Indirect and Direct Planetary Illumination Modeling for Robotic Surface Exploration Sensing

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Robotic exploration of outer planetary bodies will rely on perception systems for autonomous navigation as ground-based control becomes less effective at these long distances due to communication time delay. Passive perception systems for space flight missions using solid-state solutions, such as electro-optical multispectral cameras, are preferred over mechanically scanned systems, such as laser scanners, to remove the risk associated with moving parts. Passive perception systems, however, are reliant on the natural illumination on the planetary body. The illumination can be direct lighting from the sun or indirect lighting from reflected sunlight of a neighboring body. The amount of illumination is also affected by astronomical events such as eclipses. In this paper, we describe our planetary illumination modelling for a general planetary body and reflectance bodies. Our simulation software leverages the JPL NAIF SPICE library to provide high fidelity solar system geometry for the basis of our direct and indirect modelling. Output data products include total, direct, and indirect irradiance plots for a given latitude and longitude on the planetary surface for a given time period and time step. In addition, irradiance statistics over the entire planetary surface can be represented in global maps.

Nomenclature

NAIF	=	Navigation and Ancillary Information Facility
SPICE	=	Spacecraft, Planet, Instrument, Camera, Event
API	=	Application Programming Interface
NASA	=	National Aeronautics and Space Administration
SPK	=	Spacecraft and Planet Kernel
PCK	=	Planet Constants Kernel
LSK	=	Leap Seconds Kernel

I. Introduction

Robotic exploration of outer planetary bodies will rely on perception systems for autonomous navigation as ground-based control becomes less effective at these long distances due to communication time delay. Passive perception systems for space flight missions using solid-state solutions, such as electro-optical multispectral cameras, are preferred over mechanically scanned systems, such as laser scanners, to remove the risk associated with moving parts. The solid-state solutions are more likely to survive the hazards of spacecraft launch, entry, and landing. Moreover, a passive perception system requires less power consumption and doubles as both a navigation resource for sensing and a scientific resource for imaging[1].

Passive perception systems, however, are reliant on the natural illumination on the planetary body. The illumination can be direct lighting from the sun or indirect lighting from reflected sunlight of a neighboring body. The amount of illumination is also affected by astronomical events such as eclipses. In this paper, we describe our planetary illumination modelling for a general planetary body and reflectance bodies. Our simulation software leverages the JPL NAIF SPICE library to provide high fidelity solar system geometry for the basis of our direct and indirect modelling.

With the recent adoption of the NASA Ocean Worlds program to study Europa, of particular interest will be the mission operations impact from the illumination on Europa and the indirect lighting influence of Jupiter, being 45x bigger than Europa with a bond albedo of 0.34 but at a distance 5x greater to the sun than Earth. Europa's tidally locked orbit around Jupiter is 3.5 Earth days resulting in frequent solar eclipses on Europa. For surface operations on

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Europa, a rover will spend about 40 hours without direct illumination. A motivation of this work is to provide indirect illumination data that could impact sensor design and mission planning for potential night-time rover operations.

II. Background

Previous works have focused on direct illumination for lunar operations for power analysis and simulation of surface appearance using terrain models[3-5]. In this work, we include indirect illumination from an arbitrary number of reflectance bodies at a planetary scale and occlusion events. Our modelling is based on the NAIF SPICE Toolkit and solar irradiance.

A. NAIF SPICE Toolkit

JPL's NAIF (Navigation and Ancillary Information Facility) SPICE Toolkit is a suite of software tools designed to produce and archive ancillary data used to give telemetered data context and meaning. Examples of ancillary data include instrument calibrations, instrument and spacecraft operating modes, and observation geometry. The SPICE Toolkit has been extensively used in mission design, science observation planning and science data analysis. Modules in the toolkit include ephemeris and state vector calculations (position and velocity of bodies), time translations, reference frame and coordinate conversion, natural body constants, solid geometry, instrument field of view geometry, vector mathematics, and matrix algebra[2]. The ephemeris module includes options to report state vectors with light time and stellar aberration correction, providing the state vector data as it would appear to an observer given the finite speed of light and the velocity of the observer rather than instantaneous values.

Celestial body motions are described through SPK (spacecraft and planet kernels) files, natural body constants are described through PCK (planetary constants kernel) files, and ephemeris time conversions are described through LSK (leap seconds kernel) files. All kernel files are available through the NAIF ftp site.

