CAMERA EXPOSURE TIME DETERMINATION FOR ARTEMIS I LUNAR FLYBY

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Abstract. *During Artemis I, a flight test was conducted using the Optical Navigation Camera to image Lunar terrain at low altitude prior to the Return Powered Flyby (RPF) burn. The vehicle descended rapidly toward the surface and transitioned over the Lunar Terminator during the time frame in which the images were to be gathered, creating challenging lighting conditions which required the development of a novel technique for exposure time determination to gather imagery of appropriate quality for post flight analysis. The resulting technique leveraged simple photometric models and simulations, as well as the spacecrafts altitude and pointing direction to determine the necessary change in exposure times over the course of the flyby, resulting in a successful flight test.*

Introduction. Imagery can play an impactful role in spacecraft navigation at almost any point during a mission. Determining the correct camera settings for a particular scenario is a critical component in implementing any imaging system for spacecraft navigation. These settings are dependent on the properties of the specific imaging system and navigation task for which it is being used. Different camera settings, particularly exposure time, will be required to perform different navigation functions on future missions, such as starfield imaging, long range bearing, or terrain imaging for Terrain Relative Navigation (TRN).[123] Each of these cases requires unique camera settings to maximize the performance of image processing algorithms and the generation of measurements. Particularly with respect to terrain imaging, the lighting environment close to the surface can cause a large variation in required exposure settings for TRN. Lighting conditions impacting the imagery are not only a function of the position and orientation of the planetary surface with respect the illumination source, but also of the observer's relative pose to the surface at the time the images are gathered. While imagery can be simulated via rendering engines to test image based navigation algorithms, determining realistic camera settings is near impossible without some kind of experimental or flight data to inform the selected settings.

The Orion spacecraft features an Optical Navigation camera and associated software which was demonstrated on Artemis I to support the use of imagery for the safe return of crew and vehicle in a permanent loss of communication scenario.[4] During Artemis I, the Optical Navigation camera was utilized in two Lunar terrain imaging flight tests during the low altitude Lunar flybys. Over the course of the time frame in which the images were to be gathered, the spacecraft changed altitude rapidly. The illumination conditions at the surface also changed considerably as the spacecraft transitioned from the lit limb to the Lunar terminator over the course of the flybys. For the initial Outbound Powered Flyby (OPF), a purely phase angle based method was used to determine camera exposure settings which resulted in heavily overexposed imagery, an example of which is shown in figure 1. This required the determination of a novel technique for terrain imaging exposure times as a function of the dynamics, surface reflectance properties, and pointing direction expected during the Return Powered Flyby (RPF), in order to obtain higher quality images for the flight test.

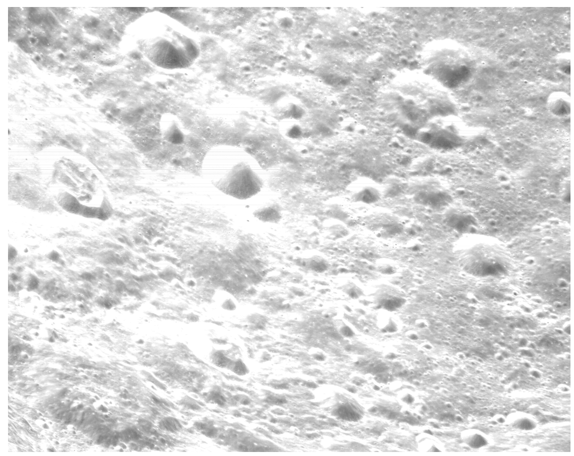

Figure 1. Image of the Lunar Terrain obtained by the OpNav camera during the Artemis I Outbound Powered Flyby (Photo Credit: NASA).

Methods and Approach. Preflight hardware-in-the-loop (HWIL) testing of the OpNav camera on the ground led to the creation of a table which related the phase angle of the observed Moon (when imaged as an extended body) to the required exposure time necessary to obtain lit limb measurements for horizon based OpNav.[5] However, these values are not directly applicable to a low altitude flyby scenario as the exposure time becomes dependent on more than just the phase angle defined by the observer and sun position relative to the Moon.

