THE LUNAR FLASHLIGHT OPTICAL NAVIGATION EXPERIMENT

John A. Christian[1*], Ava Thrasher[1], Priyal Soni[1], Liam Smego[1], Reuben Isaac[1], Jennifer Nolan[1], Micah Pledger[1], E. Glenn Lightsey[1], and W. Jud Ready[2]; [1]Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, [2]Georgia Tech Research Institute (GTRI), Atlanta, GA. *john.a.christian@gatech.edu

Abstract. *The Lunar Flashlight (LF) spacecraft launched in December 2022 and entered heliocentric space after an Earth flyby in May 2023. One of the primary experiments during the heliocentric portion of the mission was the LF Optical Navigation Experiment with a Star tracker (LONEStar). Some key results of this experiment are summarized here.*

Introduction. Lunar Flashlight (LF) was a NASA-funded technology demonstration mission[1] intended to showcase new capabilities in the areas of CubeSat propulsion, computing, communication, and sensing. It had a secondary science objective of searching for water ice on the Moon.[2] While a propulsion system anomaly prevented the ultimate insertion into lunar orbit, all of the primary technology demonstration objectives were met. An Earth flyby in May 2023 caused the spacecraft to escape the Earth-Moon system and enter a heliocentric orbit. The primary LF mission was led by JPL---however, ownership of the spacecraft was transferred to Georgia Tech (GT) in August 2023 for a brief extended mission. One of the primary technical objectives of this extended mission was to demonstrate interplanetary optical navigation (OPNAV) through the LF Optical Navigation Experiment with a Star tracker (LONEStar). This abstract contains only a few highlights from LONEStar and the reader interested in greater detail is directed to Ref. [3].

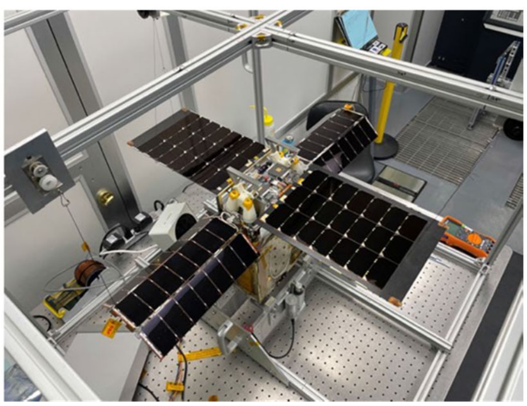

Figure 1. Lunar Flashlight spacecraft during integration and testing at Georgia Tech.[3]

Lunar Flashlight Overview. The LF spacecraft was a 6U CubeSat with deployable solar panels (see Fig. 1). The vehicle was assembled and integrated at GT and GTRI. After launch, all LF operations were conducted (mostly by students) out of a mission operations center (MOC) located on the GT campus.[4] Communication with LF was performed using the NASA Deep Space Network (DSN), with over 500 DSN contacts accomplished by the GT operations team. The mission was nominally navigated by LF team-members from JPL using radiometric observations from DSN. The JPL navigation team provided their final LF orbit determination (OD) solution in June 2023. This provided the reference trajectory used for comparison to LONEStar results during the August-December 2023 timeframe.[3,5]

LONEStar Overview. The LONEStar experiment consisted of three primary triangulation experiments, Earth-Moon observations, and an end-to-end OPNAV OD demonstration. The three separate triangulation experiments were: (1) instantaneous spacecraft localization by triangulation from two planets in the same image, (2) spacecraft localization by sequential imaging of planets in rapid succession, and (3) localization by sequential imaging of planets separated by many days. We now review some of the key findings from each of these experiments. Extensive discussion, tabulated data, plots, and other details are available in Ref. [3].

Experiment #1: Simultaneous Triangulation. During August 2023 a unique geometric configuration allowed for the simultaneous imaging of Mercury and Mars in a single image. This OPNAV imaging campaign was difficult because these two planets were well within the instrument's Sun keep out zone (KOZ). Although significant challenges with stray light were encountered (as was expected), the GT OPNAV team was able to successfully perform triangulation at six different imaging opportunities over a period of about 10 days. The OPNAV residuals ranged from about 10.5 Earth radii (best lighting) to about 295 Earth radii (worst lighting). This performance is quite good given (1) the distance to Mercury and Mars and (2) that the two planets were only separated by about 5 deg. There were no additional times during the LONEStar campaign where two planets were simultaneously visible.