B. Solar Irradiance

Irradiance is the amount of light energy from a source emitter falling on a square meter of a receiver. The irradiance S in units of W/m^2 from a source body is defined as:

$$S = \frac{L}{4\pi D^2} \tag{1}$$

where L is the source luminosity and D is the distance in meters of a target location to the source. For our model of solar irradiance, L is defined to be 3.84 x 10^{26} Watts and we consider only the solar irradiance from the visible light spectrum.

III. Design & Methodology

For both the direct and indirect illumination modelling, the geometry among the sun, reflecting bodies, and target body must be known. For the indirect illumination modelling, the luminosity is first integrated over the reflecting body to derive the reflected irradiance falling on the target body.

A. Illumination Geometry

Given an arbitrary ephemeris time, the geometry among the sun, reflecting bodies, and target body are found using the SPICE API for state vector calculations through SPK files. In our simulation, all state vectors are computed relative to the J2000 inertial frame, a non-rotating, non-accelerating reference frame whose origin is the solar system barycenter, using light time correction. Solar occlusion events from the surrounding bodies on the target body are found using the SPICE Geometry Finder module which calculates total, partial, and annular occlusions by modelling the occluder and occluded body as ellipsoids from constants found in the provided PCK files. In our current simulation, the occluded body is the sun and any occlusion event is considered a total occlusion for illumination purposes.

To model the effects of geographic location, the irradiance is adjusted by the Lambertian surface cosine law as:

$$S' = S \times \left(\vec{N} \cdot \vec{I}\right) \tag{2}$$

where $\vec{N}$ is the surface normal and $\vec{I}$ is the incident light vector. Our current simulation models the target body surface as a spheroid and assumes no atmospheric attenuation.

B. Indirect Lighting

For each reflecting body specified in the simulation, the indirect lighting model is based on computing a source luminosity over the hemisphere facing the target body location by integrating over the surface body given by:

$$S_{indirect} = \frac{\iint_{\theta,\varphi} R(\theta,\varphi)}{2\pi D^2} \quad (3)$$

$$R(\theta,\varphi) = \begin{cases} S' \times A \times \alpha, & if\ (\vec{N} \cdot \vec{O}) > 0 \\ 0\,, & otherwise \end{cases} \quad (4)$$

where θ is the latitude and φ is the longitude angle on the reflecting body, S' is the solar irradiance on the reflecting body at the given lat-long position, A is the surface area, α is the surface albedo, $\vec{N}$ is the surface normal at the reflecting body lat-long position, $\vec{O}$ is the vector from the target body location to the reflecting body lat-long position, and D is the distance from the target to the reflecting body.

C. Simulation Parameters

The planetary illumination simulation parameters are summarized in Table 1. An arbitrary number of reflecting bodies can be specified and the direct and indirect irradiance can be computed for a specific latitude and longitude location or sampled at uniform locations over the entire body. For the global map output, a single statistical value (ie: min/max/average) can be computed over the simulation time period for each location. Although the SPICE library is not thread-safe, parallelism can be achieved at the process level through a script that automatically partitions the simulation period over the requested number of processes and launches each process concurrently.

Parameter	**Description**
Target body	Name of body to calculate direct and indirect irradiance
Reflecting bodies	List of bodies to use for indirect illumination
Start and end time	Start and end simulation times
Step size	Simulation step size in seconds
Simulation mode	**Lat/Long**: generate irradiance values for the user defined location every step size **Global Map**: generate max/min/average irradiance values over the simulation period at uniform sampling locations over the body
Parallel processes	Number of concurrent processes to run

Table 1: Description of the illumination simulation parameters that can be configured by the user for simulating the direct and indirect illumination on the target body.

IV. Results and Discussion

The indirect and direct illumination for several bodies were simulated using an Intel Core i7-4910MQ 2.9 GHz processor with 32 GB of RAM and a simulation step size of 1 hour. In Figure 1, the indirect illumination on Europa reflected from Jupiter with an albedo of 0.34 is compared to the illumination on Earth reflected from the Moon with an albedo of 0.12 during Jupiter's closest approach to the Sun, as shown in Figure 2a. The large size of Jupiter yields a maximum indirect irradiance of 0.13 W/m^2. Assuming the Sun has a luminous efficacy of 93 lumens/W, the maximum indirect illuminance on Europa from Jupiter is 12 lux. This is equivalent to a 60W incandescent bulb covering 75m^2 or 807ft^2.