An attempt during the Outbound Powered Flyby (OPF) earlier in the flight directly applying the phase-angle based OpNav exposure values led to several extremely overexposed images. When the extended body of the Moon or Earth (in OpNav's case) is within the image, exposure time is only a function of phase angle to the illumination source. However, when the spacecraft altitude becomes low enough such that the object extends beyond the camera Field-Of-View (FOV), the brightness observed by the imaging system (which determines the required exposure time), becomes heavily influenced by proximity to the surface and spacecraft attitude, in addition to phase angle. This required the creation of a novel technique to relate the experimentally determined exposure values to the dynamic and complex lighting environment expected during the Return Powered Flyby. This technique leveraged approximations of Lunar surface reflectance to create simulated imagery which was used in conjunction with the spacecraft trajectory to determine what portions of the illuminated surface would be in the FOV over the course of the flyby. A parameter defined as average intensity per lit pixel $\bar{i}$ was used to relate the simulated images to the extended body images used in OpNav and their experimentally determined exposure times.

In order to simulate low-fidelity Lunar images the McEwen Model[6] was used. It is a reflectance model described in equation 3 and is a weighted combination of Lambertian (equation 1) and Lommel-Seeliger (equation 2) reflectance models designed to approximate Lunar reflectance. In these equations, I_0 is strength of the collimated irradiant light striking the sphere, α is the (presumed constant) albedo of the surface, θ is the phase angle between the observer and the light source, and (x, y) represent the coordinates of the point on the plane into which the sphere is projected. An example of how these equations and input parameters can be used to generate a rendering of a simple sphere is shown in figure 4. Assigning $\eta = \sqrt{1 - x^2 - y^2}$, the equations defining these models are as follows:

$$I(x, y)^S_L = I_0 \alpha \left[y \sin\theta + \eta \cos\theta \right] \quad (1)$$

$$I(x, y)^S_{LS} = I_0 \alpha \left[\frac{y \sin\theta + \eta \cos\theta}{y \sin\theta + \eta \cos\theta + \eta} \right] \quad (2)$$

$$I(x, y)^S_{ME} = A_L I^S_L(x, y) + (1 - A_L) I^S_{LS}(x, y) \quad (3)$$

The rendered images of a full sphere with this lighting model (approximating the Moon) at different phase angles enabled their correlation with the exposure time and phase angle relationship previously determined for OpNav from empirical results, as shown in figure 5. The average lit pixel intensity, computed for each simulated image using equation 4, could then be associated with a specific exposure time. As shown in figure 2, the trajectory for the upcoming flyby and knowledge of the spacecraft's pointing direction indicated that as the spacecraft descended it would view the lit limb before rapidly traversing over the Moon's surface toward the terminator and into darkness, with a planned attitude that would be roughly nadir pointed throughout the flyby.

The low fidelity full sphere render was created using the known phase angle θ between the spacecraft and Moon, and was projected into a plane. Assuming the spacecraft's attitude to be generally pointed orthogonal to the plane in which the image is projected, a *very* rough approximation of the spacecraft FOV was then projected onto the simulated imagery and scaled/translated based on the expected altitude to the closest point on the surface and path of the spacecraft as a function of time, as shown in figure 6. For each of these simulated images created within the approximated FOV, the average lit pixel intensity was computed with equation 4, where $\bar{i}_P$ is the average lit pixel intensity, Σ_i is the sum of pixel intensities within the simulated image, and Σ_P is the total number of illuminated pixels in the simulated image.

$$\bar{i}_P = \frac{\Sigma_i}{\Sigma_P} \quad (4)$$

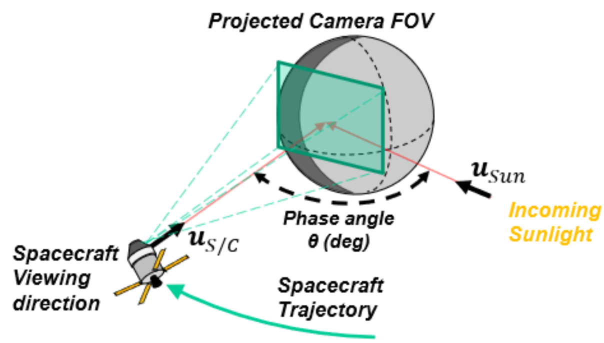

Figure 2. Diagram of the flyby, projected FOV, and phase angle geometry.

