THE NOT-REALLY-THAT-DARK SIDE OF THE MOON: LIGHT LEVELS IN SHADOWED CRATERS.

R. V. Wagner, A. K. Boyd, P. Mahanti, and M. S. Robinson, School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-3603 (rvwagner@asu.edu).

Introduction: The Danuri spacecraft (also known as the Korea Pathfinder Lunar Orbiter, or KPLO) carries the NASA ShadowCam instrument, designed to image in polar shadowed areas with a pixel scale of ~2 meters **[1]**. ShadowCam began regular orbital imaging in January 2023 and has now acquire images over one year of seasonal lighting changes. ShadowCam images enable direct measurements of illumination levels (measured in radiance) inside permanent and temporary shadows. These high signal-to-noise observations not only allow detailed morphologic mapping but also provide a quantitative measure of illumination, key measurements to support future lunar surface activities.

What are the illumination conditions within PSRs in practical terms? We converted ShadowCam radiance measurements to luminance values commonly used in photography and building lighting codes. We found that small permanently shadowed regions (PSRs) are often illuminated at comfortable indoor lighting levels. In summer, even large PSRs can be bright enough for a human to navigate comfortably without artificial lighting.

[Ir]radiance and [il]luminance: We use four closely-linked and easy-to-confuse terms for scene brightness in this abstract: *Radiance:* Electromagnetic radiation emitted/reflected by a surface. *Irradiance:* Electromagnetic radiation incident upon a surface. Both are measures of energy, with units based on watts, and no inherent connection to a particular wavelength. *Luminance:* Brightness of a surface in wavelengths humans can see. *Illuminance:* Light shining on a surface in wavelengths humans can see. Both are measures of visible light, in units based on the lumen, which is an SI unit defined using an empirical measure of the wavelength sensitivity of the human eye.

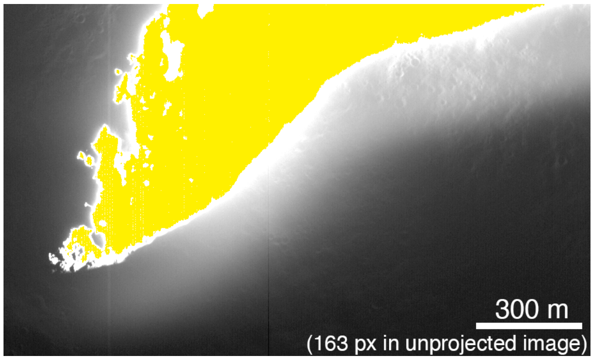

Figure 1: In-field stray light in M039293869S; yellow indicates saturation (direct sunlight). Stray light signal is ~1.5x the radiance of the underlying terrain.

Methods: We determine brightness within shadowed regions by measuring average radiance, adjusting for stray light, and finally converting to luminance.

In-field stray light compensation: ShadowCam was designed to dramatically reduce stray light (signal due to internal scattering within the camera optics, rather than true signal from the surface) relative to the LROC NAC design **[2]**. The design is very effective at minimizing stray light from outside the field of view **[2]**, however, patches of directly-illuminated terrain within the field of view have localized "halos" of stray light (**Fig. 1**). For shadowed regions within ~300 m of illuminated terrain, the stray light signal can be brighter than the signal from the underlying terrain.

Currently we do not have a model for numerically determining the stray light contribution to a pixel (a model requires knowing the radiance from each directly-illuminated pixel, where ShadowCam can only record "detector is saturated"). Thus, to compensate for this stray light, we attempt to directly measure the stray light in each observation. As an upper bound, the stray light contribution cannot be higher than the lowest recorded value (darkest pixel) in the area it contaminates (but is likely lower, as in small craters there is usually enough secondary or tertiary illumination that even the darkest pixels likely have a detectable true signal). We can also approximate stray light intensity from nearby similarly-sized shadows, equally surrounded by illuminated terrain, but without any identifiable terrain features (indicating a lack of measurable secondary light). This usually requires alcoves on the down-Sun side of a large ridge, with no Sun-facing slope to reflect light into them. We use this second type of stray light estimate in our results; using the upper-bound value generally reduces calculated brightness by a factor of two.

Luminance: While the radiance units to which ShadowCam is calibrated ($W/m^2/sr/\mu m$ from ~400 to 800 μm **[2]**) are useful for engineering design, thermal modeling, and so on, they are ill-suited to elucidating what a human would see inside a lunar shadow. For this purpose, we turn to luminance, which is calculated as radiance, measured by wavelength, convolved with the response curve of the human eye **[3]**. Since ShadowCam records the integrated energy over a much wider bandwidth than the CIE curve (**Fig. 2**), we need to determine the approximate spectrum of the incoming light, which we calculated by combining the reflectance curve of the lunar surface (mean lunar highlands **[4]**, suitable for polar regions), the reflectance of the directly-illuminated surface (lunar highlands **[4]** or Earth **[5]**), and the solar spectrum. This incoming spectrum was combined with the spectral curve for ShadowCam **[2]** and the CIE $\bar{y}$ function **[3]**, normalized, integrated, and multiplied by 683 lumens/W, giving a fixed conversion factor from ShadowCam W/m^2/sr/µm to cd/m^2 (**Fig 2**).

