwa and Utsunomiya (2012) are used.

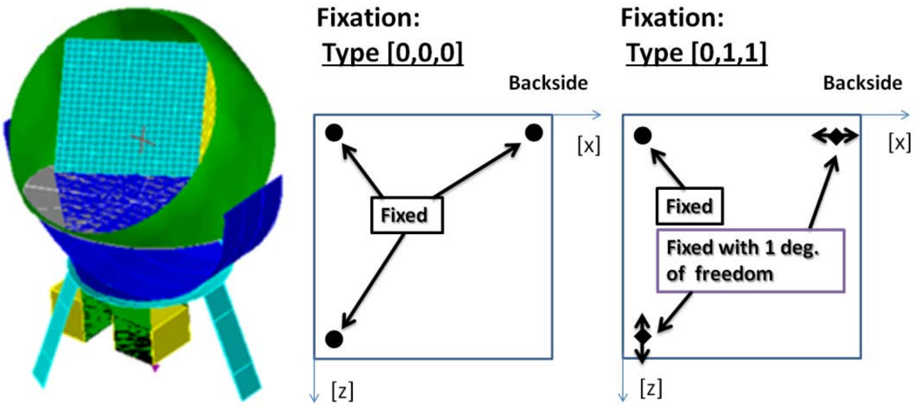

Figure 4. Left; Element model of CCM with holder for Thermal Desktop® software: Middle & Right; Fixation of Type [0,0,0] and Type [0,1,1] on the base plate of CCM.

In the CodeV® software CCM is placed in the mid course of perfectly collimated rays which are focused through perfect lens. If CCM has some deformation, the focus image is aberrated depending on its degree. Our criterion for the evaluation is that more than 50% of energy reflected by CCM is focused within the airy disk.

Results of the Optical Evaluation

Temperature variation on CCM surface is less than 0.5 degree for Si, while more than 20 degrees for CCZ-EX due to the difference of thermal diffusivity (Fig. 5). Thermal deformations based on this temperature map and [0,1,1] fixation for both materials are shown in figure 6. The difference is not so large as temperature (less than 70nm (Si) or 400nm (CCZ-EX). For the case of [0,1,1] fixation, the optical criterion is confirmed to be satisfied for both materials. For [0,0,0] fixation, however, surface of CCM is severely deformed about 60 μm (Si) or 1.5μm (CCZ-EX) due to large thermal stress. Thus the optical criterion is not satisfied for both materials. Results of four cases (Si & [0,0,0], Si & [0,1,1], CCZ-EX & [0,0,0], CCZ-EX & [0,1,1]) are summarized in figure 7. CCM made of Si or CCZ-EX with [0,0,0] fixation cannot pass the criterion, however, both materials pass the criterion for [0,1,1] case and Si shows better performance than CCZ-EX. Thus Si is considered to be better than CCZ-EX as CCM material.

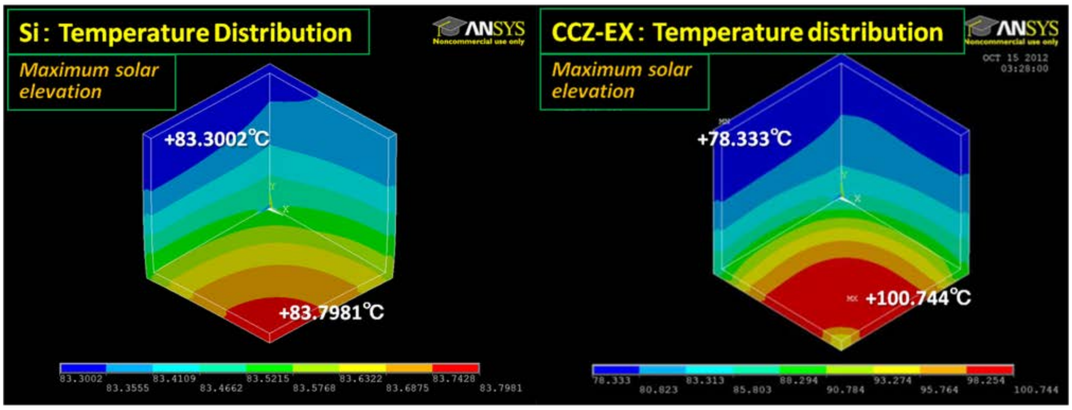

Figure 5. Temperature map on CCM surface: Left; Si: Right; CCZ-EX.

