

Optical Characterization of Laser Retroreflector Arrays for Lunar Landers

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Abstract: Laser Retroreflector Array for Lunar Landers (LRALL) is a small optical instrument designed to provide a target for precision laser ranging from a spacecraft in lunar orbit, enabling geolocation of the lander and its instrument suite and establishing a fiducial marker on the lunar surface. Here we describe the optical performance of LRALL at visible and near-infrared wavelengths. Individual corner cube reflectors (CCRs) within LRALL were tested for surface flatness and dihedral angle values. We also imaged the far-field diffraction patterns of individual CCRs as well as the entire retroreflector array over the range of possible incident angles to extract the optical cross section as a function of viewing angle. We also measured the optical properties of one of the CCRs over the lunar temperature range (100 K to 380 K) and found no significant temperature-dependent variance. The test results show LRALL meets the design criteria and can be ranged to from elevation angles above 30° with respect to the instrument base from an orbital laser altimeter such as the Lunar Orbiter Laser Altimeter (LOLA) on the Lunar Reconnaissance Orbiter (LRO). This work summarizes the test data and serves as a guide for future laser ranging to these retroreflector arrays.

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1. Introduction

Laser retro-reflector arrays (LRAs) on the Moon and other planetary bodies can act as fiducial markers for decades of laser ranging. The Apollo and Lunokhod LRAs on the lunar surface [1,2] have significantly contributed to our knowledge of the Moon [2–5]. The recent development of lunar missions from government space agencies, and commercial and private partners [6], offers a unique opportunity to support lunar science and exploration through the deployment of small LRAs on lunar landers. Placement of a small LRA on the deck of a lander or rover enables tracking with an orbital laser altimeter with a precision on the order of centimeters. An optical marker observable from orbit mounted alongside a suite of scientific instruments on the surface enables geolocation of those instruments in the lunar geodetic frame. In addition, LRAs can in turn be used to validate geolocation and ranging performance of orbital laser altimeters, as was done in support of the Advanced Topographic Laser Altimeter System (ATLAS) on the Ice, Cloud and land Elevation Satellite-2 (ICESat-2) mission [7]. Knowledge of the precise location of the array and the lander on the lunar surface is beneficial for orbit reconstruction, navigation, and broader exploration goals. Finally, optical markers such as LRAs can support precision autonomous navigation and landing without special demand for the lighting conditions, as was accomplished by the Hayabusa mission to asteroid 25143 Itokawa [8] and the Hayabusa2 missions to asteroid 162173 Ryugu [9].

The Laser Retroreflector Array for Lunar Landers (LRALL) is an instrument designed to provide a high-gain optical target which can be ranged to with a lunar-orbiting laser altimeter from any angle above 30° from the mounting plane. These low-mass, small instruments (Table 1) were designed and tested for decades of lifetime on the lunar surface. They can operate over the entire lunar day and night and are completely passive; they require no power, communication, or thermal control. LRALL was integrated with the SpaceIL Beresheet spacecraft prior to its February 21, 2019 launch and became the first NASA instrument to fly on a non-governmental mission to the Moon. Similar small LRAs were placed on the ExoMars and InSight landers [10]. For further discussion of the design, environmental testing, and future uses of LRALL please see our companion publication [11].

Here we describe the optical performance of LRALL. Our optical test program included measurement tests from the qualification of retroreflector arrays for satellite laser ranging (SLR) [12,13]. However, our test program extended beyond previous characterization to measure returns at multiple wavelengths, track performance over the lunar temperature range, and perform a detailed study of the interference effects of multiple-cube returns. We tested two versions of LRALL: one with metal-coated corner cube reflectors (CCRs), and one with CCRs that rely on total internal reflection (TIR). First, we will present the mechanical and optical design of LRALL and discuss its similarities

and differences to other lunar retroreflector arrays. Following this, the optical testing is presented in four sections. In each section, the test setup will be described first, followed by the test results and analysis. The four test sections are as follows: interferometric testing of individual CCRs for surface flatness and dihedral angle measurements, tests of retroreflector optical performance in vacuum over the expected lunar surface temperature range (100 to 380 K), far-field diffraction experiments at visible (532 nm) and near-infrared (1064 nm) wavelengths of both individual CCRs and the entire LRA to measure the optical cross section and investigate interference effects, and return pulse waveform tests to determine the pulse spreading characteristics of the LRA.

2. Instrument design

The LRALL instrument comprises eight unspooled fused silica CCRs (circularly-cut trihedral prisms) bonded to a chromate conversion-coated aluminum shell, as shown in Figure 1. The eight CCRs are set into the shell in a pattern of two concentric rings of four cubes each: one ring with a CCR surface normal at 20° from the base normal and one ring at 40° from the base normal (Figure 1C). The orientation of each CCR with respect to the overall array was randomized. Two versions of the instrument are described here: one in which the CCRs have aluminum-coated (*i.e.*, aluminum-plated or metal-coated) back faces, and one in which the CCRs are uncoated and rely on total internal reflection. The instrument parameters are given in Table 1.

The position of the optical reference point of the array with respect to the center of gravity and the base of the array are shown in Figure 1C. The optical reference point is defined as the intersection of the optical axes of the eight individual CCRs. The center of gravity of the array is co-located with the axis of rotational symmetry of the array, but offset by 6.73 mm above the basal plane of the array. As the center of gravity and optical reference point are not co-located, an elevation-dependent correction is needed to translate the range to a position with respect to the center of gravity or the base of the array.

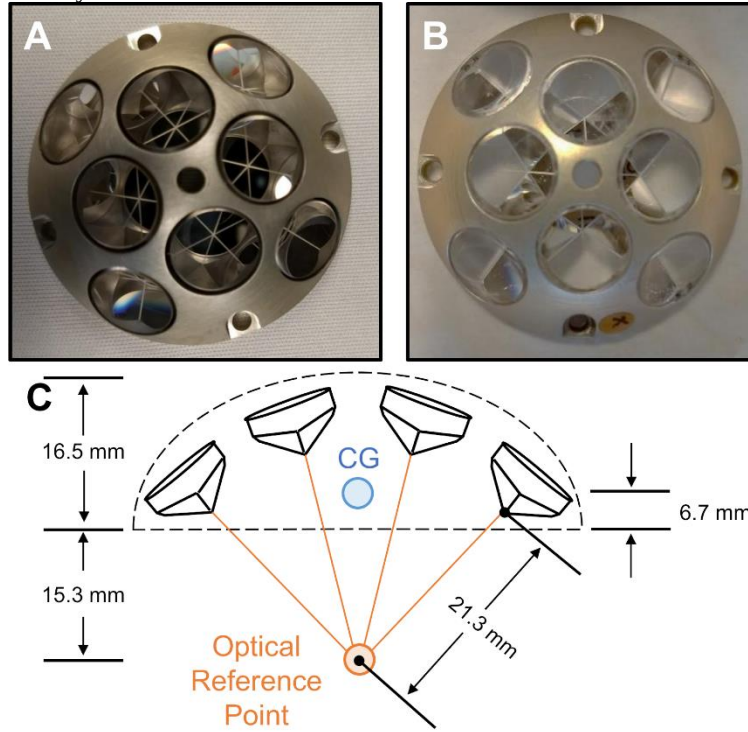


Fig. 1. Laser retroreflector arrays for lunar landers (LRALL). (A) Array with eight metal-coated CCRs. (B) Array with eight TIR CCRs. (C) Illustration showing LRALL geometry and optical reference point. CG stands for center of gravity. CCR illustration is not to scale.

Table 1. LRALL instrument parameters

Parameter	Value
Array Diameter	5.11 cm
Array Height	1.65 cm
CCR Clear Aperture	1.27 cm
Number of CCRs	8
Mass	20 ± 1 g

LRALL is designed to be mounted on landed spacecraft and ranged to from orbit (up to 300 km away), and not from Earth; these arrays are too small to be ranged to from Earth with current technology. LRALL has significant design differences from previous lunar retroreflector arrays to accommodate ranging from an orbiting spacecraft. The most prominent changes are the size of the CCRs and the non-planar design of the array.

The CCRs set into the LRA have a front-face clear aperture diameter of 1.27 cm (0.5 in.), which results in a significantly smaller cross-sectional area than the 3.8-cm CCRs in the Apollo arrays, though the smaller CCRs offer several advantages. First, the smaller CCRs have a lower mass and can be packed tightly to form a small array suited for smaller, lighter lunar landers. In addition, smaller CCRs are less susceptible to solar-induced thermal gradients which may affect the performance of larger CCRs [14,15]. For the coated CCRs, absorption of incident light by the metal coatings can create thermal gradients within the CCR and lead to phase distortions and a subsequent temporal instability and a reduction in optical cross section. The CCRs in the TIR version of LRALL are uncoated and consequently are less susceptible to degradation over time [11,14]. Uncoated glass surfaces provide improved longevity on the lunar surface, crucial for the goal of creating and sustaining lunar geodetic reference points. Spacecraft integration involves securing one or more arrays to a spacecraft deck with the appropriate fasteners in a location that gives the largest unimpeded field of view of the sky for the array(s).