Figure 2 shows examples of direct illumination simulations covering the 12 year orbit of Jupiter, direct illumination irradiance comparison of Earth, Mars, and Europa, and solar eclipse periods on Europa. Figure 3 shows an example analysis of illumination data obtained from a global map simulation on Europa for surface mission operations. The number of hours above a hypothetical irradiance threshold 20 W/m^2 is computed at each sampled geographic location for a day on Europa. The relatively small axial tilt of Europa yields similar data along each latitude.

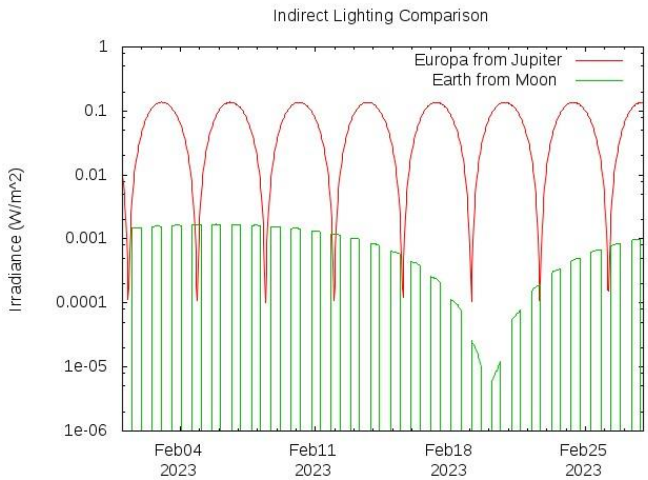
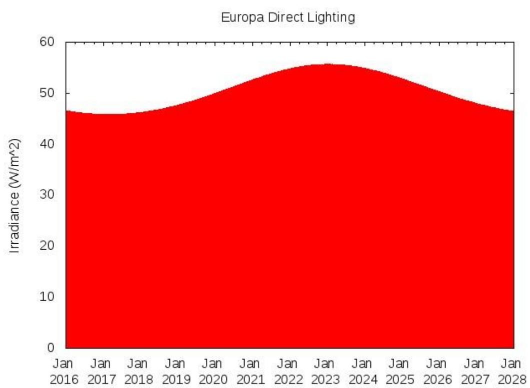
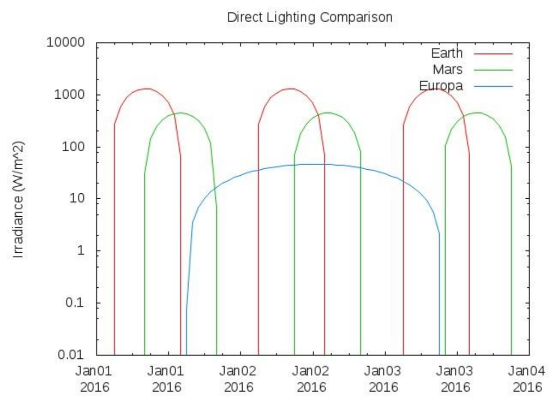


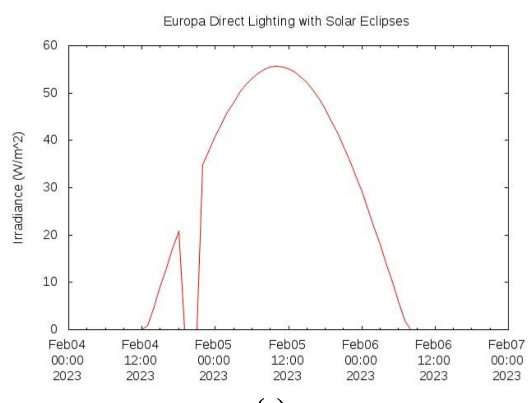
Figure 1: Comparison of indirect lighting on Europa reflected from Jupiter with an albedo of 0.34 and on Earth reflected from the Moon with an albedo of 0.12 during Jupiter's closest approach to the Sun. The maximum indirect illuminance on Europa from Jupiter is 12 lux.



(a)



(b)



(c)

Figure 2: Examples of direct lighting irradiance at the equator for (a) the 12 year orbit of Jupiter, and (b) comparison of irradiance among Earth, Mars, and Europa, and (c) solar eclipses from Jupiter as observed from Europa, lasting approximately 2 hours each orbit. While Europa has much longer daylight, its peak irradiance is 25x smaller than on Earth and 12x smaller than on Mars.

