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LUMIO: A CubeSat to Monitor Micro-meteroid Impacts on the Lunar Farside

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Abstract—**The Lunar Meteoroid Impact Observer (LUMIO) is a CubeSat mission at the Earth-Moon Lagrangian point 2 (L_2) designed to observe, quantify, and characterize the meteoroid impacts by detecting their flashes on the Lunar farside. LUMIO can be deployed as one of the payloads in the NASA Commercial Lunar Payload System or from Artemis-2 mission to a low Lunar orbit and to demonstrate autonomous navigation capabilities to reach its operational orbit around the Earth-Moon L_2. From there, its scientific mission to map and investigate the spatial and temporal characteristics of meteoroids impacting the Lunar surface will start and is expected to last for one year. LUMIO is a 12U CubeSat including a dedicated camera to monitor impact flashes in the visible and near-infrared spectrum, and also allows estimating the impact of temperature and energy. Optical navigation using the payload camera will also demonstrate increased on-board autonomy and drastically reduced mission costs. Navigation validation will be carried out using standard ground-based radiometric techniques enabled by a miniaturized X-band coherent transponder on-board. LUMIO can also use an inter-satellite link for telemetry and control via a commercial Lunar data relay system, providing a redundant communication system and lowering the need for high-gain ground stations for routine operations. The satellite bus derives from a commercial version designed for Low Earth Orbit and it will feature several improvements to operate in the Lunar environment, including a more advanced thermal control and radiation shielding. Commercial Off-The-Shelf systems will require a radiation screening and this will contribute to maintain the mission budget low and aim at a launch date in 2024.**

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1. INTRODUCTION

The Lunar Meteoroid Impact Observer (LUMIO) is a 12U CubeSat mission to a halo orbit at the Earth–Moon L_2 that shall observe, quantify, and characterize meteoroid impacts on the Lunar farside by detecting their flashes. These observations can complement Earth-based observations on the Lunar nearside, providing global information on the Lunar Meteoroid Environment and contribute to Lunar Situational Awareness.

LUMIO was one of the proposals submitted to the European Space Agency (ESA) LUnar CubeSats for Exploration (LUCE) call. SysNova is intended to generate new and innovative concepts and to verify quickly their usefulness and feasibility via short concurrent studies [1]. LUMIO was selected as one of the four concurrent studies run by ESA, winning the challenge together with another study. The prize for the challenge was an independent assessment conducted at ESA's Concurrent Design Facility (CDF) to prove the feasibility and the scientific value of the mission [2], further maturing system design and increasing the chances for the mission to be selected at a future selection. Details on this Phase-0 study have been provided in numerous publications and presentations [3–5]. The LUMIO Phase A study, funded by ESA under the General Support Technology Programme (GSTP), through the support of the nItalian Space Agency (ASI), the Netherlands Space Office (NSO) and the Norwegian Space Agency (NOSA), has been kicked off in March 2020 and has been completed in March 2021. Further details on the initial results can be found in [6], while the final design is illustrated in detail in [7].

This paper will discuss in detail the current design of LUMIO subsystems. In Section 2, mission description is shown including mission phases, operative orbit and Δv budgets. In Section 3, the spacecraft subsystems are presented including payload, Attitude control, Propulsion, Communications, Data Handling, Power generation, and Thermal Control subsystems. Lastly, conclusions can be found in Section 4.

2. MISSION ANALYSIS AND PHASES

The LUMIO mission to addressed the following issues:

- **Science Question:** What are the spatial and temporal characteristics of meteoroids impacting the Lunar surface?
- **Science Goal:** Advance the understanding of how meteoroids evolve in the cislunar space by observing the flashes produced by their impacts on the Lunar surface.
- **Science Objective:** Characterize the flux of meteoroids impacting the Lunar surface.

Figure 1 shows a simplified mission profile, divided onto the following phases:

Earth-Moon transfer: After launch, LUMIO is carried inside its mothership to a Lunar parking orbit. During the transfer the spacecraft is switched off inside its deployer and the batteries are kept charged by a power connection with the mothership.