Exposure Value: A convenient derivative value of the luminance of a scene is Exposure Value (EV), a measure photographers use to determine optimal camera settings for a scene. An increase of 1 EV is ×2 cd/m^2, and for ISO 100, $EV = log_2\left(\frac{cd}{m^2} \times 8\right)$ **[6]**. As a reference point, EV 7 approximately corresponds to an office lit by overhead fluorescent lights.

Results: See **Fig. 3** for PSR brightness measurements. Applying the above luminance conversion to ShadowCam equatorial earthshine observations **[7]**, EV ranges from ~0-0.4 cd/m^2 (-4 to +1 EV, similar to twilight), depending on the phase of the Earth disk, potentially bright enough for limited unlit operations. When stray light correction is needed, we estimate our adjusted radiances are accurate to a factor of ~2 (±1 EV).

Discussion: At their brightest, small PSRs can reach lighting levels commonly found in well-lit office buildings (EV 6-7). Even outside of the optimal lighting times, they can remain at levels sometimes found in homes (EV 4-5). Lower illumination levels are less commonly experienced, falling into a gap between comfortable indoor lighting and actual darkness (**Fig. 4**).

Empirical testing: To determine what these lower brightness levels (EV 3-5) were like in practice, we covered a table with paper printed with ~85% saturation black (to approximate the mean highland albedo of ~0.15), adjusted the lighting in the room to give light meter readings on the table of EV 3, 4, and 5, and worked at the table. EV 5 felt like normal room lighting; EV 3 was distinctly dim, but did not impede working with small objects or reading text at normal speed.

Conclusion: The term "permanent shadow" may create a false impression of intense darkness. In fact, these shadowed areas are frequently lit to levels considered to be normal indoor lighting. While smaller shadows are typically brighter than larger ones, the most important factor is the prominence of the reflecting terrain; subdued craters will generally have darker shadows.

Secondary lighting can change dramatically over the course of a day, and may be maximum at a time other than local noon, so mission planners will need to analyze the local conditions to determine the optimal times for surface activities.

Astronauts visiting PSRs are unlikely to need supplementary lighting except for detailed examination of collected samples. The biggest illumination issue for astronauts visiting PSRs may not be low light levels but rather glare from the source of secondary illumination.

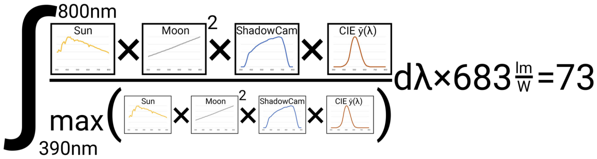

Figure 2: Radiance to luminance conversion for PSRs. All spectral graphs use the same axes.

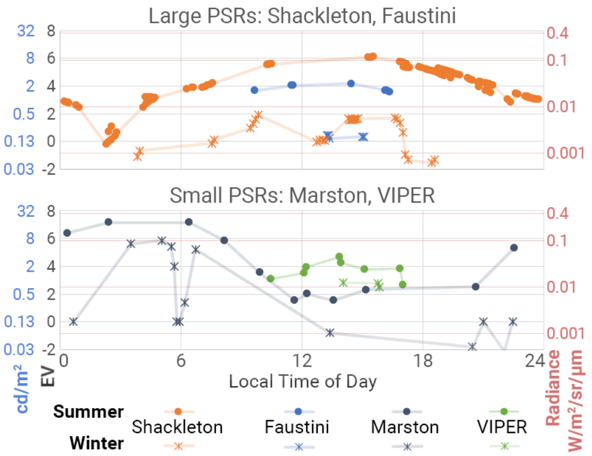

Figure 3: Summer and winter brightness over the course of a day for large (*top*) and small (*bottom*) PSRs. Marston crater (unofficial name, on the Shackleton-de Gerlache Ridge) has a ~300 m PSR. "VIPER" is the southernmost and darkest PSR (~1 km width) at the VIPER landing site, usually ~2× dimmer than the other two PSRs. Faustini and Shackleton measurements are near the centers of each, away from any stray light. 24 time units cover a lunar day, with 12 being "noon". "Summer" is sub-solar latitude ≤–1°, "Winter" is ≥+1°.

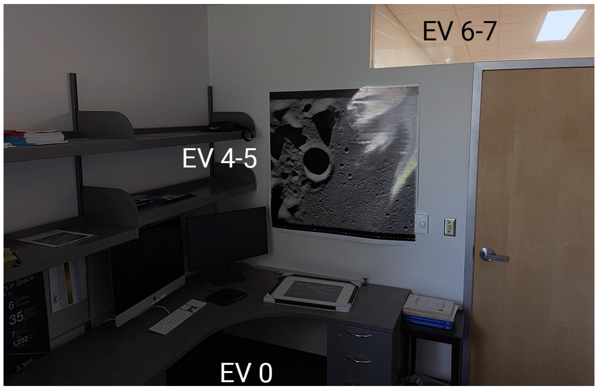

Figure 4: Simulation of PSR lighting; exterior window behind the camera is mostly covered.

References: **[1]** Robinson et al. (2023), *JASS*, 40(4):149-171. **[2]** Humm et al. (2023), *JASS*, 40(4):173-197. **[3]** ISO/CIE 23539:2023 **[4]** Boyd et al. (2012), 43rd LPSC #2795. **[5]** Glenar et al. (2019), *Icarus*, 321, 841-856. **[6]** TranslatorsCafe.com, http://tinyurl.com/y4mx42ry **[7]** Wagner et al. (2023), *ELS 2023* abstracts p. 251-252.