Using the average lit pixel intensity to exposure time correlation established using the relationships shown in figure 5, and the average lit pixel intensity values corresponding to the images created by projecting the subtended camera FOV over the rendered images in figure 6, an exposure time as a function of distance from the lit limb to the terminator (the boundary of the illuminated portion of the Moon) could be determined. Figure 7 shows the resulting relationship between lit pixel intensity in the simulated imagery vs the computed exposure time. Note that operational constraints limited the number of exposure time changes, so they were computed in a 'step' fashion corresponding to a range of lit pixel intensities. Exposure times determined using this method were uploaded to the spacecraft, and the camera collected the imagery as commanded over the course of the flyby up until overflying the terminator and transitioning into darkness.

Results and Forward Work. Figure 3 shows three of the images obtained of the terrain during the Return Powered Flyby from the crossing of the lit limb, midpoint over the Lunar terrain, and then the crossing of the terminator. The exposure times computed led to a successful flight test which obtained high quality imagery of the Lunar surface over the course of the flyby by taking into account the rapidly changing illumination conditions resulting from the changing spacecraft altitude, illumination angle, and approximate spacecraft attitude.

The imagery obtained contains highly distinguishable details and terrain features, making it very valuable for the development of Terrain Relative Navigation (TRN) and feature (e.g. crater) identification algorithms. In addition, as we extend optical navigation techniques to multiple phases of a planetary approach (e.g. lit limb navigation transitioning to TRN), we will have to address the necessary changes in exposure to obtain data of the correct quality depending on the algorithm its being used for. While the technique presented here is very approximate, it could certainly be developed further as a way of determining camera settings using empirical data coupled with knowledge of the lighting angle and vehicle state to benefit collecting imagery for Terrain or Hazard Relative Navigation as a spacecraft descends and sensor settings must be adjusted away from those appropriate for lit limb navigation.

References.

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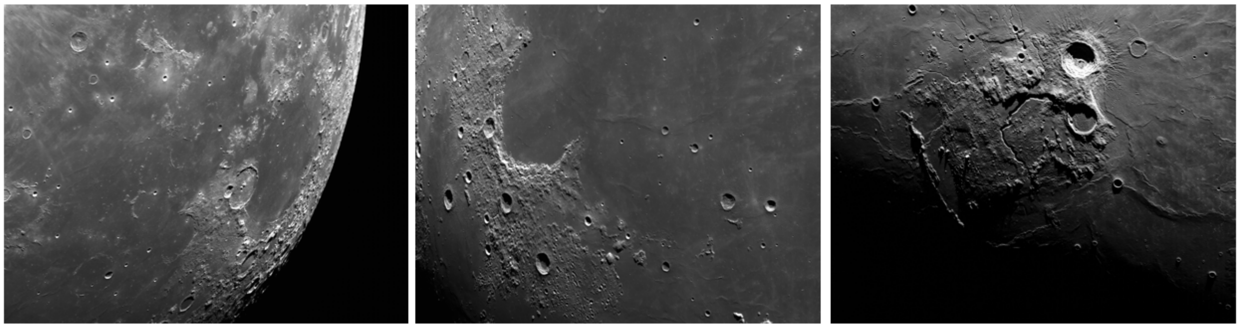


Figure 3. Selected images from the Return Powered Flyby, showing the initial crossing of the limb (left), Lunar terrain midway through (middle), and crossing the terminator at the end of the image gathering (right). (Photo Credit: NASA)