Parking: LUMIO is released in its Lunar parking orbit by the mothership. After achieving an operational attitude (detumbling) and deployment of the solar arrays, the payload and all subsystems are commissioned. The spacecraft communicates with the Earth to determine its orbit and receive telecommands. LUMIO stays in the parking orbit and, when necessary, performs station keeping and wheel desaturation maneuvers.

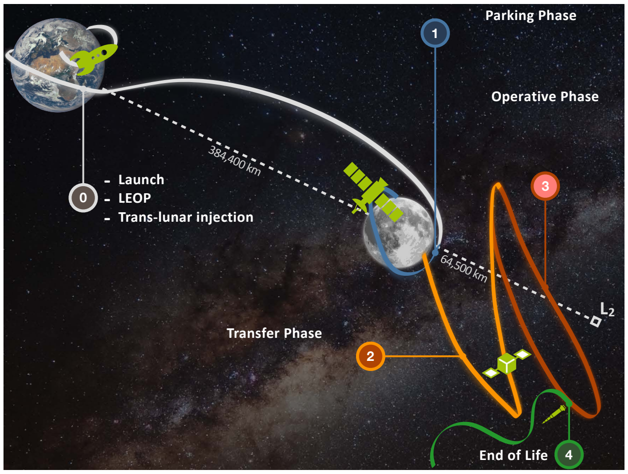

Figure 1. Mission timeline.

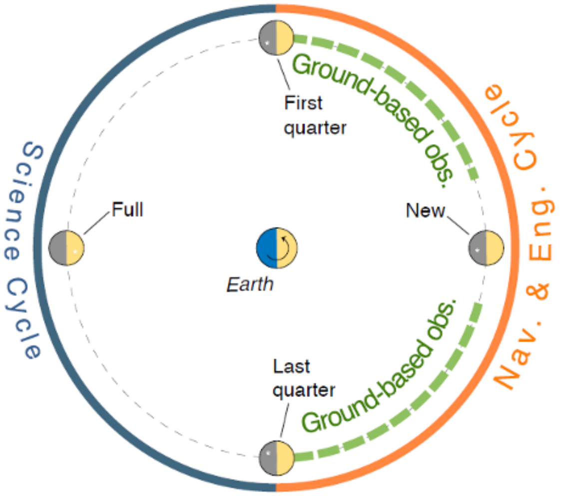

Figure 2. Operative orbit concept of Operations.

Transfer: LUMIO autonomously transfers from the Lunar parking orbit to the final operative orbit. The transfer is performed by a Stable Manifold Injection Manoeuvres (SMIM), two Trajectory Correction Manoeuvres (TCM), and a Halo Injection Manoeuvres (HIM). Also, during this phase, the spacecraft will be able to communicate with the ground, in order to determine its state and perform the flight dynamics tasks.

Operational phase: In this phase, expected to last at least one year, LUMIO accomplishes its scientific objectives. The phase is divided in two sub-phases: the science cycle (blue solid line in Figure 2) and the navigation and engineering cycle (orange solid line in Figure 2). During the science cycle, lasting approximately 14 days, the Moon farside has optimal illumination conditions to perform impact flash observations. In this cycle, scientific data (images) are continuously acquired, processed and compressed while during the navigation and engineering cycle (also lasting approximately 14 days), orbit determination, station keeping and data downlink to Earth are performed.

End-of-Life: This phase puts the spacecraft in safe conditions for other spacecraft which may come in contact with it: the end-of-life maneuvers will be performed to bring the spacecraft into an orbit limiting collision risks and then all spacecraft subsystems will be passivated and de-activated.

The quasi-periodic halo orbit (sometimes referred here as quasi-halo orbit) about Earth–Moon Lagrangian point 2 (L_2) is designated as the operative orbit. This resulted from a thorough trade-off analysis among a set of fourteen quasi-halos orbits computed in the high-fidelity Roto-Pulsating Restricted n-Body Problem (RPRnBP) [8]. The trajectory of the selected orbit is shown in Figure 3 and 4.

The mission Δv budget is presented in Table 1 for the Artemis-2 launch opportunity considering an optimized transfer strategy from the corresponding release orbit. It also includes a set of deterministic and stochastic maneuvers. The optimized Δv budget for the Commercial Lunar Payload Services (CLPS) launch opportunity is significantly lower (119.5 m/s including margins, as opposed to the 201.8 m/s of the Artemis-2 case) mainly because of its significantly less demanding SMIM maneuver. For further details on the Δv

Table 1. ΔV budget for LUMIO [9].

