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The Lumio Radio Science Experiment

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1. Introduction

The European Space Agency mission LUMIO (Lunar Meteoroid Impacts Observer) aims to characterize the lunar and near-Earth meteoroid environment by imaging impact flashes on the far side of the Moon [1]. During its 1-year operative phase along a quasi-periodic Halo orbit about the Earth-Moon Lagrangian point L2, LUMIO will observe the lunar far-side while keeping its line-of-sight to the Earth unobstructed.

With this geometry, the LUMIO spacecraft may be the first miniaturized satellite to exploit its radio communication system to carry out bistatic radar (BSR) observations of the near-limb regions of the Moon, which may help characterize the surface roughness and dielectric constant around recent impact sites [2].

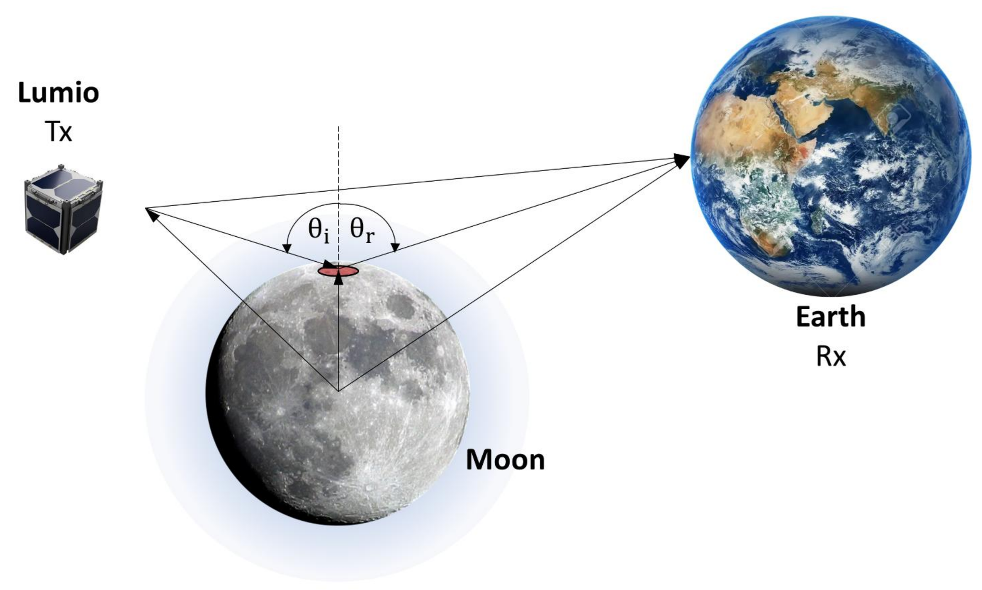
Furthermore, high-frequency VIS-NIR images collected by the LUMIO-Cam during science operations represent an opportunity for testing innovative orbit determination techniques such as using precise timing of stellar occultations to complement ground-based radiometric measurements. Stellar occultation measurements are expected to improve the navigation accuracy during science observation windows [3,4], aiding in absolute positioning of the impact sites and reducing the reliance on ground tracking.

2. Lumio RSE objectives

1. **Technology demonstration**
   - Orbit determination tests using far-side and near-side images.
   - Testing open-loop capabilities of ASI's 64 m Sardinia Deep Space Antenna;
2. **Bistatic radar**
   - Context: Halo orbit allows for downlink bistatic observations of the near-limb surface.
   - Motivation: specular reflection may help constrain the surface roughness (cm/m level), near-surface composition, and porosity.
3. **Radio Occultations**
   - Context: the Moon has a thin and highly variable ionosphere (up to $10^{-3}\ e/cm^{-3}$).
   - Motivation: characterize electron density and its correlation with local events.

3. Bistatic radar and radio occultations

Figure 1: Schematic representation of the Lumio bistatic radar experiment in downlink configuration



Assumptions

- Downlink geometry
- Spherical Moon with dielectric constant $\varepsilon = 3$ [5]
- Omnidirectional s/c antenna with transmitted power of 3.8 W
- Unmodelled losses due to small scale roughness $A_r = 1$
- X-band ($\lambda = 3.6\ cm$)
- 34 m DSN receiving antenna

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi)^3 T^2 R^2} \cdot \sigma_{pl} \cdot \Gamma(\theta, \varepsilon) \cdot A_r$$