3. Dihedral angle error and surface flatness of CCRs

Two primary optical figures of merit for a CCR are the surface flatness and the dihedral angle error (DAE) or deviation in angle from 90° between the three facets of the trihedral prism. A rough surface or large DAE will spread the retroreflected beam and reduce the overall optical gain of the instrument for this application. The design specification for LRALL was for each CCR to have a surface flatness of $1/10 \lambda$ at 532 nm and exhibit an average DAE within ± 0.5 arcsec. This is in contrast to small LRAs for satellite laser ranging in low-Earth orbit where one of the dihedral angles is often spoiled to account for the velocity aberration. The performance of each CCR was measured using a laser interferometer (Zygo Verifire) operating at 633 nm. The LRA was mounted in front of the interferometer such that a single CCR in the array was near normal to the incident laser and all other CCRs were blocked. Each CCR was measured four times. All CCRs on all LRAs were tested and showed similar results, meeting the specifications for DAE and surface flatness. Figure 2 shows representative results for the DAEs from one of the LRAs.

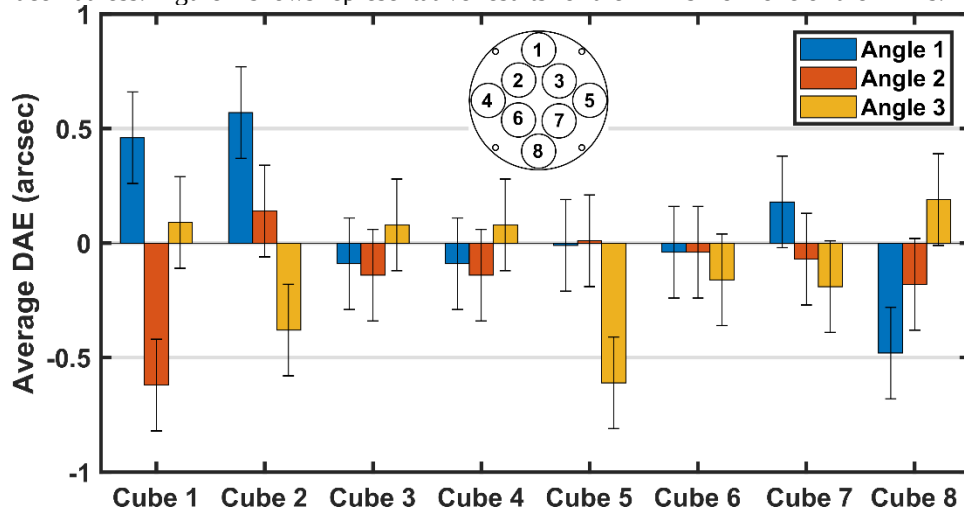


Fig. 2. Dihedral angle error measurements of CCRs for a representative LRALL instrument. Angles 1, 2, and 3, corresponding to the intersections of the three prism facets, were designated prior to test and held consistent throughout testing.

4. Dihedral angle error variance over the lunar temperature range

4.1 Temperature Test Motivation

The thermal extremes experienced on the lunar surface over the course of the diurnal cycle – from 95 K to 385 K at the equator [16] – can induce thermal gradients in both coated and uncoated CCRs [14,15,17], though metal-coated CCRs are more susceptible to this effect. This effect can lead to reduced optical cross-section for gradients as small as 4 K from the front surface to the rear vertex [18]. In order to test whether the 1.27-cm CCRs in LRALL would suffer degraded optical performance over the expected lunar temperature range, we mounted the array inside a cryogenic vacuum dewar behind an optically-transparent, wedged window. We then varied the temperature of the baseplate of the dewar as we measured the CCR dihedral angle errors with a Zygo Verifire laser interferometer. Changes in the interference pattern from the CCR (due to thermal gradients in the CCR or other effects) would thus manifest as higher DAE variance.

4.2 Temperature Test Setup

We attached the LRA to the dewar mounting plate with four M2.5 socket cap fasteners using 2.6 to 3.0 ft-lb of torque to simulate integration conditions. The dewar was evacuated to a vacuum level of 0.03 Torr prior to cooling to prevent frost formation on the array. The array temperature was monitored with a silicon diode thermocouple fixed within 2 mm of the LRA on the aluminum mounting plate. Heating from cryogenic temperatures was performed via a 100-W cartridge heater fixed to the rear of the mounting plate. Measurements were obtained from 100 K to 380 K in 20 K steps. The heating rate was held at 3 K per minute between temperature steps.

The LRA heating in the test configuration was conductive via the array shell to the outer front surface of the CCR and radiative from the baseplate to the back of the CCRs, which differs from the front-surface radiative heating that the CCRs will experience on the lunar surface. In our case, the inability to directly measure the 1.27-cm CCR temperature in real-time, as well as space limitations of the cryogenic dewar needed to reach the lower end of the lunar temperature range while measuring the DAE precluded the use of a solar simulator. We believe the thermal conditions in our test setup represent a more extreme test environment than the lunar surface, as the heating was more localized and rapid than under surface conditions. Temperature measurements were obtained during heating of the system, which began after cooling of the array with liquid nitrogen to 100 K. The measurement temperatures were held with a proportional-integral-derivative (PID) heating loop for roughly one minute at each measurement temperature during which the interferometric measurements were obtained.

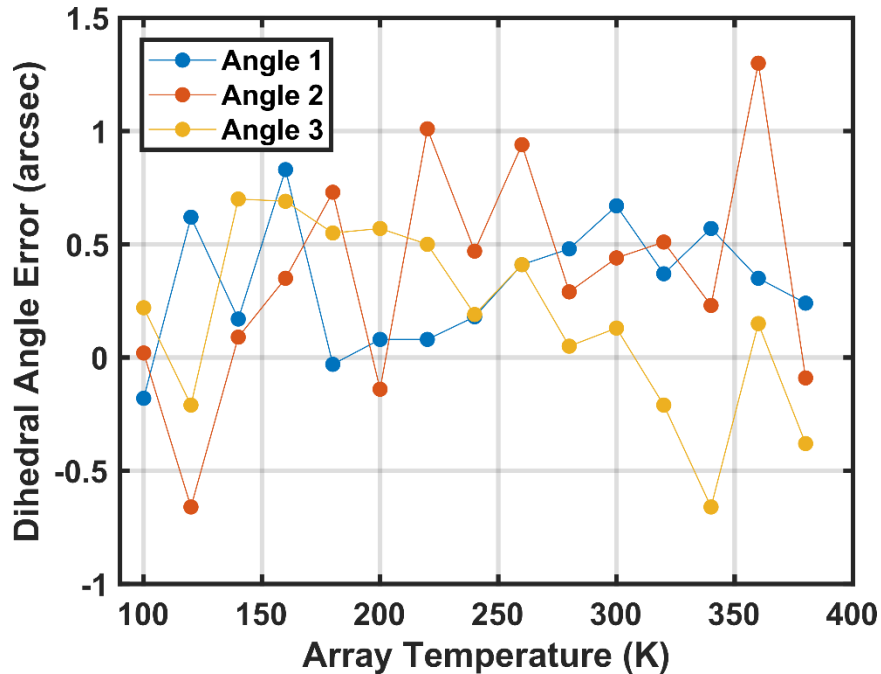


Fig. 3. Measured retroreflecting properties of a TIR CCR over the expected lunar surface temperature range. Angles 1, 2, and 3, corresponding to the intersections of the three facets, were designated prior to test and held consistent throughout testing.

4.3 Temperature Test Results

We observed small variations in the DAEs over the lunar surface temperature range, and the three angles in the CCR exhibited different trends from one another (Figure 3). Measurements of the DAEs taken at room temperature prior to cooling were -0.19 arcsec, 0.61 arcsec, and 0.14 arcsec for angles 1, 2, and 3 respectively. Thus, for the entire observed temperature range, all three DAEs varied over a range near the tolerance of the CCRs (± 0.5 arcsec). This suggests that no strong axial or radial thermal gradients were present in the 1.27-cm CCRs that would impact optical performance under test conditions. On the lunar surface solar illumination can induce thermal gradients in the CCRs due to thermal breakthrough (loss of total internal reflection) of the TIR CCRs at angles above $\sim 17^\circ$ and conduction through the aluminum shell [19]. However, the small size of the CCRs in LRALL (1/3 the diameter of the Apollo CCRs) should reduce the magnitude of thermal gradients while on the lunar lander deck. Some margin also exists in the link for the potential of thermally-induced reduction in optical cross section based on our calculation of the maximum ranging distance of 170 km for LOLA [20]. The non-planar design of the array should also enable ranging to multiple CCRs in the array during a single pass should thermal breakthrough at certain times of day reduce the optical cross section of a portion of the array.