Maneuver	Deterministic, m/s	Stochastic, 3σ, m/s	Margin
Delta-V	8.31		5%
SMIM	129.21		5%
TCM		18	100%
HIM	12.21		5%
1-year S/K		4.34	5%
Disposal	2		100%
Total (without margins)			174.07 m/s
Total (with margins)			201.78 m/s

budgets, please refer to [9].

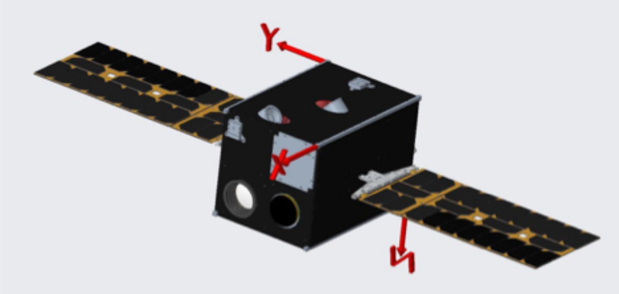

Figure 5. Satellite rendering.

3. SPACECRAFT DESIGN

After a few iterations from the previous phases, the current design of the spacecraft, with the spacecraft mass (including safety margins) being 28.69 kg, is reached and it can be seen by the rendering in Figure 5. The two internal configuration overviews are shown in the Figure 6 and 7 [7].

The following summarize the spacecraft subsystems design.

Payload (LUMIO-CAM)

LUMIO-CAM is a compact imager that will observe, quantify and characterize meteoroid impacts on the Lunar far side by detecting their impact flashes. The instrument, for which a rendering can be seen in Figure 8, has been designed to operate in the bandwidth between $450\,\mathrm{nm}$ and $950\,\mathrm{nm}$, implementing a double focal plane assembly configuration. The instrument architecture is composed of three main parts: one optical head, two focal plane assemblies and the proximity electronic. The optical head includes an optical barrel, a dioptric objective composed of five lenses, with a focal length of 127 mm, a field-of-view of $\pm 3°$, and a $150\,\mathrm{mm}$ baffle to limit the influence of stray light during payload operations coming from the Sun and from the Earth. The baffle has been developed to fully fit inside the satellite volume. The focal plane assembly includes the two detectors and their Thermo-Electric Cooler: two identical 1024×1024 Charge-Coupled Device (CCD) detectors are positioned after a dichroic cube to split the incoming light on two separate bands: this solution has been selected to estimate the flash temperature. The Proximity Electronic generates the two detectors scanning and acquisition digital signals and manages the acquisitions of the housekeeping parameters.

Attitude Determination and Control System

The ADCS design is of crucial importance in the mission to guarantee Moon pointing for the science requirements, antennas pointing towards the Earth and the Moon, along

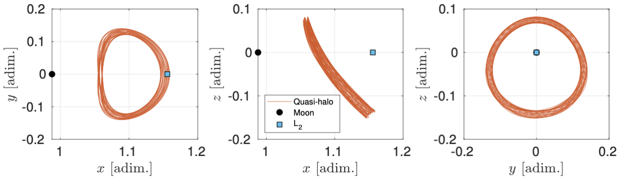

Figure 3. Projection of the selected operative Earth–Moon L_2 quasi-halo in the Roto-Pulsating Frame. Dimensions are provided relative to the average Earth-Moon distance.

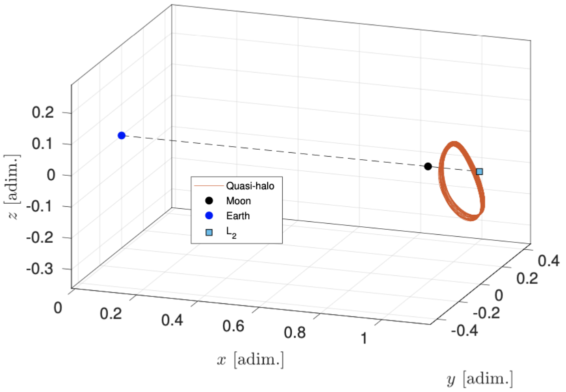

Figure 4. Selected operative Earth-Moon L_2 quasi-halo orbit in the Earth–Moon synodic frame. Dimensions are provided relative to the average Earth-Moon distance.