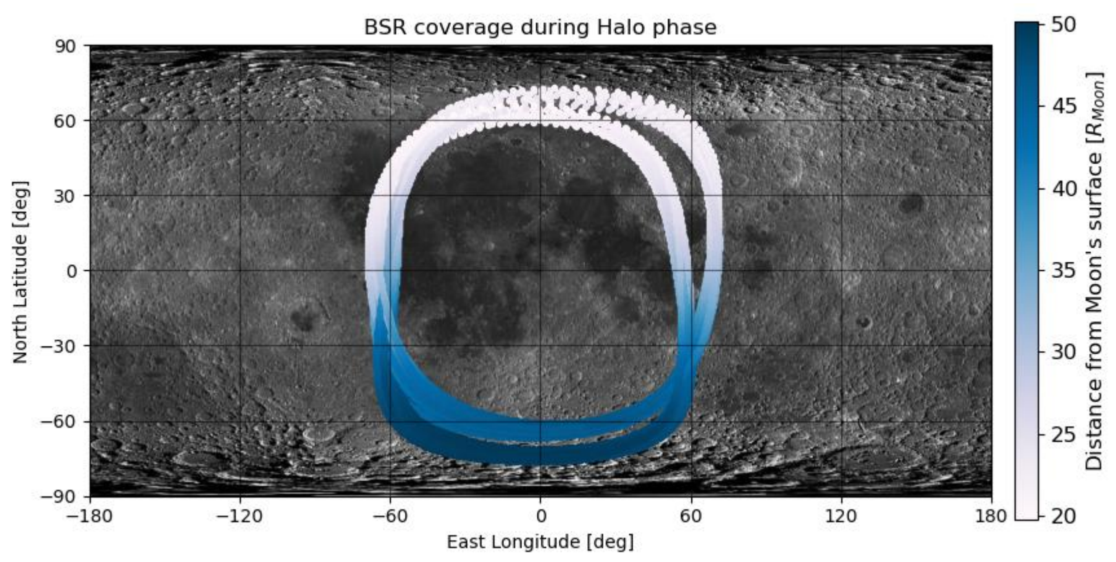


Figure 2 Bistatic radar coverage from May 2027 to August 2028 (Halo phase); color-code shows the LUMIO to specular point distance

Figure 2 shows the BSR coverage, which is limited to the Earth-facing side of the Moon. Due to the spacecraft proximity, the most promising targets are in the Northern hemisphere.

Incidence angles of observation range between 62° and 70° throughout the whole Halo phase, hence the SC component of the reflection is expected to be dominant. Thanks to the redundant geometry, the preliminary link budget identified several 80-hour periodic windows where $P_R/N_0 > 18\ dB/Hz$ in both same sense and opposite sense circular polarizations. The inclusion of small-scale roughness, antenna elevation, and considerations regarding the differential Doppler shift between direct and scattered paths could reduce the favorable observation windows; however, detection of significant echoes is still expected. Conversely, the current CONOPS does not allow for radio occultations of the near surface, as the signal path distance during the Hale phase is $> 5R_M$, which is much higher than the expected ionosphere thickness of 100 km.

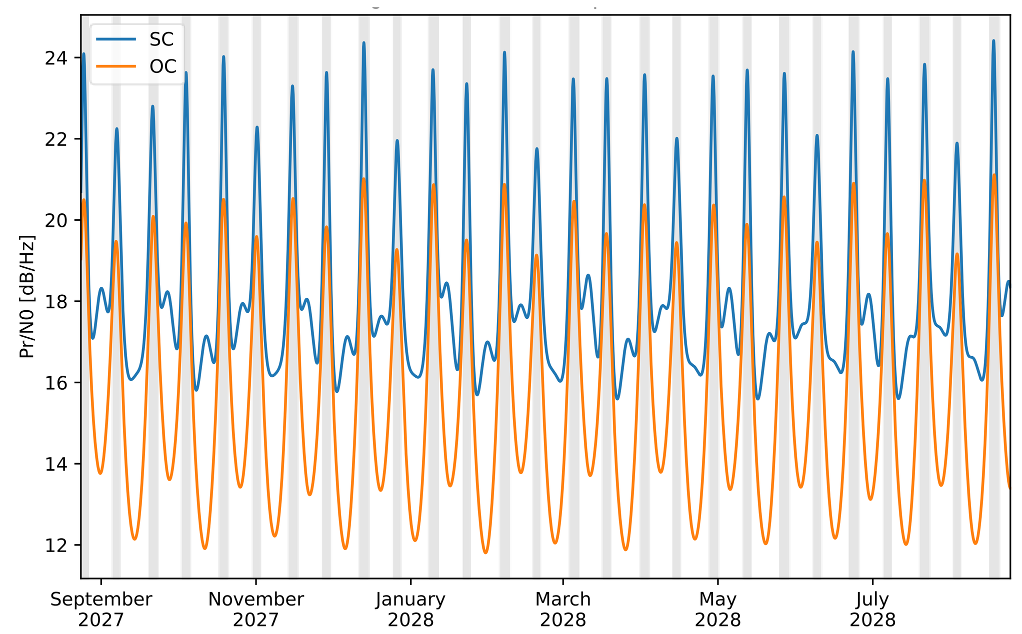


Figure 3 Link Budget for the Lumio downlink BSR experiments for the whole Halo phase. Areas highlighted in light grey are areas where the P_R/N_0 is above 18 dB/Hz in both polarizations. SC refers to same sense of transmission, and OC indicates the orthogonal sense with respect to transmission.