Experiment #2: Rapid Sequential Triangulation. After completion of the simultaneous triangulation experiment, LONEStar activities turned to sequential triangulation with observations of Jupiter and Saturn. The spacecraft was commanded to view one planet and then slew to view the other planet. Time between sequential plant observations was as short as about 135 seconds. The relative brightness of Jupiter (and sometimes Saturn) required separate exposures for OPNAV observations and star observations. Using a midpoint triangulation algorithm, the GT OPNAV team produced instantaneous localization results with residuals of about 7-15 Earth radii (i.e., <0.02% range to Jupiter and <0.008% of the range to Saturn).

Experiment #3: Extended Sequential Triangulation. In many cases, it may not be convenient to quickly slew the spacecraft to view different celestial bodies for navigation. Therefore, using a subset of the data from Experiment #2, we were able to perform dynamic triangulation[6,7] with observations of Jupiter and Saturn separated by many days. This also allows for a method of performing initial orbit determination (IOD). Using this approach, with four observations (two of Jupiter, two of Saturn) no closer than 2.5 days from each other and over a total span of 13 days, the GT OPNAV team produced an IOD solution with residuals of about 22 Earth radii in position and 0.13 km/s in velocity.

Earth-Moon OPNAV. As the LF spacecraft departed the Earth-Moon system, the GT OPNAV team collected regular images of the Earth and Moon. These two bodies were always far enough away to be visible in the same image during the LONEStar campaign. We performed horizon-based OPNAV of the Earth.[8] Since the Moon was too small for horizon-based methods, we rendered a template of the Moon (assuming a lunar-Lambert sphere) and used normalized cross-correlation[9] to find the centroid. Triangulation with the Earth and the Moon produced instantaneous localization residuals of about 0.1-0.5 Earth radii for favorable geometry and up to about 5-8 Earth radii for unfavorable geometry.

OPNAV-Only Orbit Determination. The GT OPNAV team produced and OPNAV-only OD solution using the observations described above. No radiometric data was used at any point in production of these OD results. To begin, an IOD solution was produced using only observations of Jupiter and Saturn. Then, using this initial guess, we demonstrated precise orbit determination (POD) using only observations of the distant planets (Mars, Mercury, Jupiter, and Saturn). The dynamical model used for orbit propagation in the POD solution included both the gravitational attraction of the Sun and planets as well as solar radiation pressure. The POD solution using only distant planets produced position residuals (as compared to the JPL-produced radiometric solution) of about 9-10 Earth radii. If we then included observations of Earth and the Moon, the POD residuals fell to <0.5 Earth radii everywhere. These final residuals are on the order of uncertainty of the reference trajectory during the LONEStar campaign.

References.

[1] Cheek, N., Gonzalez, C., Adell, P., Baker, J., Ryan, C., Statham, S., Lightsey, E.G., Smith, C., Awald, C., and Ready, J., "Systems Integration and Test of the Lunar Flashlight Spacecraft," Small Satellite Conference, Paper SSC22-II-06, 2022.

[2] Cohen, B.A., Hayne, P.O., Greenhagen, B., Paige, D.A., Seybold, C., and Baker, J., "Lunar Flashlight: Illuminating the Lunar South Pole," IEEE Aerospace & Electronic Systems Magazine, Vol. 35, No. 3, 2020, pp. 46-52. https://doi.org/10.1109/MAES.2019.2950746

[3] Krause, M., Thrasher, A., Soni, P., Smego, L., Isaac, R., Nolan, J., Pledger, M., Lightsey, E.G., and Ready, W.J., "LONEStar: The Lunar Flashlight Optical Navigation Experiment," *The Journal of the Astronautical Sciences*, Vol. 71, 2024.

[4] Starr, M., Hauge, M., and Lightsey, E.G., "Shining a Light on Student-Led Mission Operations: Lessons Learned from the Lunar Flashlight Project," AIAA SciTech, 2024.

[5] Cox, A., Kangas, J., and Demcak, S., "Final LFL extended trajectory delivery form the JPL Navigation Team," Navigation File Release Form, Jet Propulsion Laboratory, 2023.

[6] Henry, S., and Christian, J.A., "Absolute Triangulation Algorithms for Space Exploration," *Journal of Guidance, Control, and Dynamics*, Vol. 46, No. 1, 2023, pp. 21-46.

[7] Smego, L., and Christian, J.A., "Dynamic Triangulation for Cislunar Initial Orbit Determination," *AAS/AIAA Astrodynamics Specialist Conference*, 2024.

[8] Christian, J.A., "A Tutorial on Horizon-Based Optical Navigation and Attitude Determination with Space Imaging Systems," *IEEE Access*, Vol. 9, 2021, pp. 19819-19853.

[9] Lewis, J. P. "Fast Normalized Cross-Correlation." Industrial Light & Magic, 1995.