**LUMIO CUBESAT: A MISSION TO REFINE METEOROID POPULATION KNOWLEDGE**

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**Introduction:** Vast amounts of meteoroids and micrometeoroids continuously enter the Earth–Moon system and consequently become a potential threat [1]. Lunar meteoroid impacts have caused a substantial change in the lunar surface and its properties. The Moon having no atmospheric blanket to protect itself, it is subjected to impacts from meteoroids ranging from a few kilograms to 10's of grams each day. The high impact rate on the lunar surface has important implications for future human and robotic assets that will inhabit the Moon for significant periods of time [2, 3]. Therefore, a greater understanding of the meteoroid population in the cislunar environment is required for future exploration of the Moon.

Moreover, refining current meteoroid models is of paramount importance for many applications. For instance, since meteoroids may travel dispersed along the orbit of their parent body, understanding meteoroids and associated phenomena can be valuable for the study of asteroids and comets themselves. Studying meteoroid impacts can help deepening the understanding of the spatial distribution of near-Earth objects in the Solar system. The study of dust particles can be also of interest because, together with the solar wind, they determine the space weather. Finally, it is critical to be able to predict impacts by relying on accurate impact flux models. That because the impact of small asteroids with Earth, even slightly larger than meteoroids, can cause severe damage.

In this context, the Lunar Meteoroid Impacts Observer (LUMIO) is a CubeSat mission to observe, quantify, and characterise the meteoroid impacts by detecting their flashes on the lunar far-side. This complements the knowledge gathered by Earth-based observations of the lunar nearside, thus synthesising a global information on the lunar meteoroid environment. LUMIO envisages a 12U CubeSat form-factor placed in a halo orbit at Earth-Moon L2 [4]. The mission employs the LUMIO-Cam, an optical instrument capable of detecting light flashes in the visible spectrum [5]. LUMIO is one of the two winner of ESA's LUCE (Lunar CubeSat for Exploration) SysNova competition, and as such it is being considered by ESA for implementation in the near future. The Phase A study has been conducted in 2020 under ESA GSTP contract, after a successful, independent mission assessment performed by ESA's CDF team. The consortium of the Phase A design is formed by Politecnico di Milano, Leonardo S.p.a., ISISPACE, Delft University of Technology, and S[&]T Norway.

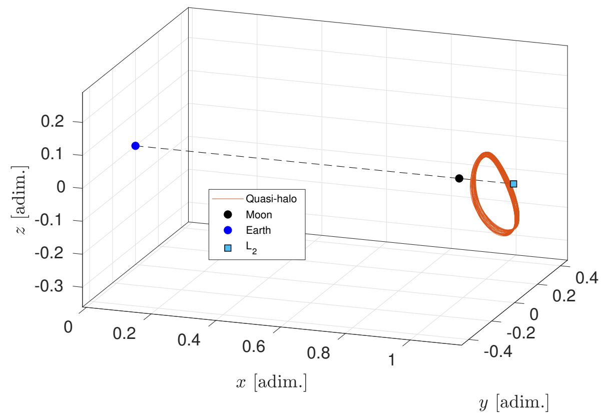



**Figure 1: Selected operative Earth–Moon $L_2$ quasi-halo orbit in the Earth–Moon synodic frame.**

In this work, an overview of the present-day LUMIO CubeSat Phase A design will be given, with a focus on the concept of operations and the predicted scientific output of the mission.

**Mission overview:** The mission utilises a 12U form-factor CubeSat which carries the LUMIO-Cam, an optical instrument capable of detecting light flashes in the visible spectrum to continuously monitor and process the data. The mission implements a novel orbit design and latest CubeSat technologies to serve as a pioneer in demonstrating how CubeSats can become a viable tool for deep space science and exploration. The selected operative Earth–Moon $L_2$ quasi-halo orbit of LUMIO expressed in the Earth–Moon synodic frame is shown in Figure 1 [4].

In the circular restricted three-body problem (CRTBP), the libration points are at rest with respect to a frame co-rotating with the smaller and larger primaries. Consequently, a halo orbiting the Earth–Moon $L_2$ always faces the lunar farside, see