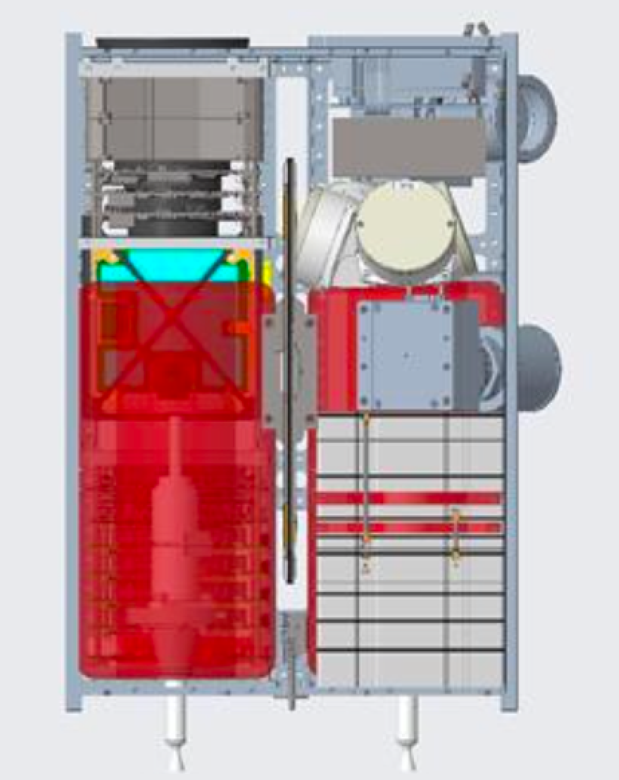

Figure 6. Internal view, -Y

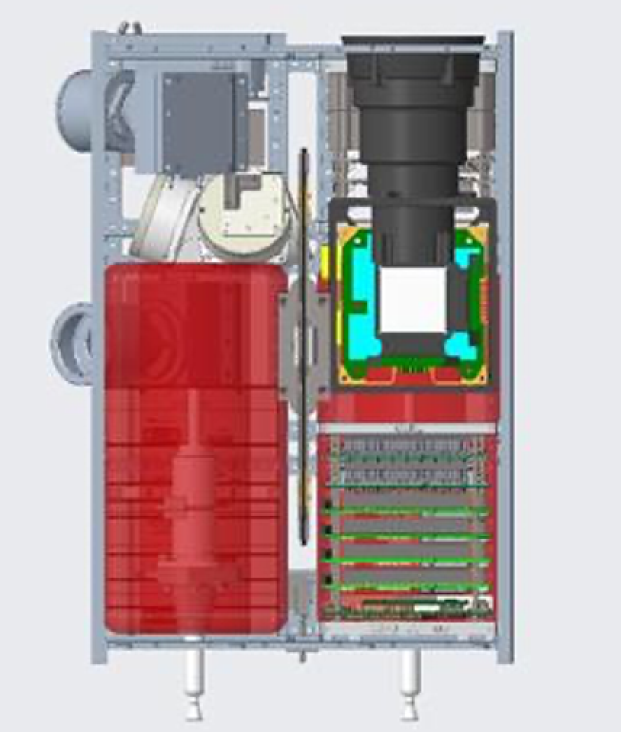

Figure 7. Internal view, +Y

with the need to maximize the power generation by pointing the solar panels towards the Sun. The same attitude strategy proposed in [6] has been maintained. The operational attitude requires the roll axis to be oriented towards the Moon and the pitch axis lying on the CubeSat-Moon-Sun plane. The yaw axis completes the ortho-normal frame. Please refer to Figure 9 for further details on the attitude in the different modes of operations.

The selected sensor suite is composed by six fine Sun sensors (one per CubeSat face, provided by Lens R&D), two star trackers (AURIGA, made by Sodern), and one Inertial Measurement Unit (IMU) (SCG, produced by ISISpace). The actuators for the ADCS comprise four reaction wheels (RW25 SW50, produced by ISISpace), and one Reaction Control System (RCS), explained more in details in Section 3. Further details can be found in [7].