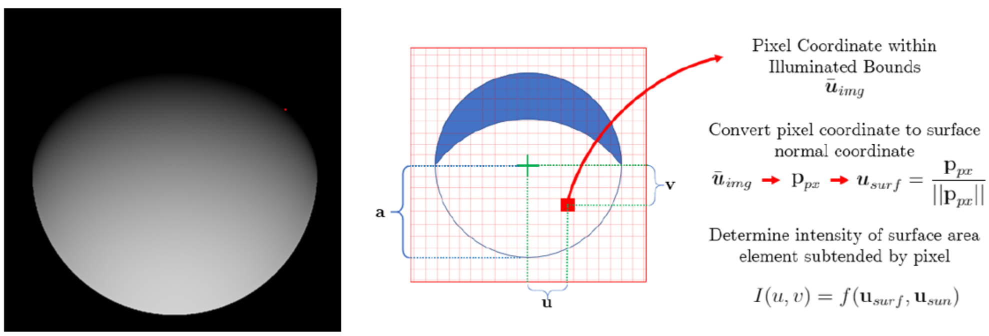
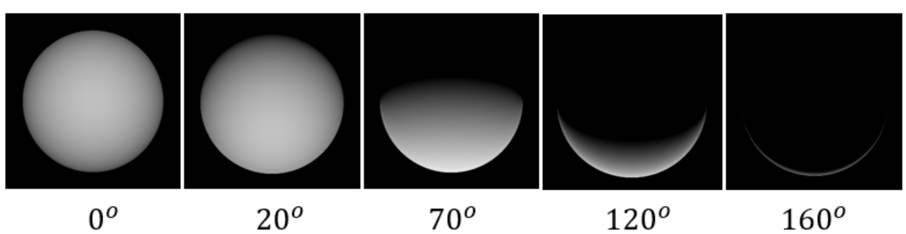


Figure 4. Diagram of how lighting models were used to construct the simulated low fidelity Lunar renders.



Phase Angle (deg)	Average Intensity per pixel range from sim $\bar{\iota}_p$	Exposure time (sec) (from OpNav)
0-20	0.6677 – 0.6498	0.000101
20-70	0.6498 – 0.5052	0.000201
70-120	0.5052 – 0.2905	0.000401
120-160	0.2905 – 0.0975	0.000601

Figure 5. Table relating phase angle, corresponding average intensity per lit pixel from simulated imagery, and empirically determined exposure time for good images with OpNav camera

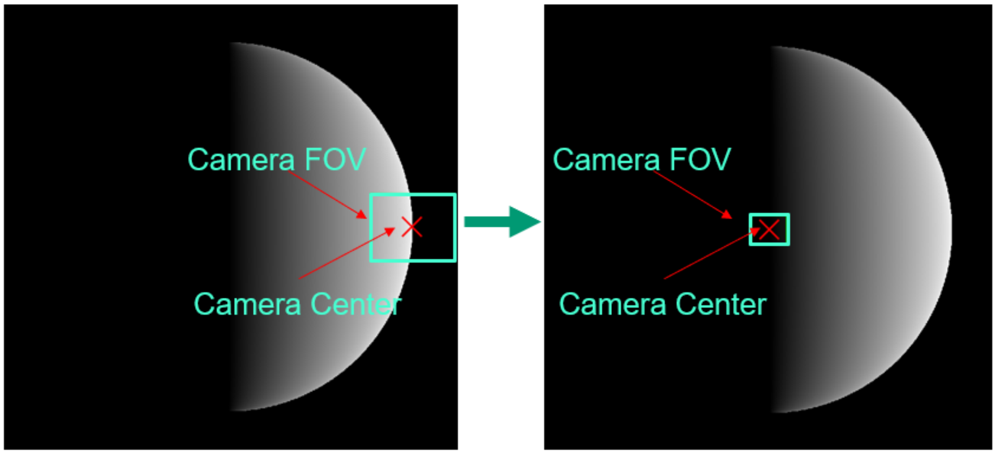


Figure 6. Left: Projected approximate FOV early in the flyby. Right: Projected approximate FOV at the end of the flyby as the spacecraft traverses the Lunar terminator.

