NEW DEVELOPMENTS IN MODELING OF ILLUMINATION CONDITIONS, AT THE MOON AND BEYOND.

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Introduction: The illumination conditions of planetary surfaces can have important implications on their thermal state and geological processes, and thus their ability to retain certain volatile species over long time periods. The Lunar Reconnaissance Orbiter (LRO) has been studying the lunar poles since its launch in 2009 [1], with a suite of instruments observing a broad range of energies and spatial scales, from high-energy particles [2] to ultra-violet [3], visible [4], near-infrared (NIR) [5], thermal infrared [6], and radio [7] radiation. In addition to the repeated imaging of the poles by the LROC WAC and NAC cameras [8] which provide ground truth but have limited spatio-temporal sampling, the topographic data acquired by the Lunar Orbiter Laser Altimeter (LOLA) have enabled the simulation of the illumination conditions at any time and place for arbitrary observers. The permanently shadowed regions (PSRs) of the Moon were determined through illumination modeling over a complete lunar nutation cycle (~18.6 years) [9]. Here, we describe our latest advances in modeling capabilities, and how they enable new calibration, analysis, and observations.

Modeling capabilities: Our earlier work [9] relied on the pre-calculation and storage of the local horizon at each surface location to speed the computations at each timestep. While most efficient for simulating long time periods, it relied on an assumption of near-zero obliquity, only applicable to the Moon and Mercury in the immediate polar regions. Our new modeling tool no longer makes any geometrical assumption, and uses double-precision ray-tracing. It was entirely rewritten in object-oriented C++, and makes use of external libraries such as libconfig, CGAL, and SPICE [10]. Flexible configuration syntax and varied input formats make our new tool more versatile and able to inform a wider range of lunar and planetary science studies.

The terrain is constructed as an unstructured set of triangular elements, from a number of basemaps given in different resolutions and projections and which can be truncated based on distance. An axis-aligned bounding box (AABB) octree is computed to speed up the ray-tracing algorithm. Surface normals and albedo can be specified, and user-defined photometric functions can be selected (*e.g.*, [11-13]).

The illumination sources can be specified as points, two-dimensional shapes (on a plane always perpendicular to the line-of-sight), or three-dimensional vertices (fixed in any SPICE-recognized frame), and their center is positioned at every timestep according to a prescribed trajectory. This allows us to simulate illumination from the Sun of course, while discretization of the solar disc into several hundred elements can account precisely for limb darkening at any wavelength. We can also model starlight from UV-bright stars [14], Earthshine, etc. Such sources may also be occulted by user-defined ellipsoids (*e.g.*, Mars for Phobos [15]).

A number of outputs can be requested, such as illumination and visibility of the sources, incident flux on the surface and shadow height; at every timestep or their average over the simulation period.

Indirect illumination (i.e., secondary scattering) can be computed as well, provided enough spatial padding for the scatterers' illumination conditions to be robustly evaluated. While computationally expensive, this capability enables exact modeling of the geometry of complex observations such as LROC long-exposure images of PSRs [16] and LAMP data [17].

Under the same intent to closely reproduce the actual observation geometry in our modeling, both direct and indirect illumination can be traced to any observer. Photometric functions are used to compute the intensity received from surface elements. Moreover, we allow boresight vectors to be defined in a SPICE frame (such as the LAMP instrument frame, fixed with respect to the telemetry-defined LRO spacecraft frame). At each timestep, intersections with the octree are determined and their illumination conditions, both direct and scattered, are assessed. Figure 1 shows a simulated WAC image using this boresight approach.

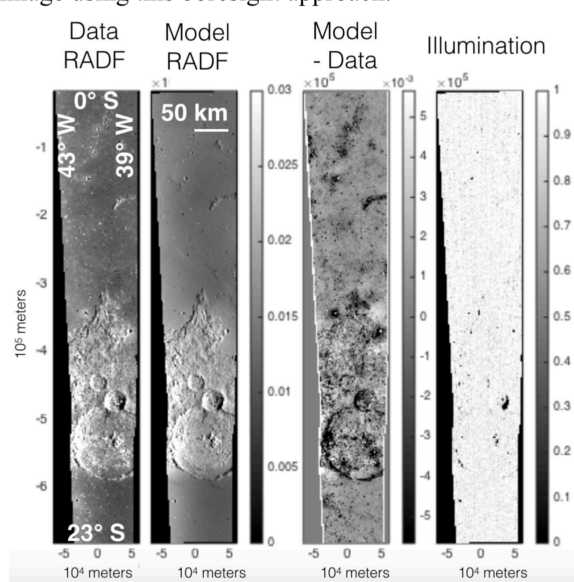

Figure 1. *Modeling of a 566-nm WAC observation using the LOLA 64ppd map and the Hapke photometric parameters from [13].*

Our modeling tool can also drive a simple one-dimensional thermal model [18] at each surface point based on computed direct solar radiation, scattered solar radiation, and thermal infrared radiation from these same scatterers. If the scatterer is not itself included in the subset region for which scattering is considered, its thermal model is only driven by direct radiation and thermal IR.

