Optical Characterization of CLPS Miniature Laser Retroreflector Arrays.

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Introduction: Laser retro-reflector arrays (LRAs) consisting of corner cube retroreflectors (CCRs) can act as fiducial markers for decades of laser ranging on the Moon and other planetary bodies. Upcoming lunar lander missions from government space agencies and commercial partners offer a unique opportunity to support lunar science and exploration through the deployment of small LRAs on lander decks. 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. When mounted alongside a suite of scientific instruments on the surface the LRA enables precise geolocation of those instruments in the lunar geodetic frame. Finally, optical markers such as LRAs can support precision autonomous navigation and landing regardless of lighting conditions, a valuable feature for lunar polar exploration.

Array Design	Hemispherical
Array Diameter	5.11 cm
Array Height	1.65 cm
CCR Clear Aperture	1.27 cm
Number of CCRs	8
Mass	20 g

Figure 1. LRALL after integration with SpaceIL Beresheet lander deck in Nov. 2018.

Here we present the optical characterization results of Laser Retroreflector Arrays for Lunar Landers (LRALL) developed under the Commercial Lunar Payload Services (CLPS) program [1,2]. 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 azimuth angle above 30° in elevation from the mounting plane. These low-mass, small instruments (Figure 1) were designed and tested for decades of lifetime on the lunar surface, including radiation testing to 19 Mrad (Si). The arrays can be ranged to from orbiting lunar spacecraft such as LRO or Gateway provided there is a laser altimeter or optical communication terminal onboard. LRALL can operate over the entire lunar day and night and are completely passive; they require no power, communication, or thermal control. LRALL units are manifested on upcoming CLPS landers, including the Astrobotic Peregrine lander, the Intuitive Machines Nova-C lander, the Masten Space XL-1 lander.

Optical Testing Program: Our optical test program baseline was derived from the qualification of retroreflector arrays for satellite laser ranging (SLR) [3,4]. However, we also tested performance at multiple wavelengths, tracked performance over the lunar temperature range, and performed a detailed study of the interference effects of multiple-cube returns.

Results: The primary optical figures of merit for the CCRs are the surface flatness and the dihedral angle error (DAE), or the deviation from 90° of the angles between the facets of the prism. All 13 LRALL units tested met the design specification of surface flatness of 1/10 λ at 532 nm and an average DAE within ± 0.5 arcsec.

Temperature Test Results. The thermal extremes experienced on the lunar surface over the course of the diurnal cycle – from 95 K to 385 K at the equator [5] – can induce thermal gradients in both coated and total internal reflection CCRs [6], 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 of the CCR [7]. We mounted the LRA in a customized vacuum dewar and chilled the array to cryogenic temperatures. Step heating from cryogenic temperatures was performed via a 100-W cartridge heater fixed to the rear of the LRA mounting plate. DAE measurements were obtained from 100 K to 380 K in 20 K steps. 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 2). For the entire observed temperature range, all three DAEs varied over a range near the tolerance of the CCRs. 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 ~17° and via conduction through the aluminum shell. However, the small size of the CCRs in LRALL (1/10 the area of the Apollo CCRs) should reduce the magnitude of thermal gradients while on the lunar lander deck.

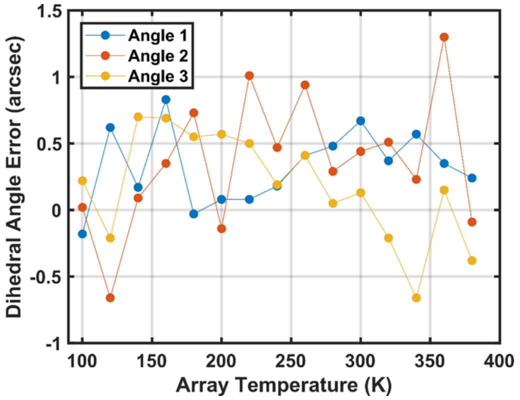

Figure 2. Measured dihedral angle errors of a total internal reflection CCR over the expected lunar temperature range.

Visible and Near Infrared Far Field Diffraction Patterns. 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). We performed a series of optical tests of the LRALL instruments to measure the optical return over a broad range of incident angles (Figure 3). The peak optical cross section occurred at 70° in elevation due to the inner ring of CCRs, with a second maximum corresponding to the the second ring.

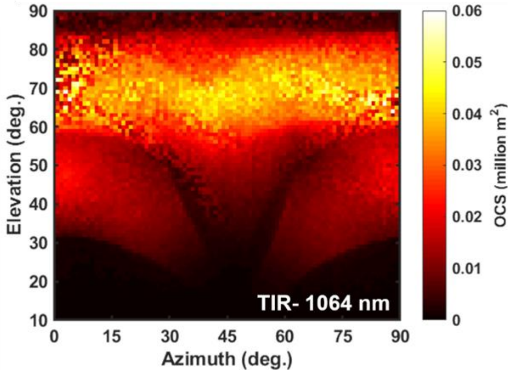

Figure 3. Map of optical return from retroreflector array as a function of incident angle at 1064 nm. Far-field diffraction patterns were obtained in one-degree intervals in both elevation and azimuth for the ranges shown; each pixel of the map represents a distinct far-field diffraction pattern from which the optical cross section was extracted.

Pulse Waveform Tests. We used a 1064-nm fiber-coupled, pulsed laser source 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. The measured pulsewidth was 48 ps (Gaussian RMS width) from the reference mirror, including the effects of the photodiode and oscilloscope. We captured the return waveforms at three laser incidence angles, as shown in Figure 4. The laser 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 as measured from the gaussian centroid positions was 39 ps, which corresponds to 6 mm in range offset.

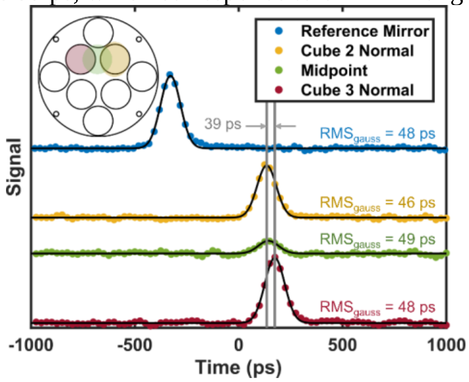

Figure 4. Pulsed laser waveforms retroreflected from LRALL. The colored circles correspond to the waveforms measured at the three illumination angles as well as a reference mirror waveform. The black lines correspond to Gaussian fits to the measured waveforms, with the Gaussian RMS width listed above each waveform.

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 λ 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. 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. Finally, the arrays did not measurably affect the return pulse waveform, and inter-cube range offsets showed an upper bound of 6 mm.

References: [1] Sun X. et al. (2019) *Appl. Opt.*, *58*, 9259-9266. [2] Cremons D. R. et al. (2020) *Appl. Opt.*, *59*, 5020-5031. [3] Degnan, J. J. (1993) *Contributions to Space Geodesy and Geodynamics: Technology*, *25*, 133-162. [4] Minott P. O. et al. (1993) *Prelaunch optical characterization of the laser geodynamic satellite (LAGEOS 2).* [5] Vasavada J. L. et al. (2012) *J. Geophys. Res.: Planets*, *117*, E12. [6] Murphy T. W. et al. (2010) *Icarus*, *208*, 31-35. [7] Goodrow S. D. and Murphy T. W. (2012) *Appl. Opt.*, *51*, 8793-8799.