5. Far-Field diffraction imaging and optical cross section measurements of individual CCRs and of the array

5.1 Test Setup and Discussion of Optical Cross Section

The far-field diffraction pattern (FFDP) is the spatial and intensity distribution of light returned to an interrogating laser source from an illuminated CCR under Fraunhofer conditions (*i.e.*, the distance from the source to the CCR is much greater than the aperture diameter). A theoretical, perfect reflecting circular surface illuminated at normal incidence has a FFDP that is the well-known two-dimensional Airy function. Far-field patterns of individual CCRs and the LRA were obtained at wavelengths of 532 nm and 1064 nm using a 2.5 m focal length parabolic reflective collimator. The collimator test setup is shown in Figure 4A. The array was mounted to a dual-axis rotation stage to allow for imaging over a range of viewing angles (Figure 4B). We placed a circular aperture between the beam splitter and first mirror that spatially filtered the beam to $\frac{1}{2}$ the initial beam diameter. The beam diameter at the LRA was measured to be 75 mm with a wavefront quality of $\lambda/8$. A linear polarizer was placed in front of the laser source to control the laser polarization with respect to the array. Unless otherwise stated (as in section 5.3), the polarization state for all tests was horizontal with respect to the LRA oriented at azimuth = 0, which is the array orientation shown in the inset of Figure 2. Individual CCR FFDPs were obtained by blocking surrounding cubes in the array, ensuring returns from only the CCR under test.

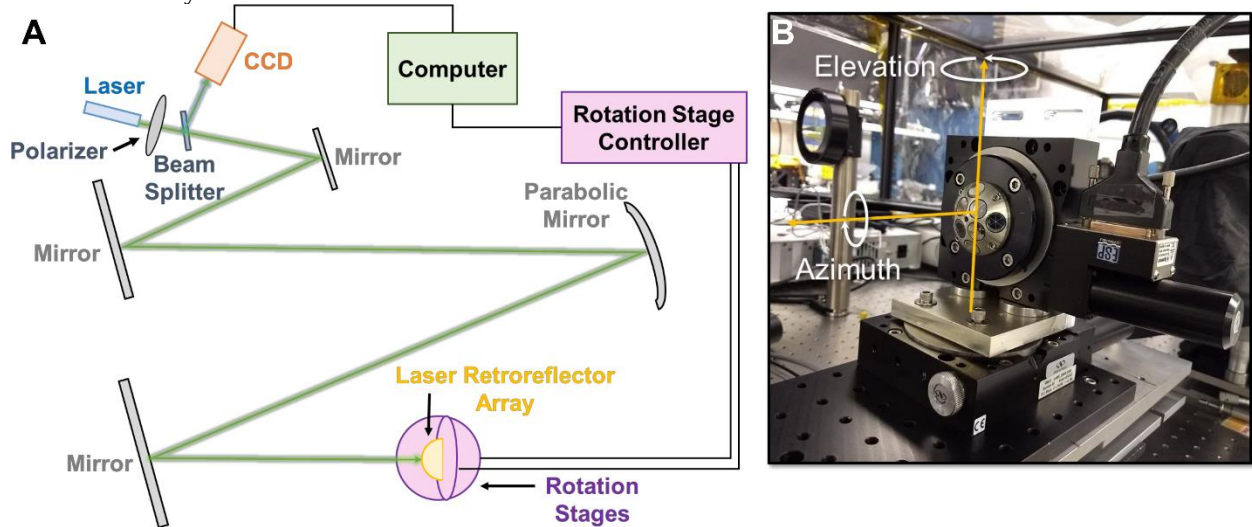


Fig. 4. Far-field diffraction pattern optical test setup.

The quantitative optical return from a CCR can be described by its optical cross section (OCS, denoted as σ). The optical cross section is intrinsic to a CCR and is given here in units of million square meters. It can be intuitively understood to be the equivalent area of a Lambertian surface that returns the same optical signal as the retroreflector(s). The peak optical cross section of a CCR under normal incidence is given by [12]:

$$\sigma = \frac{\rho \cdot A^2 \cdot 4\pi}{\lambda^2} \quad (1)$$

Where ρ is the reflectivity of the CCR (including surface and internal reflections), A is the cross-sectional area of the CCR front face, and λ is the wavelength of light illuminating the CCR. When illuminated at off-normal incidence, the peak optical cross section is reduced by a factor η based on the angle of incidence θ_i and index of refraction n of the glass given by [21]:

$$\eta = \left[\frac{2 \cos(\theta_i)}{\pi} \right]^2 \cdot \left\{ \sin^{-1} \left[\sqrt{1 - 2 \tan^2 \left(\sin^{-1} \left(\frac{\sin(\theta_i)}{n} \right) \right)} \right] - \sqrt{2} \tan \left[\sin^{-1} \left(\frac{\sin(\theta_i)}{n} \right) \right] \right\}^2 \quad (2)$$

For TIR CCRs, polarization effects further reduce the peak optical cross section. Using this framework, the quantitative optical cross section values presented here were calibrated using the optical cross section from a 1.27-cm diameter protected-gold mirror with a reflectance calibrated at each measurement wavelength.

As a multi-reflector array, the optical return from LRALL is a function of interfering returns from one to four individual retroreflectors. In the interest of completeness and to aid analysis and modelling of future laser ranging efforts, we will first discuss the results for an individual CCR, which provides simpler results from which the more complicated LRALL results can be contextualized and interpreted.

5.2 Single-CCR Optical Performance

Far-field diffraction patterns of individual CCRs in the array were obtained with an opaque plastic mask placed around the CCR under test to block light from any adjacent reflector. Diffraction patterns were captured with a 2048 x 2048-pixel CMOS camera (Basler acA2500-14gm) at 12-bit depth with a pixel size corresponding to 2.15 μ rad x 2.15 μ rad in reciprocal space. Each FFDP was compared to a calibrated, protected-gold mirror for which the peak OCS was calculated using Equation 1. The laser and camera settings were held constant between measurements of the CCRs and this reference mirror. This process enabled a pixel-by-pixel conversion from pixel intensity to optical cross section for each FFDP. After this normalization, the highest intensity pixel in each FFDP was set to zero beam deviation for single-CCR FFDPs. Figure 5 shows representative results from the metal-coated (A, B) and TIR (C, D) CCRs at normal incidence to the CCR.