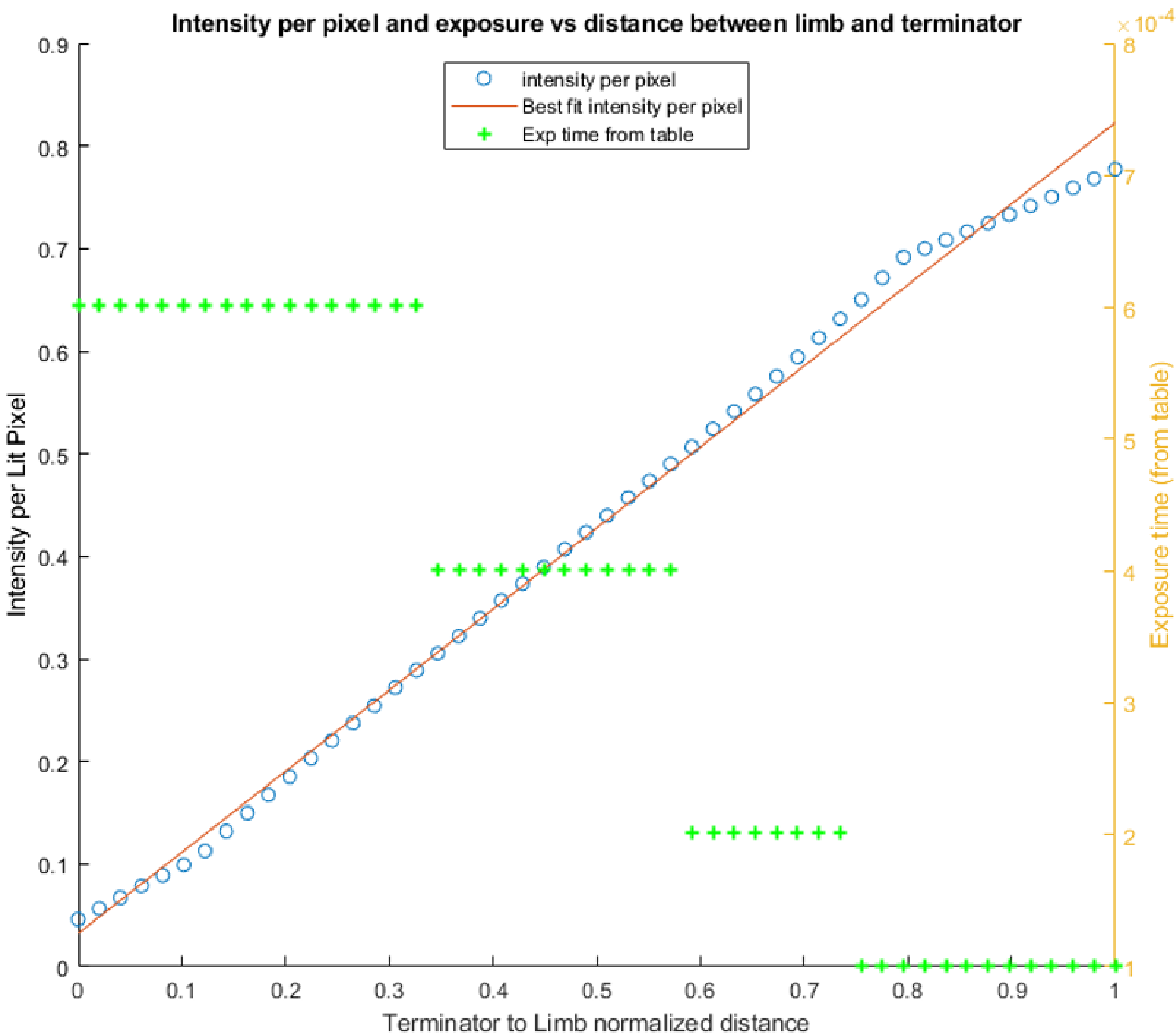


Figure 7. Graph Showing the relationship between distance from limb to terminator (x-axis), average pixel intensity in the area subtended by the approximate projected FOV (left y-axis), and correlated exposure time (right y-axis)