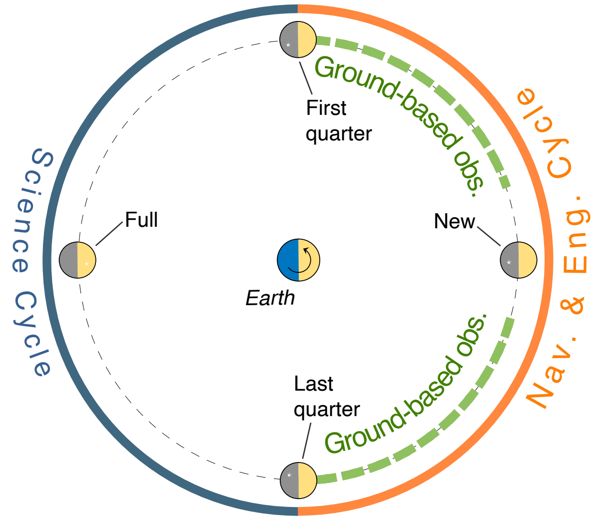
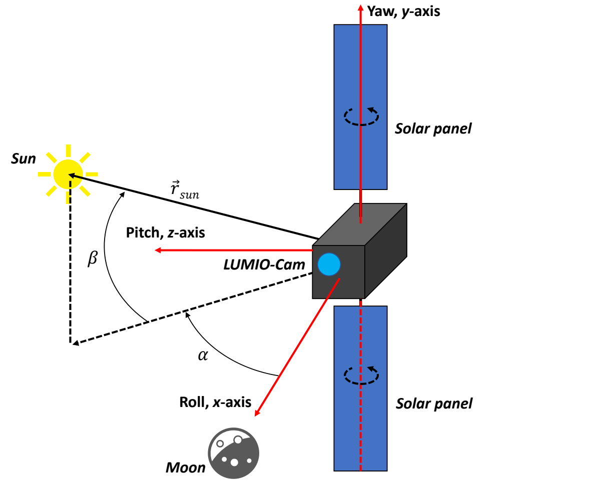
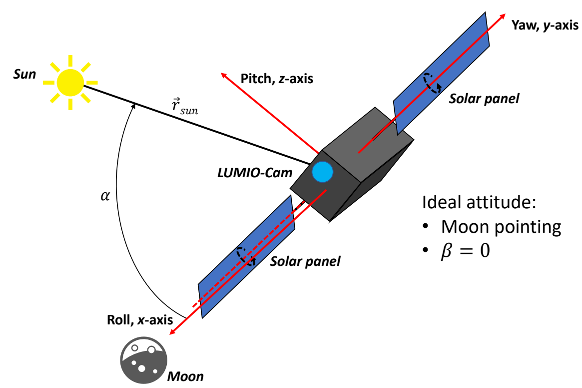



**Figure 2: LUMIO Concept of Operations.**




**(a) LUMIO body-fixed frame.**




**(b) Science cycle pointing profile.**

**Figure 3: a) LUMIO body-fixed frame. b) LUMIO pointing profile during Science cycle.**

Figure 1. On top of this, for a wide range of Jacobi energies, Earth–Moon $L_2$ halos are almost locked into a $2{:}1$ resonance, that is $2$ orbital revolutions in $1$ synodic period, $T_{\rm syn} = 29.4873$ days. The quasi resonance locking, enables LUMIO operations to be steady, repetitive, and regular.

Within the Operative Phase, each synodic month LUMIO moves along a) a *Science orbit* (blue solid line in Figure 2) during the Science cycle and b) a *Navigation and Engineering orbit* (orange solid line in Figure 2) during the Nav&Eng cycle. During the Science cycle, lasting approximately $14$ days, the Moon farside has optimal illumination conditions to perform flash observations (i.e., at least half lunar disk is dark). On the other hand, during the Nav&Eng the Moon farside illumination conditions are apt to optical navigation experiment routines. In this way, LUMIO concept of operation is tight to both resonance mechanisms and illumination conditions to properly enable scientific or other operations.

The period of the refined quasi-halo in the solar system model does not match the constant orbital period of its CRTBP counterpart, neither it matches the synodic period of the Earth–Moon system with respect to the Sun. Thus, the spacecraft orbiting the quasi-halo is not locked in a $2{:}1$ resonance mechanism, rather it oscillates with varying amplitude around a nominal value. In the real-life application the spacecraft would have to switch between Science and Nav&Eng cycles based on in-flight requirements and feasibility of operations. For example, during the Science cycle, the spacecraft shall observe the lunar surface with the optical payload to meet the mission scientific goals and requirements.

The pointing profile is different for the Science cycle and for the Nav&Eng cycle. During the Science cycle, the roll axis points toward the centre of the Moon, while the remaining degree of freedom is exploited to maximize the power generation. The roll ($x$-axis), yaw ($y$-axis), and pitch ($z$-axis) axes are defined in the schematic representation of Figure 3. During the Nav&Eng cycle, the pointing profile varies depending on the operation to accomplish. For instance, when performing a station keeping manoeuvre the pointing profile has to grant the proper alignment of the thrusters.