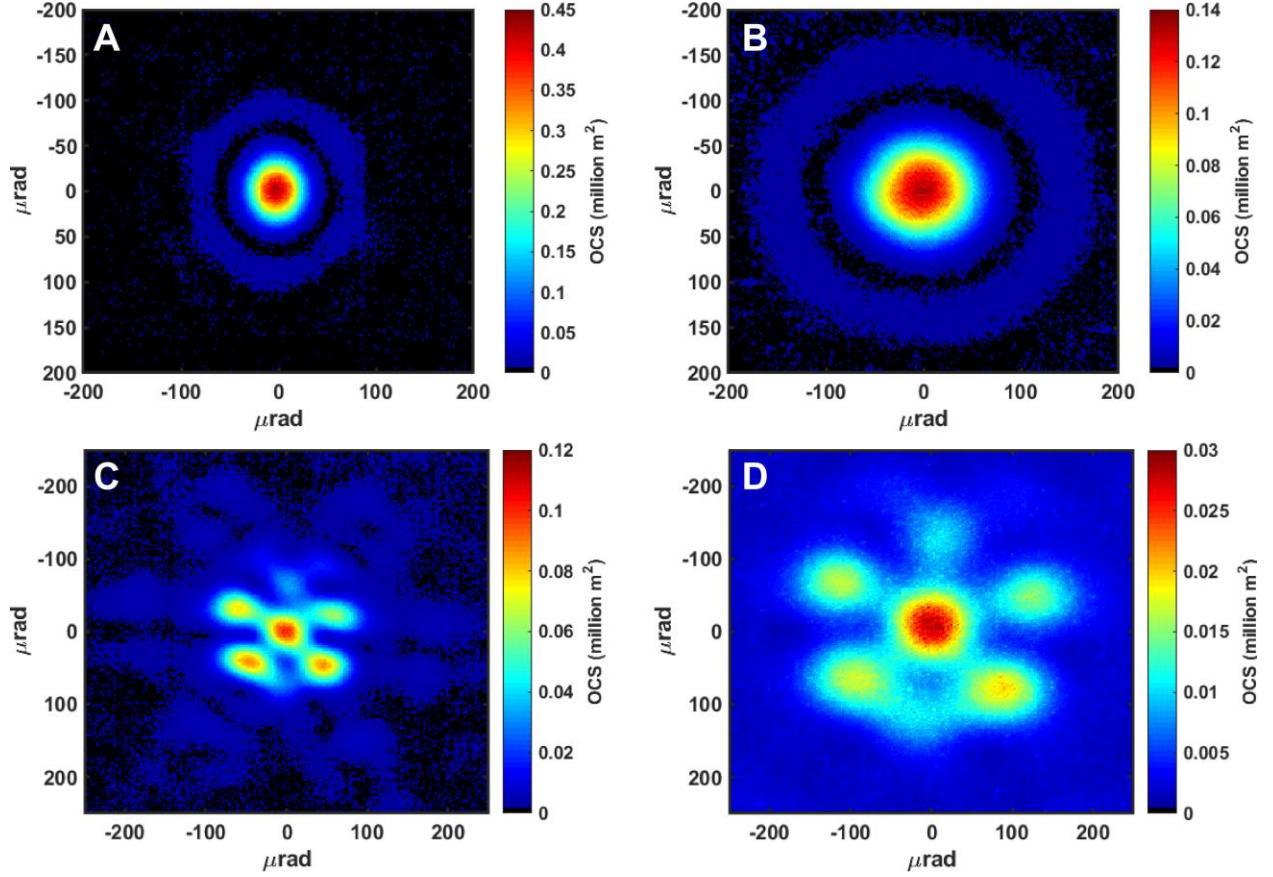


Fig. 5. Far-field diffraction patterns of individual CCRs. The patterns from the metal-coated (A, B) and TIR (C, D) CCRs were obtained under uniform illumination with collimated 532-nm (A, C) and 1064-nm (B, D) laser light. The axes correspond to beam deviation from the source as measured on the calibrated detector. The color scales correspond to optical cross section and are given by the scales to the right of each frame.

The metal-coated CCRs exhibited a circularly-symmetric optical return similar to a classical Airy pattern, as predicted from diffraction theory. In addition, the size of the Airy disk scales linearly in reciprocal space with the wavelength. Measurements of the TIR retroreflectors using linearly polarized light exhibited well-known polarization effects; the six-fold symmetry due to the the real and reflected back faces of the CCR can be seen in the FFDPs as each reflection within the cube introduces an element of elliptical polarization [22,23]. Thus, the contributions from all six unique paths through the CCR, each introducing a different phase shift, interfere to generate the six side lobes seen in the bottom of Figure 5. This effect reduces the central peak of the FFDP to 26.4% of what it would be for a perfect reflector of the same area and shape.

The numerical results for the coated and TIR CCRs at both measurement wavelengths are given in Table 2. The stated variances correspond to 1σ from five independent measurements at normal incidence. The coated CCR peak OCS values compared to the perfect reflector case (based on Equation 1) are 72% and 74% for 532 nm and 1064 nm, respectively. This difference can be explained by the aluminum coating on the cubes, which is 91% reflective and thus induces a 25% reflectance loss through the CCR for three reflections.

For the TIR CCRs, the measured peak OCS was smaller than that expected from theory. The central irradiance of a TIR retroreflector with no dihedral angle offset is expected to be 26% that of a perfect reflector, however, we measured values of 14% and 15% at 532 nm and 1064 nm, respectively. Surface reflection losses for the TIR CCRs were measured as $\sim 2\%$ per pass, which brings the expected peak OCS to 22% that of a perfect reflector. This unexpected lower peak OCS for the TIR CCRs is most likely due to the laboratory measurement setup (*ex.* laser intensity fluctuations between calibration and measurement, air currents or turbulence changing the spatial laser profile, slight misalignment of the CCR mask) as the interferometer results show a low DAE and surface flatness that would predict near-theoretical CCR performance.

Table 2. Optical test results from FFDPs of individual CCRs. The first airy pattern minimum is measured from the centroid of the FFDP.

CCR Type	Wavelength	First Airy Pattern Minimum	Measured Peak OCS (million m ²)
Coated	532 nm	50 μ rad	0.51 ± 0.07
	1064 nm	115 μ rad	0.131 ± 0.009
TIR	532 nm	40 μ rad	0.104 ± 0.017
	1064 nm	78 μ rad	0.025 ± 0.004

In addition to testing the performance at normal incidence, the peak optical cross section of individual CCRs was tracked as a function of incidence angle to determine the range of angles from which successful ranging can occur. Figure 6 shows the normalized peak optical cross section as a function of incident angle for coated and TIR CCRs. The coated and TIR retroreflectors exhibited similar retroreflective behavior; both retroreflectors showed a reduction of peak optical cross section due to the angle-dependent reduction in visible cross-section of the CCR. The drop to 50% OCS occurred at $\sim 12^\circ$ from normal incidence. The TIR CCRs showed a reduced relative return at angles above $\sim 15^\circ$ corresponding to the onset of the TIR breakthrough effect, or the loss of total internal reflection and subsequent increase in CCR optical transmission. The experimental results are compared to the predicted fall off due to the reduction in the effective area (Eq. 2), which matches well for the metal-coated CCRs.

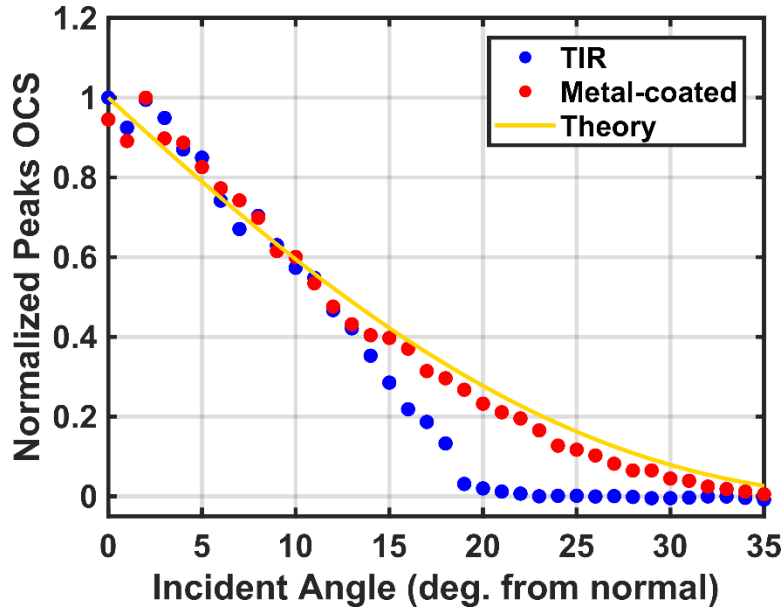


Fig. 6. Normalized peak optical cross section of metal-coated and TIR CCRs as a function of incident angle at 1064 nm. Normalized peak optical cross section is defined as the optical cross section returned to the light source normalized to the optical cross section at normal incidence for each type of CCR.

5.3 Polarization-Sensitivity of Total Internal Reflection CCRs

Understanding the polarization sensitivity of the TIR version of LRALL may be useful to interpreting future orbital ranging measurements as solid-state laser transmitters comprise the bulk of planetary laser altimeters and emit a linearly polarized beam. We captured FFDPs from single TIR CCRs at 532 nm and 1064 nm for three incident polarization states. The results are shown in Figure 7, with the polarization states indicated with respect to the CCR symmetry in the insets. Rotation of the input polarization led to changes in the pattern structure and amplitude of the optical return for both wavelengths. The six outer spots rotated counter to corresponding changes in the input polarization, and the outer lobes were preferentially excited when the polarization axis closely aligned with the lobe locations [22,24]. One notable case was the horizontal polarization case at 532 nm (Figure 7C), which exhibited a

reduced optical return across the entire pattern. As this result was not replicable at 1064 nm, we conclude that it is an artifact of the visible light measurement setup and not intrinsic to the CCR performance. The region of the FFDP relevant for ranging from lunar orbit is within $10\ \mu\text{rad}$ of the center (due to velocity aberration), thus the side lobes should not affect ranging efforts under single-CCR conditions.

