

FAST AND ACCURATE: REAL-TIME SOFT-SHADOWED RAY TRACED LUNAR AND PLANETARY GLOBAL TERRAIN FOR LIGHTING AND LANDING SIMULATIONS. D. Jung¹, F. Schrempf² and S. Son¹, ¹Korea Aerospace Research Institute (KARI), 169-84 Gwahak-ro, Yuseong-gu, Daejeon 34133, Korea. dwjung@kari.re.kr, ²Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany.

Introduction: A fast and accurate soft-shadowed 3-D ray tracing simulator for lunar and planetary global terrain is presented. Unlike previous works, this simulator can efficiently and seamlessly render full global terrain at arbitrary scales with atmosphere for interactive lighting and landing studies.

Existing planetary terrain simulators in wide use include PANGU [1] and SurRender [2]. However, PANGU has difficulty seamlessly handling arbitrary distance scales from orbit to the ground, shadows are generated ad hoc with shadow maps, and its Hapke photometric function is simplified such that accurate lighting studies are not possible. SurRender overcomes these issues, but requires vendor-specific ray tracing-capable hardware for accurate lighting simulations and atmospheres are not simulated.

Planetary terrain simulators are used for lighting studies, validating terrain-relative navigation methods, and generating training data for machine learning navigation techniques. Examples include mapping of lunar south pole permanently shadowed regions [3], and validation of autonomous Mars EDL (entry, descent, and landing) [4]. Some important simulator features that were considered for this work include the following:

Accurate lighting. Simulated landing in heavily shadowed terrain, and resource mapping, mineralogy, and heat transfer studies require accurate modeling of shadows, typically calculated using ray tracing [3][6].

Ray tracing. As a natural way to simulate light transport, ray tracing can be very accurate. However, effects such as reflections, secondary illumination, and soft (penumbral) shadows can, when calculated naïvely, cause an explosion in computational requirements. Typical current real-time ray tracing techniques therefore resort to specialized ray tracing acceleration hardware [2]. However, the renderer in this work accelerates ray traced soft shadows—one of the most time-consuming effects to simulate yet critical for lighting accuracy—on most commodity computers using mathematical optimization. Accuracy is traded for speed to an extent that is quantified in Figure 1.

Interactivity. With an interactive simulation, user and scripted changes to position, attitude, time, and camera parameters are reflected immediately. This reduces time spent waiting for a particular result and facilitates iterative experimentation.

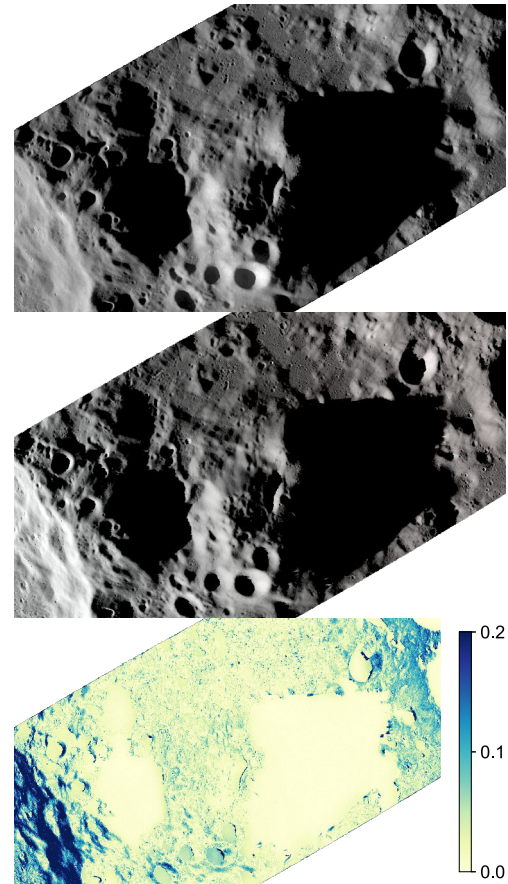


Figure 1. Quantitative comparison of LRO WAC image M109998684ME (top) vs. simulation (center) and absolute error (bottom).

Global scale simulation. Scalability is a valuable feature when simulating orbital and surface viewpoints or smooth transitions between the two, and is critical for enabling better interactivity.

Implementation: The simulator introduced in this work uses an optimal ray tracing algorithm developed in-house [7] that can render physically accurate soft shadows with a full Hapke reflectance model [8], planetshine, and Mie and Rayleigh atmospheric scattering at smooth (>30 Hz) framerates even on low-end computers with Intel Skylake integrated graphics (Table 1). The only requirement is OpenGL 2.1 with `GL_EXT_gpu_shader4`, although more recently a version using OpenGL ES 3 and ANGLE has been

developed that can provide greater performance on recent hardware due to translation to accelerated DirectX and Metal instructions.