**Scientific Output:** The LUMIO scientific output estimation of the Phase A design is herein presented. Our approach relies on a combined modelling and simulation of LUMIO's Payload, Orbit,

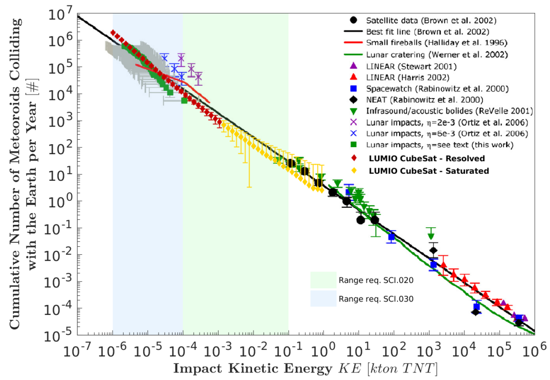



**Figure 4: Comparison of the estimated LUMIO lunar CubeSat scientific return with the scientific return of previous programmes. Note that some points do not have the bottom bar because they reach negative values and the plot is in logarithmic scale. Logarithmic scale plot. Data for comparison taken from [3].**

and Environment (POE) [5, 6, 7, 8, 9]. The LUMIO-POE tool has been developed in order to conduct preliminary parametric analyses, which feed back the design of both the payload and the mission operative orbit. A Monte Carlo analysis was carried out with LUMIO-POE. The operational orbit considered was the *quasi-halo* about Earth-Moon $L_2$ Lagrangian Point previously shown. Note that the sequence of Science and Nav&Eng cycles discussed as concept of operations has been taken into account. The current nominal design of the LUMIO-Cam has been used in the simulation. Results are shown in Figure 4, where the estimated scientific return of the LUMIO lunar CubeSat is compared with the one of previous programmes. In the plot, red diamonds mark the resolved impacts while yellow diamonds represent impacts which saturate at least one of the two LUMIO-Cam detectors.

**Conclusion:** LUMIO lunar CubeSat is one of the two winner of ESA's LUCE (Lunar CubeSat for Exploration) SysNova competition, the Phase A study LUMIO has been conducted during 2020 and completed successfully in the beginning of 2021. LUMIO is a 12U CubeSat equipped with the LUMIO-Cam, an optical instrument capable of detecting impact flashes to continuously monitor and process the data. The mission implements a sophisticated transfer phase and orbit design, and will make use of the most advanced COTS CubeSat technology to serve as a demonstrator for the use of CubeSats as viable, low-cost platform for interplanetary science and exploration missions. In this paper, an overview of the mission, the concept of operations, and a prediction of the outcome of the LUMIO lunar CubeSat have been presented and discussed.

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**References:** [1] Z. Ceplecha, et al. (1998) *Space Science Reviews* 84(3-4):327 doi. [2] J. Oberst, et al. (2012) *Planetary and Space Science* 74(1):179 doi. [3] R. M. Suggs, et al. (2014) *Icarus* 238:23 doi. [4] A. M. Cipriano, et al. (2018) *Frontiers in Astronomy and Space Sciences* 5:29 doi. [5] F. Topputo, et al. (2017) Lunar meteoroid impacts observer (phase 0) Final Report, ESA SysNova Competition for Innovation No. 4, Lunar CubeSat for Exploration (LUCE), ESA ITT AO/1-8643/16/NL/GLC/as. [6] G. Merisio (2019) *Payload, Orbit, and Environment Simulation for LUMIO Mission Coverage Analysis (MSc Thesis)* Politecnico di Milano, Milan, Italy. [7] J. M. Madiedo, et al. (2015) *Planetary and Space Science* 111:105 doi. [8] A. Z. Bonanos, et al. (2018) *Astronomy & Astrophysics* 612:A76 doi. [9] S. Bouley, et al. (2012) *Icarus* 218(1):115 ISSN 0019-1035 doi. [10] J. M. Madiedo, et al. (2015) *Astronomy & Astrophysics* 577:A118 doi. [11] C. H. Acton Jr (1996) *Planetary and Space Science* 44(1):65 doi. [12] P. Brown, et al. (2010) *Icarus* 207(1):66 doi. [13] J. L. Ortiz, et al. (2006) *Icarus* 184(2):319 doi. [14] D. Koschny, et al. (2009) *Meteoritics and Planetary Science* 44(12):1871 doi. [15] L. R. Bellot Rubio, et al. (2000) *The Astrophysical Journal Letters* 542(1):L65 doi. [16] R. M. Suggs, et al. (2017) *Planetary and Space Science* 143:225 doi. [17] R. Walker, et al. (2018) Lumio cdf study final report, ref. cdf-r-36, february 2018.