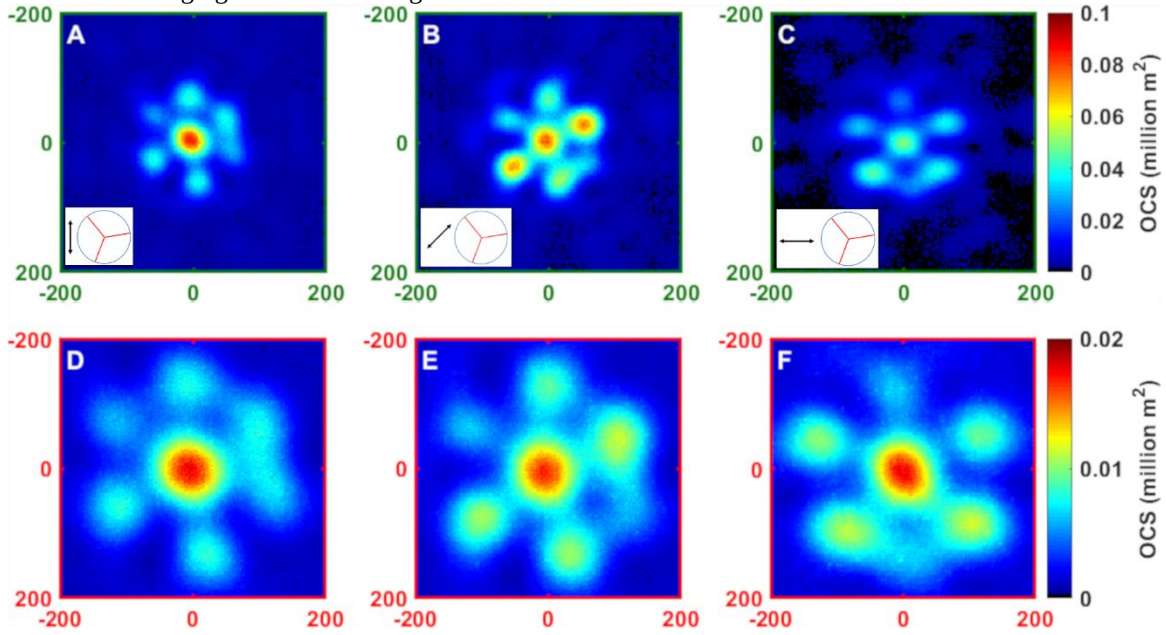


Figure 7. Polarization dependence of far field patterns from TIR CCRs. Far field patterns were obtained from illumination at 532 nm (A, B, C, outlined in green) and 1064 nm (D, E, F, outlined in red). The frame axes correspond to beam deviation in μrad and are the same for all images. (insets) The polarization axes for the three polarizations tested (black arrows) with respect to the CCR. Edges of the facets of the CCR are shown in red. The color scale corresponds to optical cross section with warmer colors denoting higher optical cross section, and cooler colors denoting a lower optical cross section. The optical cross section scale for (A-C) is given by the colorbar next to (C) and the scale for (D-F) is given by the colorbar next to (F).

5.4 Array Reference Frame

In order to clarify discussion of the optical test results from the full array, we will briefly describe our orientation terminology. As a hemispherical object, vectors incident to the LRA may be described by two angles (as in a spherical coordinate system), which we have termed the azimuth and elevation (Figure 8) that are defined with respect to an LRA-centric reference frame.

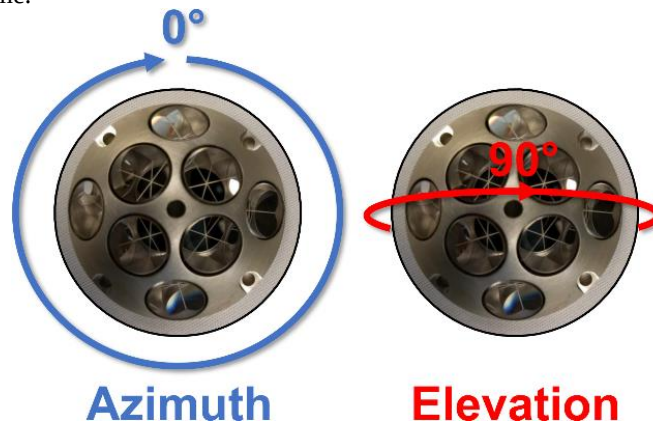


Fig. 8. LRA schematic describing angle terminology overlaid on a top-down view of the LRA.

The angle termed azimuth refers to rotation about an axis running through the center of the array from the top to the base (Figure 8, left), with zero azimuth defined by the center of one of the four outermost CCRs. The angle termed elevation refers to rotation about an axis perpendicular to the azimuth axis and running from 0° (corresponding to

viewing the array edge on) to 90° (corresponding to viewing the array from directly above, as is shown in Figure 8). Thus, any incident vector can be uniquely defined by its azimuth (0° to 360°) and elevation (0° to 90°).

5.5 LRALL Far-Field Diffraction Patterns and Optical Cross Section

We performed a series of optical tests of both the coated and TIR LRALL instruments to measure the optical return over a broad range of incident angles. With these results we hope to aid and give context to future laser ranging measurements to these instruments on the lunar surface. Using the measurement setup described in Section 5.1, far-field diffraction patterns were obtained at one-degree angular steps from 0 to 90° in azimuth and 10° to 90° in elevation under constant illumination conditions, for a total of 7200 distinct FFDPs per array tested, per wavelength. As the array contains four-fold rotational symmetry, measuring one quarter of the hemisphere will yield information on all observable angles, assuming the individual CCRs within an array perform similarly.

A subset of FFDPs for the TIR version of LRALL is shown in Figure 9 in equirectangular projection with the color scale corresponding to optical cross section. The highest optical return occurred at 60° to 80° in elevation as is apparent from the bright central lobes at those angles. FFDPs in that elevation range also exhibited interference fringes as returns from multiple CCRs contributed to the diffraction patterns. This multiple-CCR interference causes the intensity in those patterns to change as a function of time due to wavelength-scale variations in array position and incident angle. The pattern obtained at normal incidence to the array was notably dim, and that pattern (as well as the other patterns in this high-elevation interference regime) did not qualitatively resemble the single-cube FFDPs shown in Figure 5. At elevations below 50° the patterns resembled those of single CCRs at various incident angles. The orientation-dependent polarization effects of the CCRs described in section 5.3, when combined with the interference effects shown here, complicates precise prediction of the instantaneous cross section.

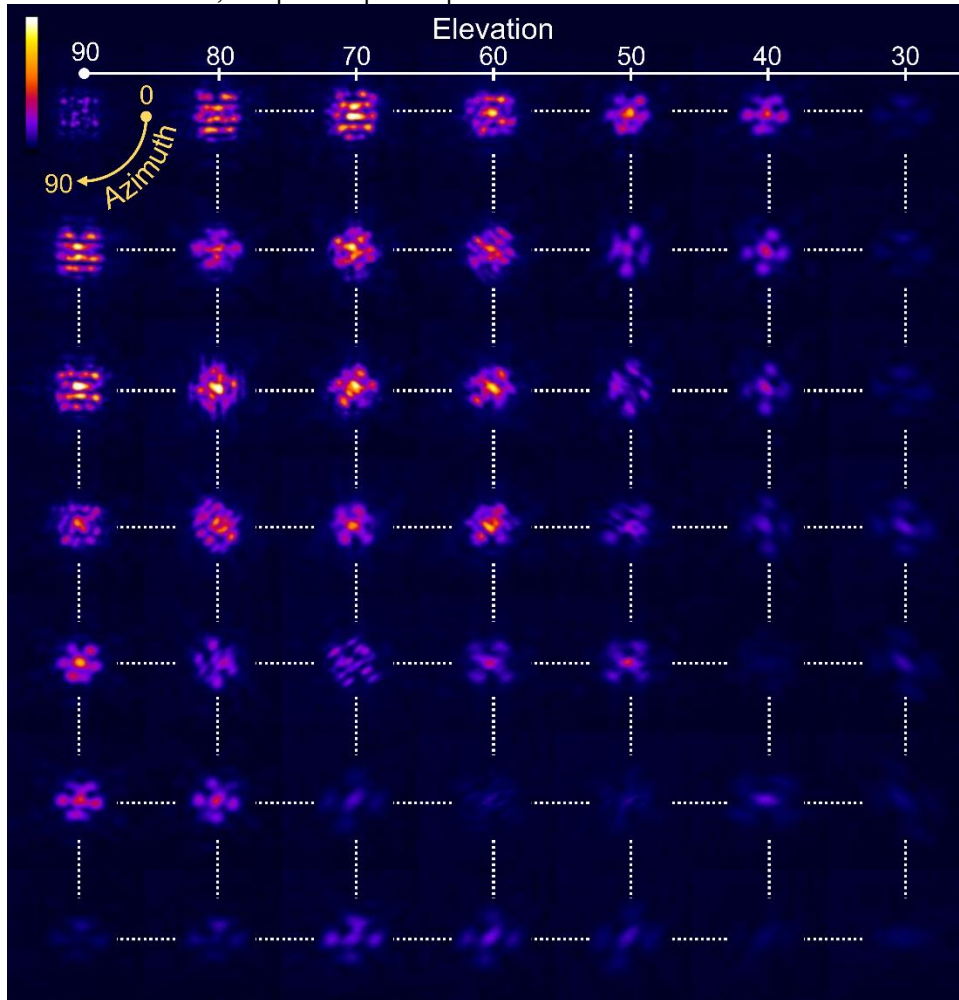


Fig. 9. Montage of FFDPs from LRALL (TIR CCRs) in equirectangular projection. The color scale is shown in the upper left and corresponds to relative optical cross section, with warmer colors corresponding to higher optical return. FFDPs were all obtained under identical imaging and illumination conditions.