The simulator is based on celestia.Sci [9], a fork of Celestia, and thus enjoys its advanced scripting and SPICE ephemeris support. Scenes are fully interactive in position, attitude, time, and field of view.

A quadtree-based virtual tile loading scheme allows scalable simulation at arbitrary distance scales without requiring huge amounts of memory. For example, the Moon can be viewed from the Earth's surface through its atmosphere or within meters of the lunar surface with only the minimum spatial resolution of data products (e.g., 1m for LRO NAC) being the practical limiting factor. DEM tiles within the field of view are merged on-the-fly before being used to displace terrain to prevent cracks from appearing.

Results: Figure 1 shows a quantitative comparison of LRO WAC lunar south polar region imagery with simulation [7]. As detailed in ref [7], the errors are overestimated because some are caused by ghosting artifacts (stray light) in the WAC image and are thus spurious. Table 1 shows that performance is more than sufficient for both interactive use and for rapidly generating images for training and validating machine learning systems. Figure 2 is a qualitative comparison of a SELENE controlled descent HDTV image with simulation. Excepting differences in viewpoint (an exact SPICE trajectory is not available), the simulation closely reproduces shadows and lighting in the HDTV image. Figure 3 demonstrates handling of atmospheric scattering and shadow rendering simultaneously, on a global scale.

Acknowledgments: We thank Andrew Tribick for bug reports and feedback. This work was supported in part by funding from the Korea Ministry of Science and ICT through the “Development of Pathfinder Lunar Orbiter and Key Technologies for the Second Stage Lunar Exploration” project.

References: [1] Parkes S. et al. (2004) *Space Ops 2004*. [2] Brochard R. et al. (2018) *69th IAC*. [3] Speyerer, E. J. and Robinson M. S. (2013) *Icarus*, 222(1):122–136. [4] Johnson A. et al. (2017) *Proc. 40th AAS G&C*, 143-158. [5] McClanahan T. P. et al. (2009) *40th LPSC*, #2092. [6] Amoroso E. et al. (2016) *LEAG*, #5037. [7] Jung D. et al. (2019) arXiv: 2005.06671. [8] Sato H. et al. (2014) *J. Geophys. Res. Planets* 119, 1775-1805. [9] Schrempp F. et al. (2013) <http://forum.celestialmatters.org/viewtopic.php?f=11&t=473>

Table 1. Performance when rendering Figure 2 for different graphics hardware and windows sizes [7].

GPU / Dimensions	1920×1080	512×512
NVIDIA GTX 970M	185 Hz	402 Hz
Intel Iris 540	50.5 Hz	196 Hz

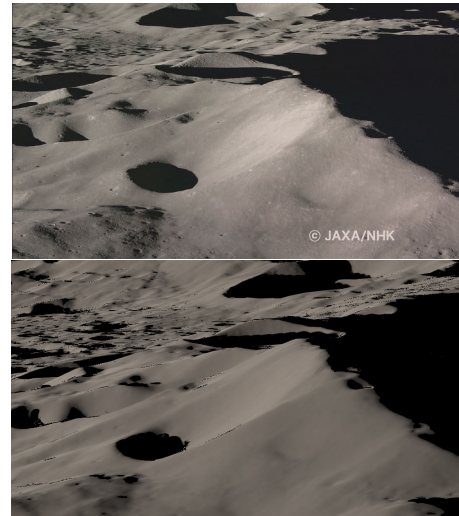


Figure 2. Qualitative comparison of color-corrected SELENE imagery (top: sh_20090610T181259_ti1_0000 © JAXA/NHK) vs. simulation (bottom).

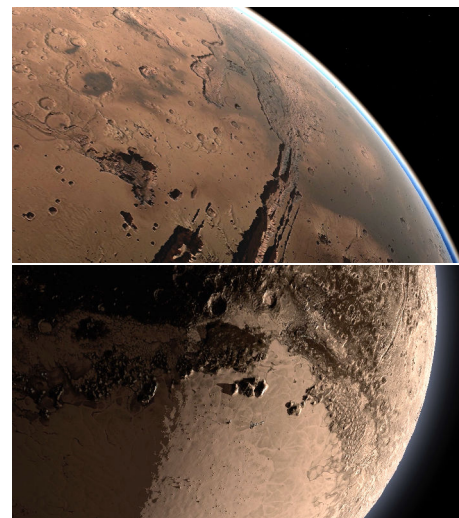


Figure 3. Mars (top) and Pluto (bottom) global simulations with atmospheres.