Propulsion

The propulsion system design is also of crucial importance for the success of the LUMIO mission [9]. It accomplishes various functions: orbital transfer from the initial Lunar orbit to the final halo orbit around L_2, station keeping, reaction wheel desaturation, end of life disposal maneuvers.

Figure 8. The LUMIO-CAM [7].

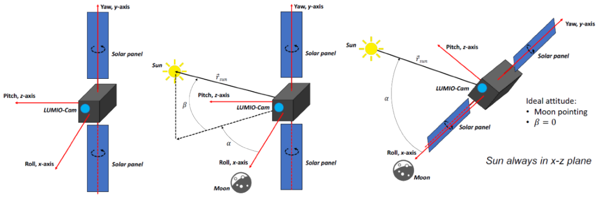

Figure 9. LUMIO reference attitudes, from left to right: body-fixed frame, roll axis pointing to the Moon, science cycle and navigation experiment pointing profile.

The initial design choice was the VACCO Hybrid ADN MiPs system, which allowed to have in the same unit the main propulsion thruster and four $10\,\mathrm{mN}$ cold gas thrusters. This selection would have also allowed for de-tumbling and wheel de-saturation maneuvers with a single unit. Following design iterations proposed an alternative solution to overcome the uncertainties related to the customization of the VACCO system, based on two Aerojet MPS130-2U systems, mounted at two different corners of the spacecraft. This would allow for a total of eight $0.25\,\mathrm{N}$ mono-propellant thrusters that could therefore be used for the main trajectory corrections but also for de-tumbling and de-saturation, depending on the amount of activated thrusters and their activation strategy.

A complicated trade-off between an "integrated" propulsion system and alternative solutions in which two fully separate systems were considered can be found in [9], where more options have been considered regarding the initial study. Two more options for the major propulsion system have been analyzed: the NanoAvionics EPSS system and a system from Bradford-ECAPS based on their flight-proven HPGP $1\,\mathrm{N}$ thruster. For the RCS, two options have been considered: the GomSpace 6DOF cold gas system and a custom-designed version of the ARM water resistojet system produced by Aurora.

Communications

The communications system design is based on an architecture involving a combination of Inter-Satellite Link (ISL) and Direct-to-Earth (DTE) link. The ISL is expected to involve, as relay satellite, the SSTL Lunar Pathfinder satellite: this is a commercial data relay spacecraft developed by SSTL under ESA contract to serve Lunar assets. Considering the high visibility of the relay satellite (up to 22 hours a day), this provides a very good coverage compared to a single ground station on the ground. The data rate is unfortunately limited because of the available volume on the satellite to fit a higher gain antenna.

The ISL link budgets for the different communication links have been calculated considering the final mission configuration and using the real antenna patterns. Considering an approximate Equivalent Isotropic Radiated Power (EIRP) for LUMIO in S-band of $9\,\mathrm{dBW}$, including a $3\,\mathrm{dB}$ safety margin, the achievable data rates with the Lunar Pathfinder are in the order of 0.5–$4\,\mathrm{kbps}$ (depending on the relative distance, minimum $31\,000\,\mathrm{km}$ and maximum $89\,000\,\mathrm{km}$). The selected radio for this link is the ECW31 produced by Syrlinks (S-band uplink/downlink), which would require customizations to support the Proximity-1 standard [10]. Considering the low achievable rates and the lack of coherent operations in the Lunar Pathfinder transponder, the ISL cannot be used for navigation purposes. Despite the low accuracy, not sufficient for the mission purposes, autonomous navigation

Figure 10. Sardinia Deep Space Antenna (SDSA) [12].

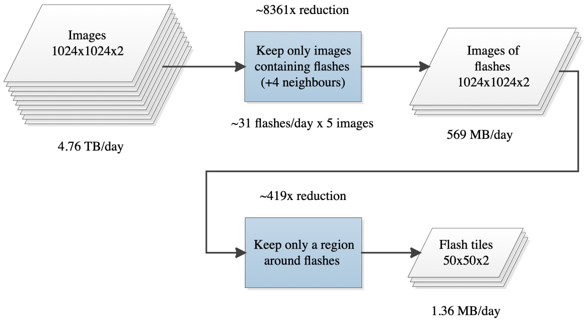

Figure 11. LUMIO payload data reduction strategy.

can be achieved by Linked Autonomous Interplanetary Orbit Navigation (LiAISON) navigation techniques [11].

