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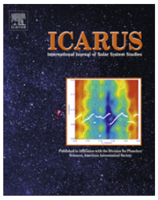

Lunar eclipse observations reveal anomalous thermal performance of Apollo reflectors

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ABSTRACT

Laser ranging measurements during the total lunar eclipse on 2010 December 21 verify previously suspected thermal lensing in the retroreflectors left on the lunar surface by the Apollo astronauts. Signal levels during the eclipse far exceeded those historically seen at full moon, and varied over an order of magnitude as the eclipse progressed. These variations can be understood via a straightforward thermal scenario involving solar absorption by a ~50% covering of dust that has accumulated on the front surfaces of the reflectors. The same mechanism can explain the long-term degradation of signal from the reflectors as well as the acute signal deficit observed near full moon.

1. Introduction

Corner-cube reflectors (CCRs) were placed on the Moon by the Apollo astronauts during the Apollo 11, Apollo 14, and Apollo 15 landings. Each reflector consists of an array of solid, circularly-cut fused silica CCRs 3.8 cm in diameter, installed for the purpose of lunar laser ranging (LLR) operations that could test gravitational physics, elucidate details of the lunar interior, and improve knowledge of Earth orientation and precession (Murphy, 2013).

Soon after commencing LLR observations with the Apache Point Observatory Lunar Laser-ranging Operation (APOLLO: Murphy et al., 2008) in 2006, two problems became evident. First, the signal strength returning from the lunar reflectors is diminished by approximately a factor of ten compared to carefully calculated theoretical expectations (Murphy et al., 2007). Second, the reflector arrays suffer an *additional* order-of-magnitude signal reduction when the lunar phase is within about 20° of full moon (Murphy et al., 2010). Historical data indicate that the full-moon deficit condition slowly developed during the first decade after placement on the lunar surface. The combined effect of the two facets of signal reduction is that signal strength is never greater than about 10% of expectations at any lunar phase, reducing to ~1% near full moon—schematically depicted by the dash-dot line in Fig. 1.

The Apollo CCR arrays were designed and built in an impressive 6-month period by Arthur D. Little, Inc., including a substantial effort dedicated to thermal design in order to minimize thermal gradients within the solid prisms. It is well-understood that thermal gradients within an optical device impose variations in the refractive index, leading to thermal lensing effects. The central intensity of the far-field diffraction pattern (FFDP) emerging from the CCR is severely diminished when differences of even a few degrees Kelvin exist across the corner cube (Goodrow and Murphy, 2012). Total internal reflection (TIR) corner cubes, despite producing lower central irradiances compared to CCRs with reflective coatings, were selected for the Apollo reflectors so that incoming sunlight would be completely reflected when arriving within 17° of normal incidence—and larger incidence angles at certain azimuth angles. Total reflection of incident energy, and especially the lack of direct absorption in rear-surface coatings, translates to reduced thermal gradients within the CCR material. Engineering documents presented a number of thermal modeling predictions for the performance, based on the FFDP central irradiance of the reflector array as a function of Sun angle (Little, 1969; Faller et al., 1973). Incorporating details of azimuthal orientation and tilt of the reflector tray on the Moon, the central irradiance for each Apollo reflector was expected to remain above 60% of the nominal value for all Sun illumination angles (Fig. 1).

Note that around full-moon phase, when the tilted arrays are all facing the Sun, the reflectors are expected to behave quite well, since this is the domain in which TIR rejection of incident solar energy is indeed total. We have found, in contrast, that reflector signal strength is at its worst near full moon, as indicated by the dash-dot line in Fig. 1.

Various possible mechanisms were presented in Murphy et al. (2010) to account for both facets of observed signal reduction simultaneously. Each of the scenarios involved anomalous absorption or scattering of photons, leading to both the overall signal

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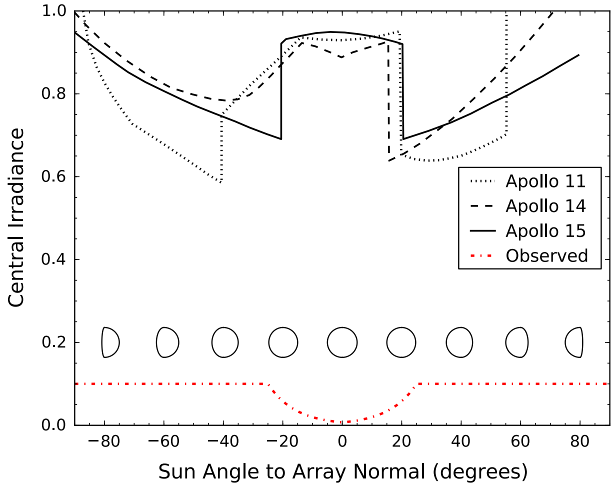

Fig. 1. Expected design performance of the three Apollo reflectors as a function of Sun angle, considering azimuthal orientation, breakthrough of TIR, and tilt angle of the mounting tray to the lunar surface (Faller et al., 1973). Adding 180° to the horizontal axis effectively corresponds to the lunar phase angle, *D*, pictorially represented as illuminated portions of the lunar disk. The dash-dot line near the bottom represents the approximate best performance observed from Apache Point in recent years, suffering an overall factor of 10 degradation at most phases and approaching losses in excess of 99% near full moon (Murphy et al., 2010).