Due to the size of the LOLA receiver and the ranging distance from orbit (nominally 50 km), the LOLA receiver (or a similar future altimeter in lunar orbit) will only intersect and measure a small portion of the retroreflected FFDP (*i.e.*, a $2.8 \mu\text{rad}$ cone for LOLA). Thus, the return from a single pixel (size: $2.2 \mu\text{rad} \times 2.2 \mu\text{rad}$) of our measured FFDP will determine the received optical signal from orbit, which we label the Lunar Orbit Optical Cross Section (LOOCS).

To extract this pertinent parameter from our laboratory measurements, we averaged the optical cross section at the pixels nearest $\pm 11 \mu\text{rad}$ from the zero-deviation pixel. This is the nearest approximation to the optical return that LOLA would observe due to velocity aberration in a 50 km circular orbit at each flyover azimuth (*i.e.*, the values in these maps are *not* azimuthally averaged). For the FFDPs involving returns from more than one CCR the pixel location defined as zero deviation was determined from measurements of the masked, individual CCRs ensuring proper extraction of the LOOCS (which is not always the pixel with the highest optical return due to interference effects). This zero-velocity-aberration pixel determination was made at each wavelength to account for variations in the measurement system at the different wavelengths. First, we will present the results for the aluminum-coated LRA followed by the TIR version of LRALL. The LOOCS maps constructed from the experiments performed at 532 nm and 1064 nm are shown in Figure 10 for the coated version of LRALL and Figure 11 for the TIR version.

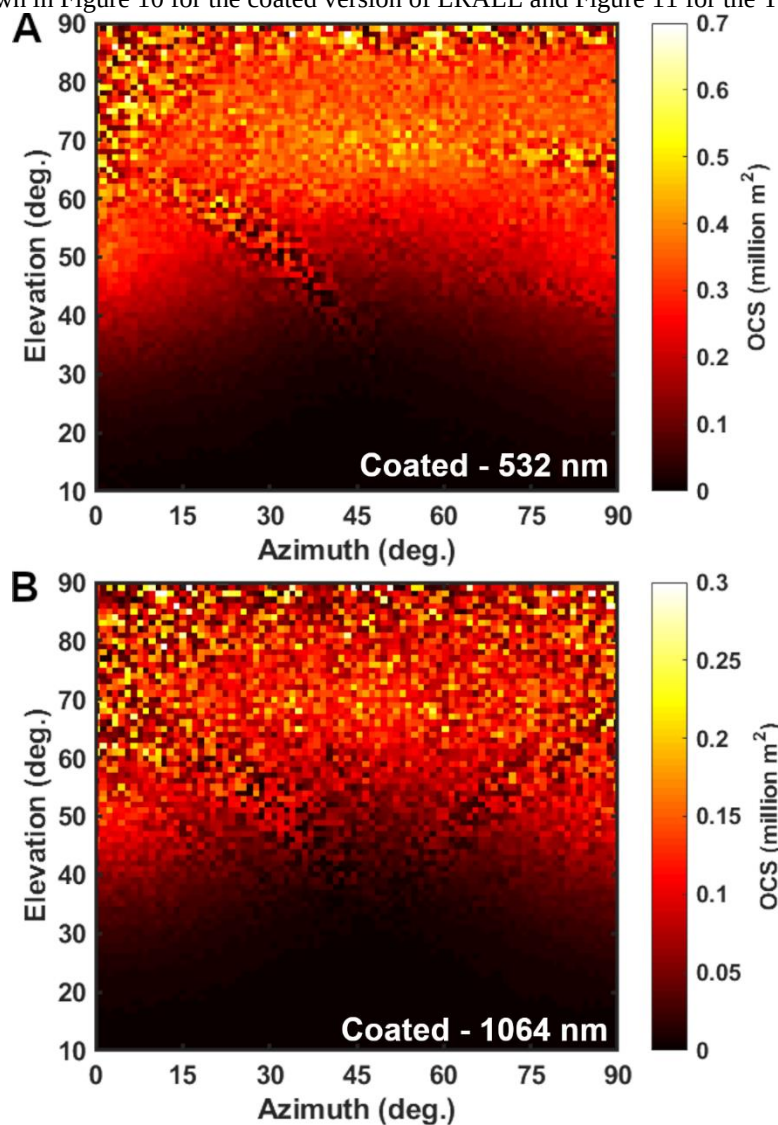


Fig. 10. Map of optical return from the retroreflector array as a function of incident angle for the LRA with metal-coated CCRs. (A) Map created from FFDPs using 532-nm illumination. (B) Map created from FFDPs using 1064-nm illumination.

The color scales correspond to the LOOCS with warmer, lighter colors denoting higher optical return. Elevation and Azimuth angles refer to terminology defined in Figure 8. Far-field diffraction patterns were obtained in one-degree intervals in both elevation and azimuth for the ranges shown; each pixel of the map represents a distinct far-field diffraction pattern from which the LOOCS was extracted. The pixel-to-pixel variation is real and is a result of sampling a complex interference pattern.

The first result of note is the similarity of the performance between wavelengths. As demonstrated in Figure 5, illuminating a retroreflector with differing wavelengths will shrink or expand the FFDP in angular space based on the wavelength per diffraction theory. Similarly, the reduced optical cross section at 1064 nm compared to 532 nm is expected from Equation 1. Less predictable are the subtle variations in the structure of the maps. Importantly, the structure is defined by significant returns above 30° degrees elevation at all azimuths, which shows LRALL meets the measurement objectives for ranging from the full-sky above 30°. These results suggest that future laser altimeters operating at longer wavelengths in the near or mid-infrared would be suitable for ranging to the coated version of LRALL from an orbital platform, with corresponding OCS values that roughly scale as $\lambda^{-1/2}$ and proportionally with the reflectivity of the metal coating.

Fine structure can be seen in the form of diagonal dark features running from high elevations to low and from 0° and 90° to 45° in azimuth. These bands are the high-elevation angles furthest from any CCRs, as the outer ring of cubes are located at azimuth values of 0°, 90°, 180°, and 270°. The LOOCS variation between adjacent pixels is particularly striking, and is due to time-dependent interference of retroreflected light from multiple CCRs. The magnitude of the highest LOOCS is about 1.5 to 2 times higher than the peak OCS of a single CCR (Figure 5), which confirms that constructive interference is a factor in determining the LOOCS.

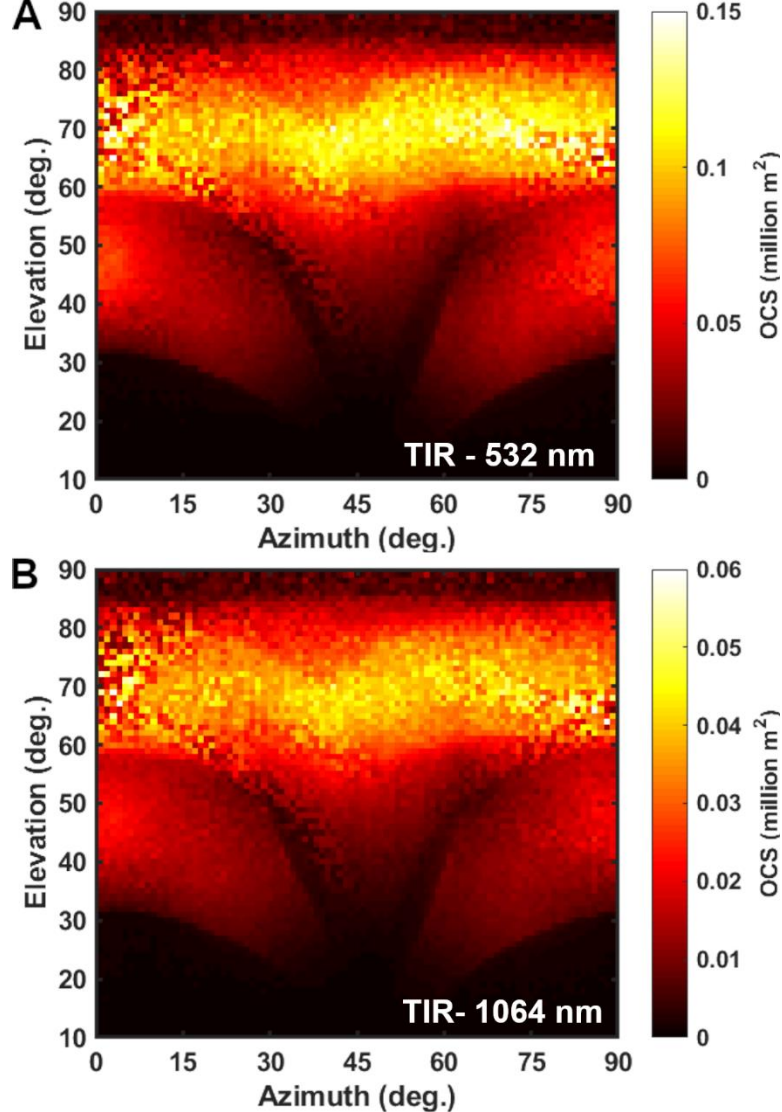


Fig. 11. Map of optical return from retroreflector array as a function of incident angle for the TIR version of LRALL. Following the conventions of Figure 10, (A) and (B) correspond to 532 nm and 1064 nm, respectively. The pixel-to-pixel variation is real and is a result of sampling a complex interference pattern.