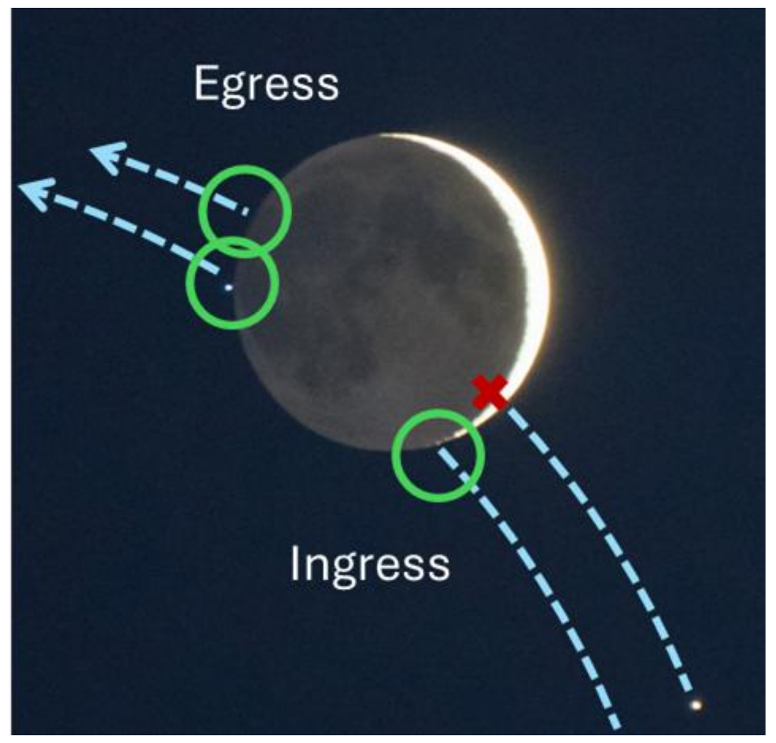
4. Orbit determination using stellar occultations

The LUMIO orbit determination performance is assessed through a multi-arc covariance analysis using JPL's MONTE s/w [6]. Formal position and velocity uncertainties are evaluated for each science arc in two scenarios:

- ***Radiometric only***: simulated observables include two-way range and Doppler at X-band between LUMIO and the ESTRACK ground stations, assuming a 3-hour coverage at the beginning and end of each science cycle and a 2-hour coverage in the middle (> 1 track per week and total tracking time of 8 h every 15 days)
- ***+Occultations***: adding precise time of stellar occultations behind the Moon's disk to the radiometric measurements and assuming a conservative noise of 1 s to account for the LUMIO-Cam sampling rate (66 ms), the onboard clock jitter, and optics diffraction.

For the trajectory propagation, we considered: relativistic point-mass gravity from the Sun, the Solar System planets, and their moons; spherical harmonics up to the degree and order 20 for the Earth and the Moon (respectively GL0660B and EIGEN-GL04C models); solar radiation pressure using a standard flat-plate model for a 12U Cube-Sat with deployed solar panels; stochastic non-gravitational accelerations acting in the spacecraft body axes at 8-hour interval batches (to simulate the unmodeled dynamics).

Figure 4: Schematic representation of stellar occultation events as seen from the LUMIO-Cam. Blue line: apparent star motion; red: discarded events; green: processed events (only events occurring in the shadowed portion of the Moon's disk are used within the covariance analysis).



Assumptions

- Stellar catalog UCACT-PI (merges UCAC2 and Tycho-2 with parallax from Hipparcos;
- Stars with visual magnitude > 6
- Earth/Sun separation > 17.5° from camera boresight (stray light)
- Occultations occurring on the Sun side of the terminator plane are removed anticipating pixel saturation.