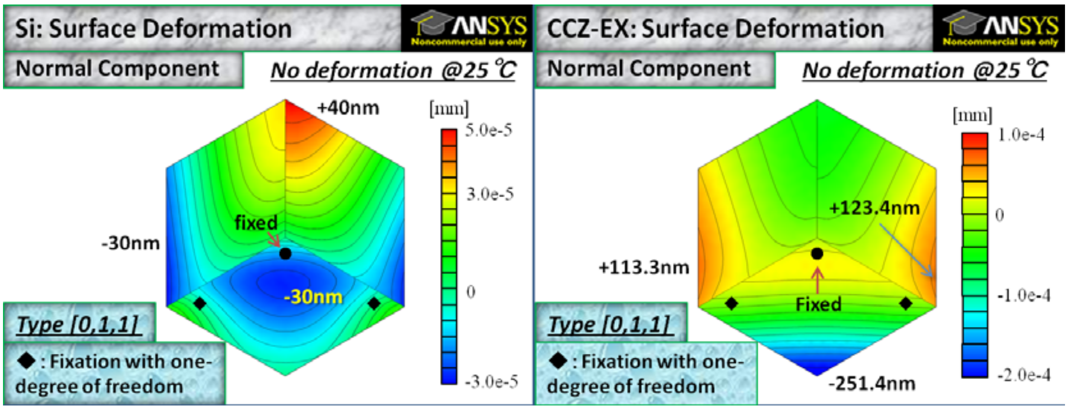

Figure 6. Deformation map on CCM surface: Left; Si [0,1,1]: Right; CCZ-EX [0,1,1].

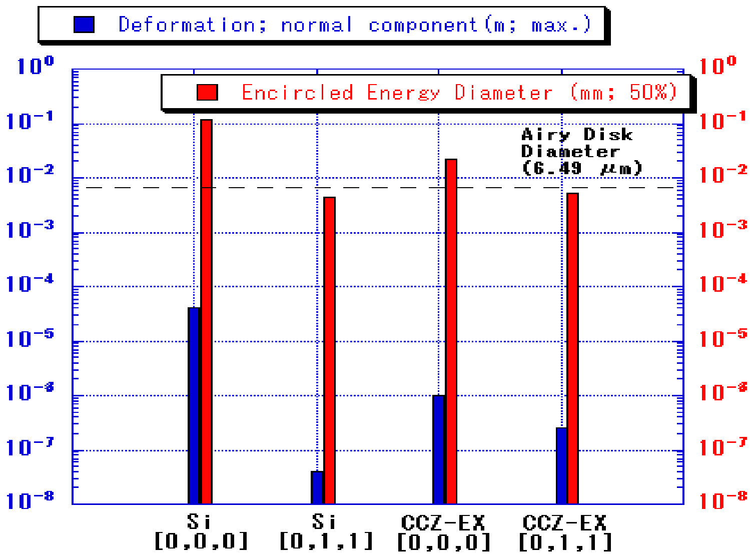

Figure 7. Maximum normal deformation (blue bar) and 50% Encircled Energy Diameter (red bar) for each case. See text for more explanation.

Conclusion and Future Works

If CCM is supported on three fixed points ([0,0,0] fixation), its surface is severely deformed and optically useless for any material. However, for the case of [0,1,1] fixation, both Si and CCZ-EX pass the optical test. Si shows better optical performance than CCZ-EX, thus Si is considered to be superior to CCZ-EX as CCM material. In addition, Si is better on other aspects such as density (2329 kg/m^3(Si) vs. 2500 kg/ m^3(CCZ-EX)), specific Young modulus, and polishing or grinding quality. For the next step we will perform thermal, mechanical, and optical modeling of whole CCM system including holder, together with the investigation of the way how to fabricate CCM and how to realize [0,1,1] fixation. Concurrently we will investigate the influence of lunar radiation environment to the CCM surface reflectivity and/or flatness, and will search for more resistant coating material than silver.

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