The DTE link is used for payload data downlink, ranging and tracking in nominal conditions. The link is relying on one ground station and the trade-off took into account both S- and X- band. The final selection was the Sardinia Deep Space Antenna (SDSA), shown in Figure 10, as a baseline after comparing it against several other institutional and commercial solutions. LUMIO requires radiometric navigation as a baseline, thus X-band provides better performances regarding S-band in terms of Doppler accuracy. Considering the ground selection, the European Deep Space X-band transponder has been selected for DTE communication [13]. This provides a data downlink rate of $450–900\,\mathrm{kbps}$ and an uplink rate of $10\,\mathrm{kbps}$. Because of the different power consumption on the ISL and DTE on-board receivers, it was selected to maintain the former always active (also considering the good availability of the link) for nominal commanding from ground (via the Lunar relay). The DTE link will instead be used for payload data downlink, thanks to the much higher speed. This link will also be used for emergency operations thanks to its added simplicity and the flexibility in controlling a ground station for eventual rescue operations.

A link analysis was also performed for the radio-navigation signals to estimate the achievable line-of-sign position error. Ranging sessions have been scheduled to happen at the beginning, in the middle and at the end of the engineering phase (see Section 2 for further details): this session distribution (with a time separation between them of 7, 7 and 14 days) allows to minimize navigation measurements while still achieving the required position estimation accuracy. Two-way range measurements have been planned at the beginning and the end of every ranging session while coherent Doppler measurements have been considered every 20 minutes. It was found from simulations that 3 hours of tracking for each session would fit well within the navigation requirements.

Further details on the communications system design can be found in [14].

On-Board Data Handling

The LUMIO design features an On-Board Payload Data Processing (OBPDP) system whose task is detecting meteoroid impact flashes in the continuous stream of images arriving from the camera in real time. As its second task, this system will carry out the autonomous optical navigation experiment using sporadically recorded images [15]: this experiment aims at demonstrating fully autonomous visual navigation without aid from ground. On-board processing of the images is required because the LUMIO-CAM generates an amount of data that cannot be realistically be transmitted to Earth: it should also be considered that most of the acquired images would not contain impact flashes and such flashes would only cover a minor area on the image.

The rationale for the design of the OBPDP science products is primarily to minimize the amount of scientifically relevant data that is lost by the on-board processing. Another aim is to minimize the amount of computation that needs to be performed on-board the spacecraft. Therefore, the science products are designed to be as similar to the acquisitions (raw images) as possible and the focus of the on-board processing is on the removal of the scientifically non-relevant parts. Only the flash-containing image plus two images before and after will be kept. To further reduce the total amount of data, only a 50×50 pixel tile surrounding the flash is kept. The position (regarding the full acquired image) will also be downloaded to reference the flash position to the Lunar surface and eventually perform investigations on the crater size using other ground or space telescopes. Figure 11 summarizes the whole data-reduction process. Full frames download is also possible, as part of the optical navigation experiment [15], but also for general commissioning of the system or scientific investigations that go beyond the mentioned flash analysis.

Electrical Power System

The EPS uses two deployable and steerable solar arrays, a battery pack for energy storage and a distribution unit to regulate and distribute the power to the various subsystems. The selected configuration provides an average of $54\,\mathrm{W}$ to $58\,\mathrm{W}$ during the various mission phases with a total battery storage capacity of $180\,\mathrm{Wh}$.

The different mission phases have been divided into multiple “modes” resulting in the maximum power usage of $54\,\mathrm{W}$ during the science phase, $54\,\mathrm{W}$ during attitude correction , $47\,\mathrm{W}$ during the navigation and engineering phase and up to $67\,\mathrm{W}$ when the propulsion system is used. Although the highest power consumption occurs during the propulsion heating and the transfer phase, the phase that drives the power budget is the science one. This is because the spacecraft only has to operate in the propulsion heating and transfer modes for a limited amount of time while it spends the vast majority of its time in the science phase.