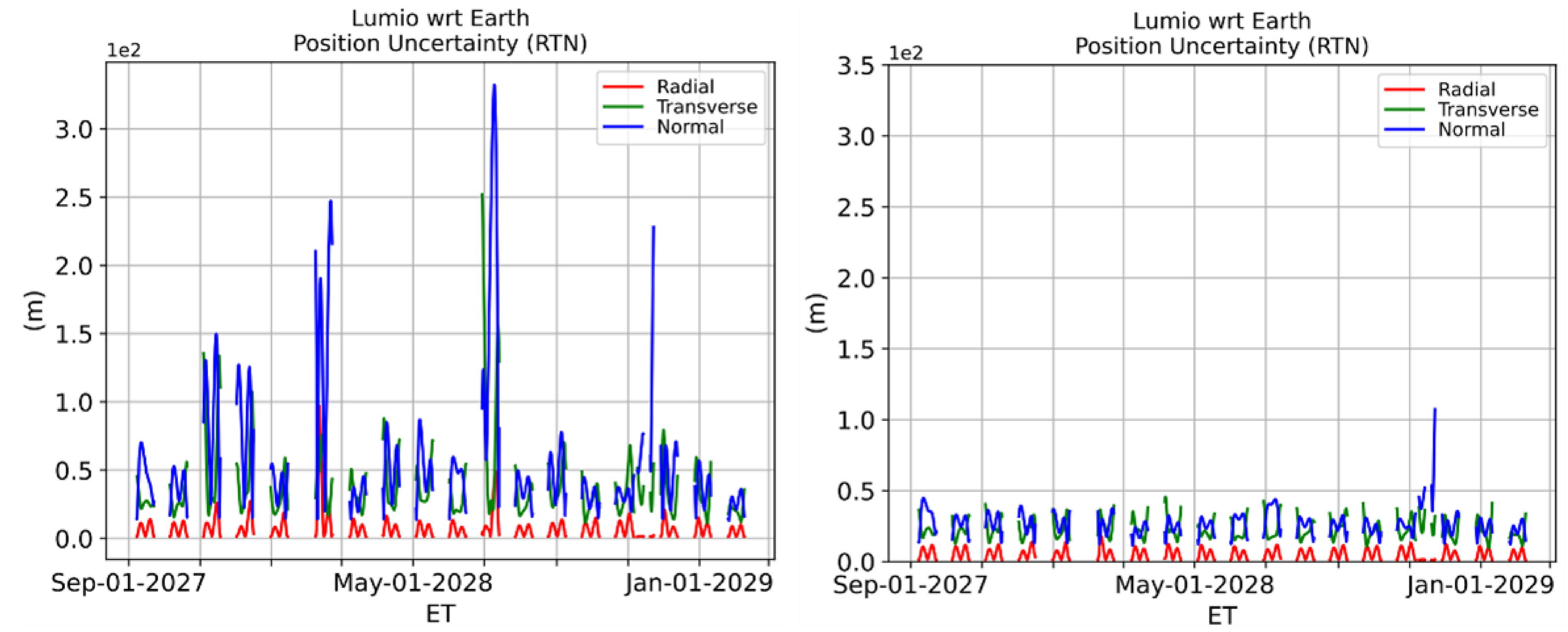
Preliminary results indicate that occultations may significantly lower the spacecraft positions uncertainty obtained with only radiometric observables. The more significant improvement is obtained in the transverse and normal coordinates, with average uncertainty reductions of 40% and 55% respectively, as shown in Table 1 and Figure 5.

The radial uncertainty is the most accurate one thanks to the line-of-sight information content provided by the Doppler and range data and has a relative improvement of 33%.

Table 1: Average position uncertainty (1σ) during the science phase.

Radial			Transverse			Normal		
Radiom.	+Occult.	Ratio	Radiom.	+Occult.	Ratio	Radiom.	+Occult.	Ratio
9.08 m	6.07 m	0.67	37.78 m	22.54 m	0.60	60.0 m	27.22 m	0.45

Figure 5: Estimated LUMIO position uncertainty during science cycles in the radial, transverse, and normal reference frame with respect to the Earth. Left: scenario with only radiometric data; right: scenario with radiometric data and stellar occultation measurements.



5. Conclusions and future work

This work has outlined the proposed LUMIO Radio Science Experiment, its main objectives, and expected performances, highlighting the potential of bistatic radar observations and stellar occultations to enhance the characterization of lunar impact flashes.

Future work will focus on consolidating the operational pipeline and selectin potential observation targets.

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References

[1] A. Cervone, F. Topputo,, et al., "LUMIO: A CubeSat for observing and characterizing micro-meteoroid impacts on the lunar far side," Acta Astronautica, Vol. 195, 2022, pp. 309–317.

[2] Simpson, R. A. (1993). Spacecraft studies of planetary surfaces using bistatic radar. IEEE Transactions on Geoscience and Remote Sensing, 31(2), 465-482.

[3] M. Psiaki and J. Hinks, "Autonomous lunar orbit determination using star occultation measurements," AIAA Guidance, Navigation and Control Conference and Exhibit, 2007, p. 6657.

[4] M. Landgraf, G. Thiele, D. Koschny, and B. Udrea, "Optical navigation for lunar exploration missions," 57th International Astronautical Congress, 2006, pp. C1–7

[5] Tyler, G. L. (1968). Oblique-scattering radar reflectivity of the lunar surface: Preliminary results from Explorer 35. Journal of Geophysical Research, 73(24), 7609-7620.

[6] Evans, S., et al. (2018). MONTE: the next generation of mission design and navigation software. CEAS Space Journal, 10(1), 79–86.

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