DEMONSTRATION OF THE ORION OPTICAL NAVIGATION SYSTEM ON ARTEMIS I

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Abstract. *The Orion Optical Navigation (OpNav) System is a first-of-its-kind navigation capability that was demonstrated in space on the Artemis I mission. The OpNav System was tested under a variety of conditions, resulting in over one thousand images of Earth, Moon, and starfields. Pairing the images with ground tracking information, not only did Artemis I provide a basis to evaluate the performance of the Orion OpNav system, but produced a valuable set of imagery/data that can be used to further development and testing of other optical navigation systems.*

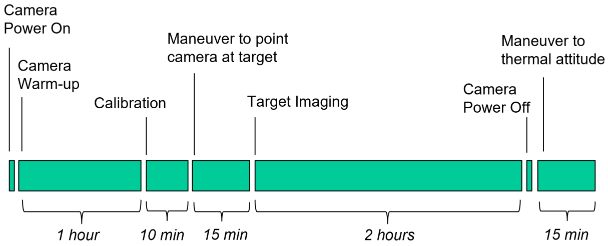

Figure 1. Nominal OpNav pass timeline.

Introduction. The OpNav System's primary purpose was a back-up source of navigation measurements in the event of permanent communication loss (PCL) with Orion. The demonstration of the OpNav System on Artemis I was the culmination of nearly 10 years of effort, including development of image processing algorithms, integration onto Orion, and hardware-in-the-loop testing.

The OpNav System comprises two capabilities: starfield calibration and target image processing for range and bearing. Calibration was performed using starfield images and associated attitudes[1] to characterize the camera focal length, distortion, etc. The image processing utilized both a non-iterative horizon-based algorithm[2,3] and an iterative method[4] to produce a position estimate target body (Earth or Moon) relative to the camera.

The OpNav System was used approximately once every 24 hours, in short "passes". Each pass consisted of a starfield calibration followed by target imaging.

OpNav Operations and Checkout. Fig. 1 depicts the nominal timeline of an OpNav pass. The camera was powered on and allowed to warm up for an hour in order for the detector to achieve thermal stability. After the warm-up period, the starfield calibration was performed, which lasted 10 minutes. Then, the vehicle was maneuvered to point the OpNav camera at the desired target. Depending on the attitude of the vehicle after calibration, maneuvering could take up to 15 minutes and included a wait period to dampen any residual body rates. The target imaging portion lasted 2 hours, after which the camera was powered off and the vehicle returned to the thermally stable attitude. OpNav passes were schedule approximately once every 24 hours

Operation of OpNav required careful planning before and during flight - with the Flight Control Team and engineers working closely together. Before flight, the trajctory was analyzed and a primary target was selected for each pass. Target selection was based off several constraints (range to target, phase angle, etc.) to determine the optimal target to ensure successful image processing. Camera exposure look-up tables were generated based on the known sensitivity (from ground testing) of the OpNav camera. The exposure tables were broken down by target and approximate phase angle.

To operate OpNav, the Flight Control Team manually configured the vehicle and OpNav. Armed with the target and exposure plan, operators commanded the vehicle to maneuver to point the camera at the desired target and commanded the OpNav camera to take images. The first two Earth and first two Moon passes were prescribed for the checkout and certification of the OpNav System. Each pass lasted 2 hours, where images were collected, position estimates generated, and the measurements processed into the onboard navigation filter. During that time, engineers monitored the OpNav System from the ground. Images were not downlinked real-time, but copious amounts of diagnostic data were telemetered that provided insight into the health of the system and the success of the calibration and image processing. Once the pass was complete, engineers inspected the onboard navigation state (as aided by OpNav) and compared against ground tracking data. The onboard navigation state was found to be within the pre-determined accuracy limit, and OpNav was declared certified for use. At that point, in the event that a loss of communication occurred, the OpNav Sytem would have automatically been triggered to operate as the primary navigation source in order to get Orion home. While Orion did not experience a loss of communication with the ground during Artemis I, OpNav continued to be used throughout the rest of flight in a limited capacity. The target imaging portion of the OpNav passes were shortened to 10 minutes each to collect additional test imagery under various conditions. At the end of the mission, images were retrieved from the vehicle and post-processed to get a detailed analysis of OpNav performance.

Artemis I Imagery. A trove of imagery was collected during the Artemis I flight and downlinked for post processing.

Table 1. Summary of Earth Passes.

Range (nmi)		Phase Angle (deg)	
Min	Max	Min	Max
52100	204500	50	143

Table 2. Summary of Moon Passes.

Range (nmi)		Phase Angle (deg)	
Min	Max	Min	Max
13060	147500	7	117

Starfield Imagery. A calibration was performed before each pass to help characterize the stability of the camera parameters[5] during flight. Each calibration collected approximately 30 starfield images, sweeping across 20 degrees of sky over the course of 10 minutes.

Post separation with the Interim Cryogenic Propulsion Stage (ICPS), Orion maneuvered to point the OpNav camera at ICPS and collected images that will be used to facilite the development and testing of a long-range bearing to target-vehicle capability that will a major part of docking camera operations on Artemis II+.[6]

Earth Imagery. Six Earth passes were performed during Artemis I, collecting over 500 images of Earth under various ranges and lighting conditions. Figs. 2 and 3 show Earth images taken from the OpNav camera. Table 1 provides a summary of the passes.