Thermal Control

The thermal control system has been designed to ensure spacecraft thermal stability throughout the mission lifetime, by keeping all subsystems within their acceptable temperature ranges. Because of the available power and volume on-board and the relatively benign orbit scenario, it was decided to select a completely passive design, identifying proper coatings for the external spacecraft panels to maintain the critical nodes' temperature within the admissible operative range. The Phase A study allowed to conclude that it is possible to keep all spacecraft components within their allowed temperature range, greatly simplifying the overall satellite design.

4. CONCLUSIONS

The LUMIO mission, with the primary science goal of observing and characterizing meteoroid impacts on the Lunar farside, will significantly improve the current meteoroid distribution models and possibly reduce their uncertainty. LUMIO will be fully complementary, in both space and time, to Earth-based observations, and will, therefore, represent a fundamental contributor to Lunar Situational Awareness.

LUMIO is a 12 Unit CubeSat equipped with the LUMIO-CAM, an optical instrument capable of detecting impact flashes while continuously monitoring and processing images. In this paper, the current design of LUMIO, its subsystems and its mission characteristics have been presented and discussed. The design shows the mission is feasible and it can reach the required performances. The mission's Phase B is expected to start at the end of 2021 or at the beginning of 2022 and the launch is expected in 2024.

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BIOGRAPHY

Stefano Speretta *received his MSc and PhD from Politecnico di Torino in Italy. He currently works as an Assistant Professor at the Delft University of Technology in The Netherlands. He focuses on radio communications and autonomous radio-navigation for distributed space systems. With an industrial background, he was involved in multiple small satellite missions targeting Earth observation and deep space exploration.*

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Alessandra Menicucci *Biography not available at time of submission.*

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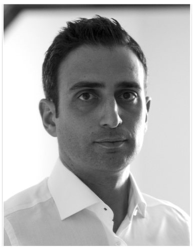

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Demetrio Labate *received his Master Degree in Electronic Engineering at the University of Florence and he started his career at Officine Galileo (now Leonardo) in 1990 as optical designer after an intensive on site course on optics. Since 1995 he started working in the Space Dept. as Project Manager for several ESA and ASI studies of optical instruments for Earth Observation satellites. His interests focused for many years on the development of hyperspectral systems for both space and avionics applications. Recently he was involved in ESA studies relevant to definition and design of CubeSat payloads. Currently he is Program Manager / Senior Advisor within the CTO department of Leonardo Electronics Business Unit with responsibility for studies and new developments. He is lecturer of the "Master in Satellite Systems and Services" at University of Sapienza in Rome and of the "Department of Aerospace Science and Technology" at Politecnico of Milan, where he gives lessons on Space optical instrumentation design and principles of satellite remote sensing.*

Katarzyna Woroniak *received her MSc in Aerospace Engineering with Aerospace Propulsion minor from Warsaw University of Technology. She has 5 years of professional experience as a space systems engineer for CubeSats, Earth Observation satellites and ground segment. Currently she works in ISISPACE designing, testing and operating CubeSats. Her missions are mainly focused on scientific research, Earth Observation and deep space exploration.*

Detlef Koschny *holds a Ph.D. in planetary science obtained at the Technical University of Munich, Germany. He has been involved in many space-based camera systems on missions to Titan, Mars, the Moon, and a comet. He has been building up the field of Planetary Defence at the European Space Agency. He is involved in scientific projects observing fireballs and Lunar impact flashes using ground-based cameras and telescopes. He thinks that observing Lunar impact flashes will help us to better understand the flux density of decimeter- to meter-sized objects in the Earth-Moon system.*

Roger Walker *is the head of the CubeSat Systems Unit at the European Space Agency (ESA) in The Netherlands. He has 14 years of experience with CubeSat-related activities withing ESA, managing 7 on-going programs and 7 already concluded ones. He is the point of contact for other ESA directorate, European industry and research institutes related to CubeSat programs. He is the team leader for CDF studies on small satellites and the technical chain for the CubeSat Workshop at the Small Satellite Systems & Services (4S) Symposium and convener of the ESA CubeSat Industry Days.*