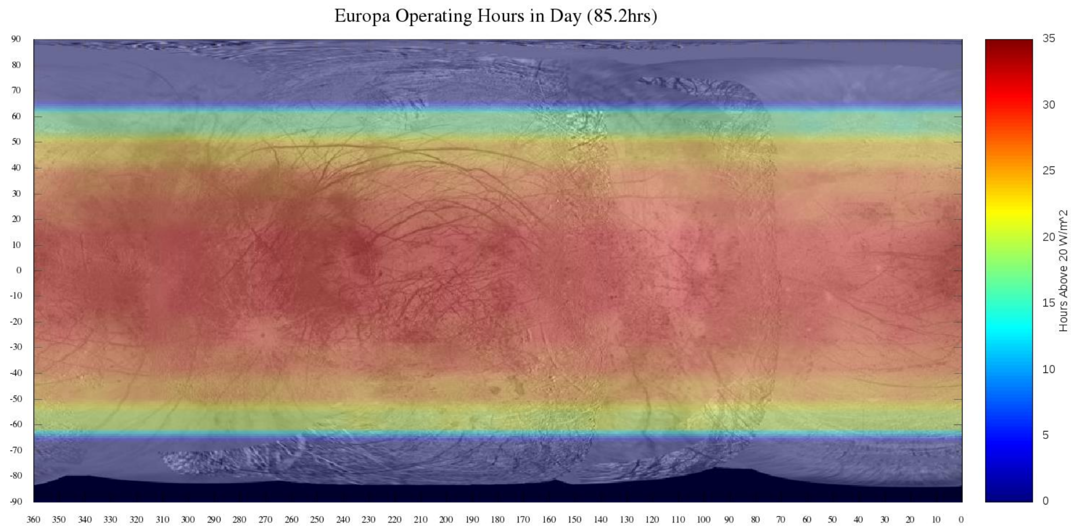


Figure 3: Example of mission operations analysis map describing the operating hours in a Europa day above an irradiance of 20 W/m^2.

V. Conclusion

We have presented a planetary illumination simulation framework for indirect and direct irradiance for an arbitrary number of reflecting bodies with occlusion events. We have demonstrated how the indirect illumination data for Europa could impact sensor design and mission planning for potential surface and night-time rover operations. Our simulations have shown that Europa receives 4% of the direct irradiance as compared to Earth while the indirect irradiance from Jupiter is 100x greater compared to the indirect lighting from the Moon on Earth. Future works of interest to enhance the surface lighting model would be to incorporate digital elevation data, derived from shape-from-shadow methods as in the Ames Stereo Pipeline[6], multi-spectral irradiance modelling, and atmospheric attenuation effects.

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References

[1]Tunstel, E., & Howard, A. “Sensing and perception challenges of planetary surface robotics.” Proceedings of IEEE Sensors 2002 (Vol. 2, pp. 1696-1701). 2002.

[2]Acton, C.H. "Ancillary Data Services of NASA's Navigation and Ancillary Information Facility;" Planetary and Space Science, Vol. 44, No. 1, pp. 65-70, 1996.

[3]Nayar, H., Balaram, B.J., Cameron, J., Jain, A., Lim, C., Mukherjee, R., Peters, S., Pomerantz, M., Reder, L., Shakkottai, P. and Wall, S., “A Lunar Surface Operations Simulator.” In International Conference on Simulation, Modeling, and Programming for Autonomous Robots (pp. 65-74). 2008.

[4]Nayar, H., Jain, A., Balaram, B.J., Cameron, J., Lim, C., Mukherjee, R., Pomerantz, M., Reder, L., Myint S., Serrano, N., and Wall, S. "Recent Developments on a Simulator for Lunar Surface Operations." In AIAA SPACE 2009 Conference & Exposition, vol. 3, p. 4. 2009.

[5]Fincannon, H. J. "Lunar polar illumination for power analysis." AIAA 6th International Energy Conversion Engineering Conference (IECEC). 2008.

[6]Moratto, Z.M., Broxton, M.J., Beyer, R.A., Lundy, M. and Husmann, K., “Ames Stereo Pipeline: NASA's open source automated stereogrammetry software.” In Lunar and Planetary Science Conference (Vol. 41, p. 2364). 2010.