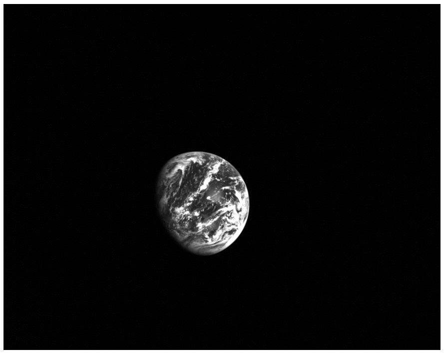

Figure 2. Image of Earth from Artemis I.

Figure 3. Thin Crescent Earth Image.

Moon Imagery. Twenty Moon passes were performed during Artemis I. Table 2 summarizes the pass conditions.

In addition to images of the Moon with a fully resolved limb, the Artemis I flight performed two lunar fly-bys that afforded the opportunity to take images of the lunar surface. The conditions during the lunar fly-bys were significantly different than the lighting conditions during the nominal OpNav passes, so the exposure tables were not valid. Engineers developed a novel technique using photometric models[7] to determine the appropriate camera exposure time.

Figure 4. Image of Moon from Artemis I.

Figure 5. Full Moon Image.

OpNav Performance. The primary test objective for OpNav on Artemis I was to certify the system for use on future Artemis missions, as well as characterize the performance of the algorithms. Overall, the OpNav System performed well, successfully processing 100% of the images taken.

The exposure tables mentioned in the *OpNav Operations and Checkout* section were used as a reference starting point to command the camera, but the lack of ability to operate the camera in real space conditions before flight (i.e. take real images at various distances to Earth/Moon under different lighting conditions) meant the table values were only an educated guess. To combat this, and to reduce the need for operators to pre-determine exact exposure values for all conditions, the OpNav System included an exposure feedback loop. Individual pixel intensities were evaluated to determine if the limb was over or

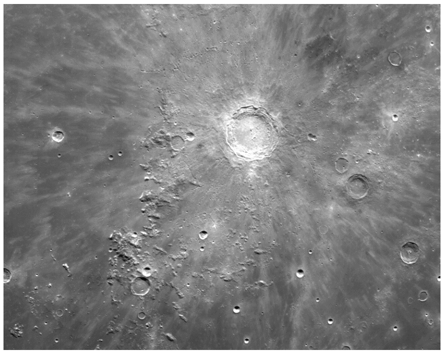

Figure 6. Lunar Surface Image.

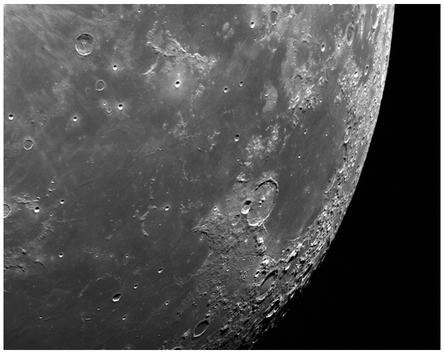

Figure 7. Lunar Surface Image.

under exposed. Based off the exposure status, the exposure for the next image was adjusted up or down until an ideal exposure was reached. Fig. 8 shows a sequence of Moon images as the exposure is being adjusted down.

Figure 8. Exposure Adjustment in Sequence of Moon Images.

To assess the performance of the image processing algorithms, OpNav measurements were compared against ground tracking data to determine measurement accuracy and then compared against the pre-flight predicted error models. Figs. 9 and 10 show the Moon measurement performance. The measurement is given as a range and bearing, however for ease of interpretation, the results are shown as radius and centroid, in pixels, overlaid with the 3-σ error models. Overall, the OpNav system performed very well. A detailed analysis of the OpNav performance can be found in [7].

Artemis II and Beyond. The success of the Artemis I mission led to the certification of the OpNav system to be used on future Artemis missions. The images gathered from the OpNav camera will be used to further improve the accuracy and robustness of the image processing algorithms. The Artemis II mission will continue to use OpNav in daily image gathering passes, and, if called upon, will use it as the primary source of navigation data in the event of a loss of communication with the ground.

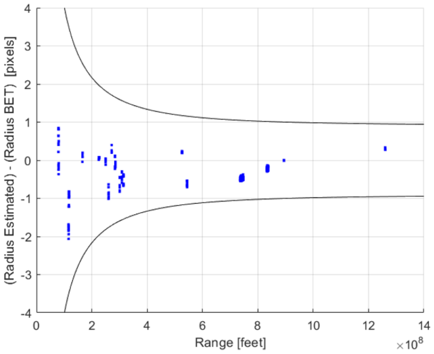

Figure 9. Moon Radius Residuals for All Passes.

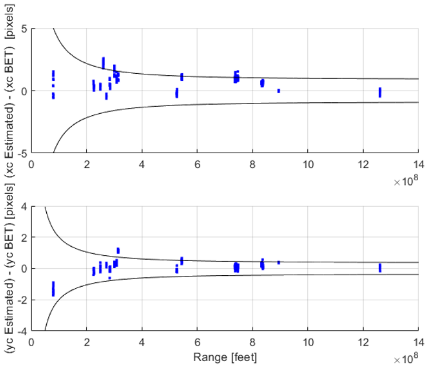

Figure 10. Moon Centroid Residuals for All Passes.

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