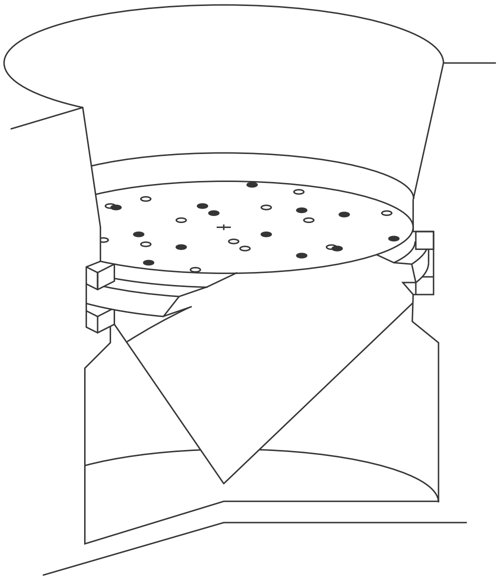

Fig. 2. Schematic representation of an Apollo corner cube prism situated in its aluminum cup (cut-away in drawing), held by Teflon rings sandwiching the tabs protruding from the prism edges. Dust grains are illustrated as dark spots on the front surface of the CCR. Each real grain has a virtual analog (open symbols, diametrically opposite the center mark from the real grain) demarking the entry point for a ray that will ultimately strike the real grain on exiting the corner cube. The covering fraction represented in the drawing is substantially less than that posited in this paper, where real (filled) grains obscure approximately half of the surface area.

deficit and poor performance at full moon via solar–thermal lensing. The simplest and most plausible of the scenarios is the slow accumulation of dust on the front surface of the reflectors as dust is transported across the lunar surface both electrostatically and by impact activity (Stubbs et al., 2006; Farrell et al., 2007; Grün et al., 2011). Hartzell et al. (2013) found that intermediate-sized grains approximately 10 μm in diameter are most successfully lofted in a simulated space environment. For grains in this size range, geometrical obscuration would dominate over diffraction effects for visible light.

Part of the rationale for attributing the full-moon deficit to a thermal problem is due to strong performance during past total lunar eclipses—generally becoming visible within minutes of totality—as gleaned from the archive of lunar laser ranging normal points available through the International Laser Ranging Service (Pearlman et al., 2002). This observation strongly suggests that solar illumination is a key factor. Because the APOLLO LLR facility is capable of operating in the high-background conditions at full moon, we had the opportunity to follow the performance of the reflectors through an entire eclipse event on 2010 December 21.

We present here the heuristic performance expectations of a reflector array suffering solar-induced thermal gradients during the course of a total eclipse, exploring briefly the dust deposition that would be necessary to create the previously reported performance deficits. We then present the observed performance during eclipse, demonstrating a close match to the heuristic expectations. We conclude that the lunar reflectors are not operating according to their design, likely burdened with a fine layer of dust. Detailed thermal simulations of the CCRs and mounting trays in the lunar environment are not within the scope of this paper, for which the primary objective is presentation of the eclipse observations.

2. Thermal expectations

We have detailed separately the effect of axial and radial thermal gradients within a CCR on the central irradiance of the FFDP. The conclusion is that a temperature difference across the CCR of only a few degrees can destroy the central irradiance (Goodrow and Murphy, 2012). A simple model for what may be plaguing the lunar reflectors is that dust on the front surface absorbs solar radiation when the array points nearly face-onto the Sun—as is the case near full moon. The CCRs are recessed into an aluminum tray by half their diameters (see Fig. 2), so that illumination of the front surface is complete only at full phase. Solar energy absorbed by the dust is radiatively and conductively transferred into the front surface of the CCR, creating a thermal gradient within the CCR that was not anticipated in the design. The gradient translates to a varying refractive index, or thermal lensing, imparting phase delays for different optical paths within the CCR.

For instance, if the front surface of the corner cube is hotter than its vertex, a ray path entering and exiting the CCR near its outer radius will stay relatively close to the front surface as it traverses the interior of the CCR, experiencing a slightly larger average refractive index and therefore greater phase delay compared to a central ray that penetrates deep into the CCR and into cooler material. The result is a spherical wavefront advanced in the center and retarded at the edges. The divergence translates into a loss of peak intensity in the far field, and thus reduced return signal. Radial temperature gradients produce similar-scale effects on the wavefront and FFDP. Thermal expansion also plays a role, but far less pronounced than the refractive effect (Goodrow and Murphy, 2012).

2.1. Dust covering fraction and thermal impact

We model the putative front-surface dust absorption as covering a fraction, f, of the front surface in small grains randomly and uniformly distributed across the surface. Assigning to the dust an albedo, $\alpha \approx 0.1$, results in a front-side thermal input in full sun of $I_0A(1-\alpha)f$, where $I_0 \approx 1370\ \mathrm{W\ m^{-2}}$ is the solar irradiance and A is the frontal area. Light that successfully enters the CCR will re-emerge through the front surface after retroreflection, to again find probability, f, of absorption by dust (see Fig. 2 for a schematic example). The probability of transmission through both passages of