The LOOCS map for the TIR version of LRALL is distinct in several ways from that of the coated array. First, the LOOCS declines sharply at elevations *above* 80°, and peaks strongly near 70° elevation across all azimuths. This optical “dead spot” at high elevations near normal incidence to the array is due to the slightly narrower retroreflection angular range of TIR CCRs (Figure 6), as well as interference of the side-lobe returns from the four inner-ring CCRs. The diagonal dark features observed in the coated array are more distinct here, stemming from the layout of the cubes within the array. The pixel-to-pixel variations are strongest at incident angles near 70° elevation and azimuth of 0° and 90° where two of the four inner ring cubes are contributing equally to the optical return, and small shifts in the laser or array tilt of fractions of a wavelength can modify the amount of constructive or destructive interference. Again, the highest LOOCS values are 1.5 to two times the peak OCS from a single CCR, which indicates constructive interference from multiple reflectors affecting the optical return.

The maps presented in Figure 10 and Figure 11 can be used to calculate the expected return signal from an orbital laser altimeter system. If the orientation of the lander (and thus the array) is known with respect to the spacecraft orientation, the azimuth and elevation of the array during ranging can be calculated *a priori* to within the uncertainty of the spacecraft position. If the orientation of the lander or the array is not known precisely, the azimuth-averaged return can be used to calculate the expected return from a laser altimeter. We note that the FFDP measurements presented here were performed with a continuous-wave laser system. The time-varying interference effects will make precise shot-to-shot calculation of the optical cross section for an orbiting laser altimeter difficult. As is done for SLR measurements, multiple returns from the array can be used to build up a statistical description of the return rate and precise range.

5.6 Azimuthal-Averaged Optical Cross Section

The azimuth-averaged LOOCS and variance as a function of elevation, generated from the maps above, is shown in Figure 12 for the metal-coated and TIR version of LRALL at the two measurement wavelengths. Peak optical cross sections are consistent with the presented LOOCS results (to within 5%).

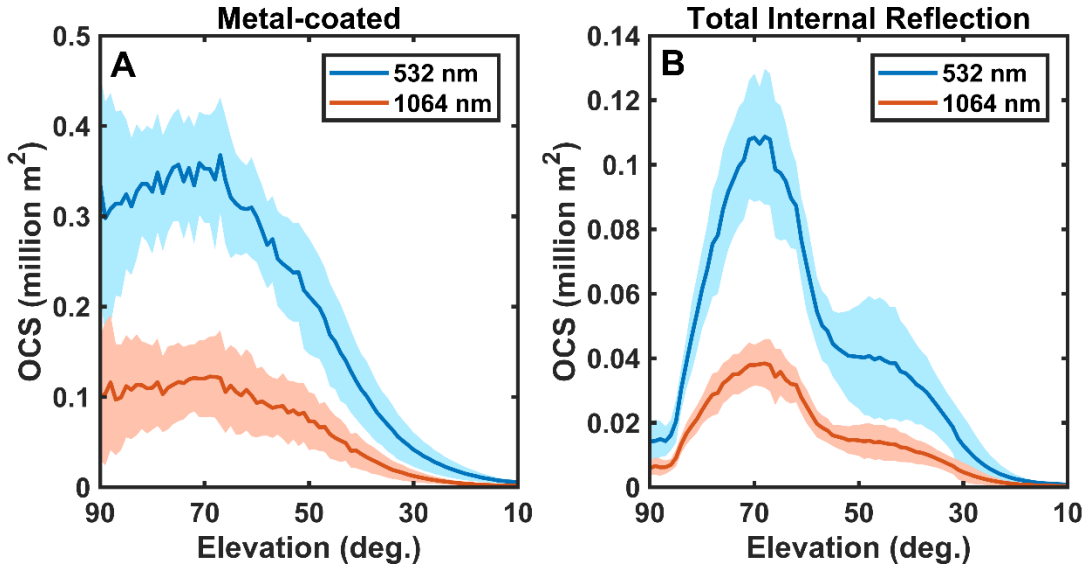


Fig. 12. Azimuthally-averaged optical performance of LRALL as a function of elevation angle. The dark blue and dark red lines denote the azimuthal average value for each elevation, while the light blue and light red shaded regions denote the 1 σ variance at each elevation from the population of all azimuth angles.

The layout of the CCRs within the array, with an inner ring of cubes at 20° off nadir (elevation: 70°) and an outer ring 40° off nadir, is apparent from the azimuthal averages. Similar features from the LOOCS maps are also resolvable, including the high-elevation “dead zone” in the TIR version, as well as multi-cube interference leading to higher variance, but also higher observed optical return.

Due to the use of only the TIR version of LRALL on the surface, further discussion will be focused on only those instruments. The empirical azimuth-averaged optical cross section for the TIR version of LRALL can be described at elevation angles ($el.$) from 10° to 90° with a two-gaussian model:

$$OCS(\lambda, el.) = B_{i,\lambda} \cdot e^{-\frac{(el.-C_{i,\lambda})^2}{2\sigma_{i,\lambda}^2}} + B_{o,\lambda} \cdot e^{-\frac{(el.-C_{o,\lambda})^2}{2\sigma_{o,\lambda}^2}} \quad (1)$$

where $B_{i,\lambda}$ is the wavelength-dependent maximum OCS at the inner ring elevation, $C_{i,\lambda}$ is the elevation of the inner ring feature, and $\sigma_{i,\lambda}$ is the width of the inner ring feature. Similarly, $B_{o,\lambda}$ is the maximum OCS at the outer ring elevation, $C_{o,\lambda}$ is the elevation of the outer ring feature, and $\sigma_{o,\lambda}$ is the width of the outer ring feature. Table 3 lists the best-fit parameters for the two-gaussian model given in the equation above computed by running a Nelder-Mead algorithm [25], with initial values extracted manually from the data. Figure 13 shows the measurement results and two-Gaussian model fit as well as the residuals for both wavelengths.

Table 3. Fitting parameters for two-gaussian model from azimuthal-averaged data from TIR retroreflector array.

Parameter	532 nm Value	1064 nm Value
B_i	0.108 million m ²	0.0382 million m ²
C_i	70 degrees	70 degrees
σ_i	9.1 degrees	9.5 degrees
B_o	0.0360 million m ²	0.0121 million m ²
C_o	43 degrees	43 degrees
σ_o	9.2 degrees	9.3 degrees

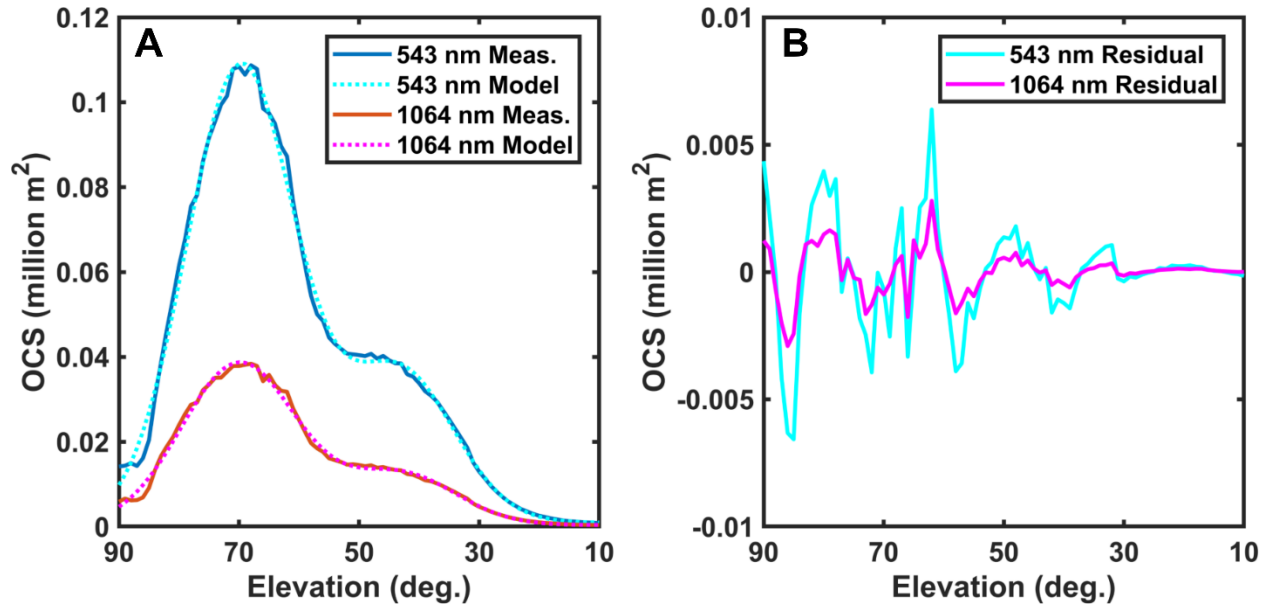


Fig. 13. Best-fit functions of the two-gaussian model. (A) Measurements and model fit to the azimuthal-averaged LOOCS as a function of elevation angle for the TIR version of LRALL. (B) Residuals from the fitting process.