The configuration files can be minimally modified to leverage the modeling infrastructure in order to compute the radiation pressure on the spacecraft or on the body itself from all these sources (from direct, surface-reflected and/or thermal radiation). This can provide increased fidelity in the modeling of radiation forces for geodetic studies [19]. Indeed, orbit determination software usually relies on simplified geometries (spherical body discretized in only a few elements), not well-adapted to small body exploration. This capability will be tested with OSIRIS-REx for which small forces are especially important given the very small size of the target asteroid Bennu [20].

LOLA LHG: An example of application of this comprehensive modeling tool is the observation planning and data analysis for the LOLA Lunar Horizon Glow (LHG) campaign in LRO's Extended Science Mission 3 (ESM3). As described in [21], near-weekly observations of the lunar limb at sunrise/sunset have been conducted to observe light forward-scattered by dust grains that may be present at low altitude (<20 km), especially near meteor streams [22]. We use this illumination modeling tool to precisely compute the slew angle required to point the instrument field of view (FOV) at the desired solar elongation angle above the local topography. During analysis, we compare the passive radiometry measurements to the predictions of coronal and zodiacal light (CZL) contributed from the 500 sub-FOV elements not obstructed by the Moon. Any significant excess can be attributed to scattering from local dust. The shadow boundary along each sightline is output to forward-model the signal expected for a given exospheric dust density model.

Conclusions: Significant modeling capabilities were added to our illumination code. These enable much-refined modeling of the exact geometry of science observations, by LOLA or any planetary altimeter or imager. This can bring about improved quantitative analysis of science data and instrument calibration, and can be integrated in the observation planning to optimize the quality of the scientific data acquired by spacecraft such as LRO during off-nadir operations.

References: [1] Chin G. et al. (2007), SSR, 129. [2] Mitrofanov I., et al. (2010), Science, 330. [3] Gladstone G.R. et al. (2012), JGR, 117. [4] Robinson M.S. et al. (2010), SSR, 150. [5] Smith D.E. et al. (2017), Icarus, 283. [6] Paige D.A. et al. (2010), SSR, 150. [7] Patterson G.W. et al. (2017), Icarus, 283. [8] Speyerer E.J. and Robinson M.S. (2013), Icarus, 222. [9] Mazarico E. et al. (2011), Icarus, 211. [10] Acton C. H. (1996), PSS, 44. [11] Barker M.K. et al. (2016), Icarus, 273. [12] Boyd A.K. et al. (2014), LPSC. [13] Sato, H. et al. (2014), JGR, 119. [14] Byron, B.D. et al. (2017), AGU. [15] Stubbs, T.J. et al. (2016), AGU. [16] Koeber, S.D. et al. (2014), AGU. [17] Mandt K.E. et al. (2018), LPSC, submitted. [18] Schorghofer N. (2017), github.com/nschorgh/Planetary-Code-Collection. [19] Mazarico E. et al. (2017), J. Geodesy, 91. [20] Lauretta D.S. et al. (2017), SSR, 212. [21] Barker M.K. et al. (2018), LPSC, submitted. [22] Horanyi, M. et al. (2015), Nature, 522.

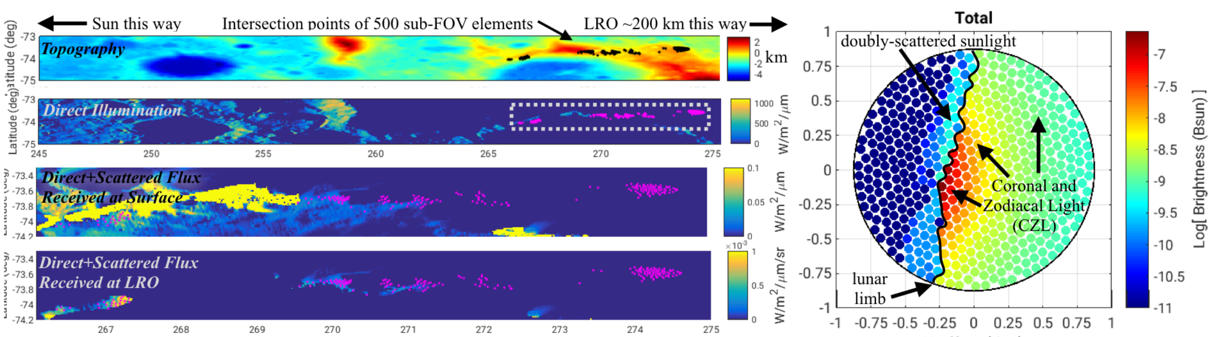

Figure 2. *LRO observed the lunar limb at sunrise on April 8, 2016 in search of Apollo 15-like lunar horizon glow. The 1.75°-FOV Laser Ranging telescope mounted on the HGA was pointed towards the Sun before sunrise. The modeling program was used to compute the intersections of 500 sightlines within the FOV (right) with the LOLA shape model (top left). While none showed direct surface illumination from the Sun, the consideration of scattered light shows that some doubly-scattered light did contribute (bottom left) to the total radiance measured, albeit only at the sub-percent level compared to the CZL signal.*