The optical cross sections at a ranging elevation of 70° are 0.108 million m² and 0.0382 million m² at 532 nm and 1064 nm, respectively. This high optical gain means LRALL will return ~ 1000 times more photons per shot than

measurements taken from the lunar surface by LOLA from a 50 km altitude. This allows LRALL to be ranged to from ranges of 100s of kilometers by LOLA or future laser altimeters.

5.7 Suitability of LRALL for Short-Wave Infrared and Mid-Infrared Laser Altimeters

Looking towards the future, LRALL can be ranged to by a wide array of laser systems in visible and infrared wavelengths. We measured the total hemispherical reflectance spectrum of one of the CCRs via spectrometer, the results of which are shown in Figure 14. The reflectance measurements were obtained at 2 cm^{-1} resolution. Hydroxyl impurities in the fused silica glass cause absorption features near $1.4\text{ }\mu\text{m}$, $2.2\text{ }\mu\text{m}$, and $2.7\text{ }\mu\text{m}$, but optical losses notwithstanding the CCR can be used with interrogating lasers from the visible through $3.5\text{ }\mu\text{m}$.

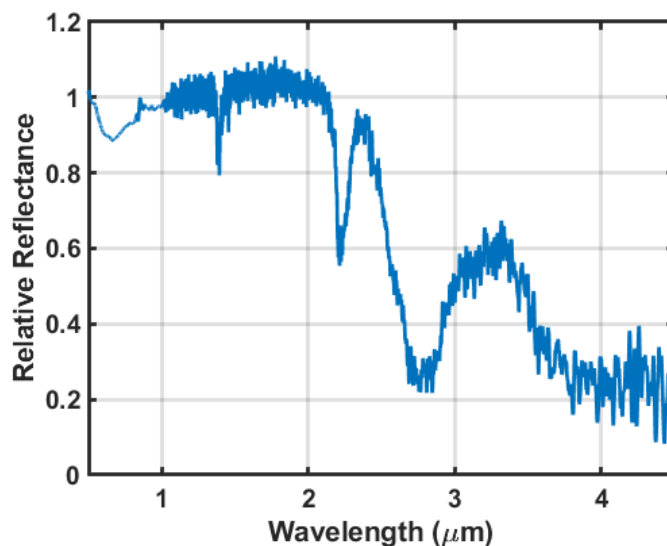


Fig. 14. Reflectance spectrum of LRALL CCR. Reflectance is shown normalized to the measured value at 1064 nm.

6. LRALL Return Pulse Waveforms and Time Delay

Precision ranging to LRALL via orbital laser altimeter requires knowledge of the effects of the array on the laser pulse shape [13]. We have designed and performed tests to measure the pulsed laser return from the LRA to check for pulse spreading or distortion by the array as well as to test for range changes as a function of incident angle which could limit the range measurement resolution. A collimation setup similar to the one in Figure 4A was constructed, although the target return collimation system used a refractive rather than reflective collimation scheme. We used a 1064-nm fiber-coupled, pulsed laser source (PicoQuant GmbH). The measured pulsewidth was 48 ps (Gaussian RMS width) from the reference mirror, including the effects of the photodiode (Thorlabs, 8 GHz bandwidth) and oscilloscope (13 GHz electrical bandwidth).

We captured the return waveforms at three laser incidence angles: first the array was tilted such that the beam was at normal incidence to Cube 2 (see Figure 2 and Figure 15 insets). Second, the array was tilted such that the beam was at normal incidence to the adjacent cube (Cube 3). Finally, the array was illuminated at an angle between Cubes 2 and 3 (see Figure 15 inset). The results of the experiments are shown in Figure 15.

The pulse shape was unchanged by the array as measured on the system described here, with a Gaussian RMS width of 46 to 49 ps compared to 48 ps when using a reference mirror. The delay time between Cubes 2 and 3 as measured from the gaussian centroid positions was 39 ps, which corresponds to 6 mm in range offset. This range offset between Cubes 2 and 3 is larger than expected based on the LRA design ($\sim 1\text{ mm}$). We note, however, that the measured value is not strictly the variance in the optical reference point between cubes, but is also affected by the offset of the rotation axis with respect to the array (*i.e.* the overall path length change in the laboratory frame). This result does set an upper bound on the range difference between these cubes, and indicates that ranging to a single-centimeter level should be possible with LRALL.

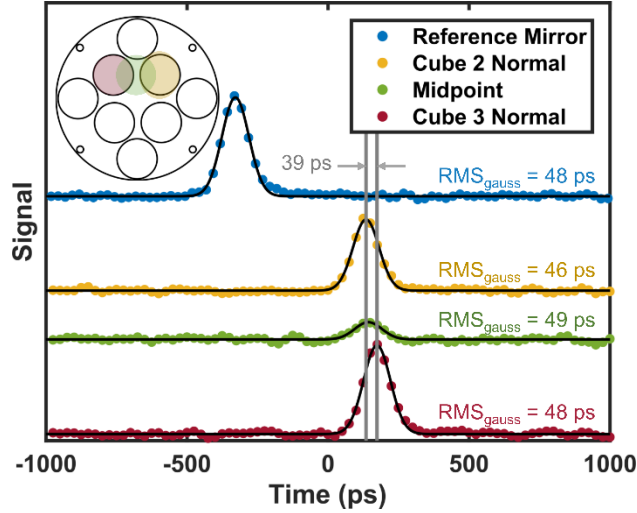


Fig. 15. Pulsed laser waveforms retroreflected from LRALL. The colored circles correspond to the waveforms measured at the three retroreflector array angles as well as a reference mirror waveform. The black lines correspond to Gaussian fits to the measured waveforms, with the Gaussian RMS width listed above each waveform. The given time is relative to the start of the Cube 2 Normal pulse, and the waveforms are offset vertically for clarity. The grey lines denote the centroid positions of the Cube 2 and Cube 3 Gaussian fits. *Inset* A schematic of the array showing the array region that was closest to normal incidence for the three measurements.

7. Summary

Here we have reported the optical performance of LRALL as determined prior to spacecraft integration. The CCRs each have a surface flatness of less than $1/10 \lambda$ at 532 nm and have dihedral angle errors of less than 0.5 arcsec. The DAEs did not vary considerably over the tested temperature range of 100 K to 380 K for a TIR CCR, indicating that significant thermal gradients that would impact performance are not expected under lunar conditions. The individual CCRs also demonstrated the expected far-field behavior, although with a reduced peak optical cross section for the TIR CCRs. Tests of the full array showed the highest optical cross section at 70° elevation, as well as a local maximum at 43° elevation corresponding to the two rings of CCRs. Interference effects between the cubes played a significant role in affecting the optical return, increasing the variance in the return. The results show that LRALL can be ranged to from angles above 30° elevation from an orbiting laser altimeter operating at wavelengths from the visible to $\sim 3.5 \mu\text{m}$. Finally, the arrays did not measurably affect the return pulse waveform, and inter-cube range offsets showed an upper bound of 6 mm.

The metal-coated version of LRALL underwent space qualification and optical testing at Goddard Space Flight Center in 2018 and was integrated with the SpaceIL Beresheet lander in November, 2018. Uncoated, total internal reflection versions of LRALL were also space-qualified at Goddard Space Flight Center, one of which was integrated in April, 2019 with the Indian Space Research Organization (ISRO) Vikram lander, a part of the Chandrayaan-2 mission.

Additional LRALL units are expected to be integrated with lunar lander missions with the purpose of establishing a network of permanent fiducial markers on the lunar surface as well as enabling precision geolocation of the lander (and its instrument suite) from orbit. Though designed for use on the lunar surface, the LRALL concept can be readily applied to other planetary bodies (*e.g.*, icy moons, asteroids, cometary cores, rocky planets, *etc.*), other types of spacecraft (*e.g.*, rovers, rotorcraft, hoppers, boats, *etc.*), and can be used in support of human exploration on the Moon and Mars.

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Disclosures

The authors declare no conflicts of interest.

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