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System design of LUMIO: A CubeSat at Earth-Moon L2 for observing lunar meteoroid impacts

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The Earth–Moon system is constantly being bombarded by a significant number of meteoroids with different sizes and velocities. Observation of the lunar surface impacts will enable characterization of the lunar meteoroid flux, which is similar to that of the Earth, and provide more detailed information on meteoroid size, velocity, temporal and spatial distribution. The Lunar Meteoroid Impacts Observer (LUMIO) is a CubeSat mission at Earth–Moon L2 to observe, quantify, and characterise these meteoroid impacts by detecting their flashes on the lunar farside. LUMIO is one of the two winners of ESA's LUCE (Lunar CubeSat for Exploration) SysNova competition, and as such is being considered by ESA for implementation in the near future. This paper will present the design of the LUMIO spacecraft that will host the payload to capture the meteoroid flashes. Key system specifications, trade-offs and consequent design iterations are presented. The final design yields a feasible spacecraft budget and a configuration that enables the LUMIO mission to be realized by 2023.

The spacecraft is a 12U form-factor CubeSat, with a mass of less than 22 kg. A zero-redundancy and COTS based approach has been adopted for the spacecraft design. A strong emphasis has been placed on realizing high onboard autonomy. A novel and autonomous navigation strategy that uses optical observations of the Earth and the Moon is proposed for navigation around the Moon and beyond. The payload and navigation are the key drivers of the pointing requirements. Pointing requirements are achieved through reaction wheels, IMUs, star trackers, and fine sun sensors. A hybrid micro-propulsion system is included for orbital control, de-tumbling, and reaction wheel desaturation. Steady solar power availability is ensured with a one-axis solar array drive assembly in combination with an innovative attitude algorithm. Communication with Earth is through the Lunar Orbiter with a low-bandwidth UHF link, which places high constraints on the data throughput. An onboard payload data processor has been designed that compresses the science data to a fraction of the raw data with no loss of information.

The paper will conclude with the key findings of a concurrent design review of the LUMIO spacecraft design that was performed at ESA/ESTEC's Concurrent Design Facility (CDF). The major design changes are outlined along with a summary and discussion of the iterated design.

1. Introduction and background

The Lunar Meteoroid Impact Observer (LUMIO) was one of the proposals submitted to the ESA SysNova LUnar CubeSats for Exploration (LUCE) call by ESA [1]. SysNova is intended to generate new and innovative concepts and to verify quickly their usefulness and feasibility via short concurrent studies. The important milestones and sequence of events are shown in Fig. 1. The LUCE call was aimed at identifying a viable low-cost concept using nano-satellites or CubeSats to enable lunar exploration.

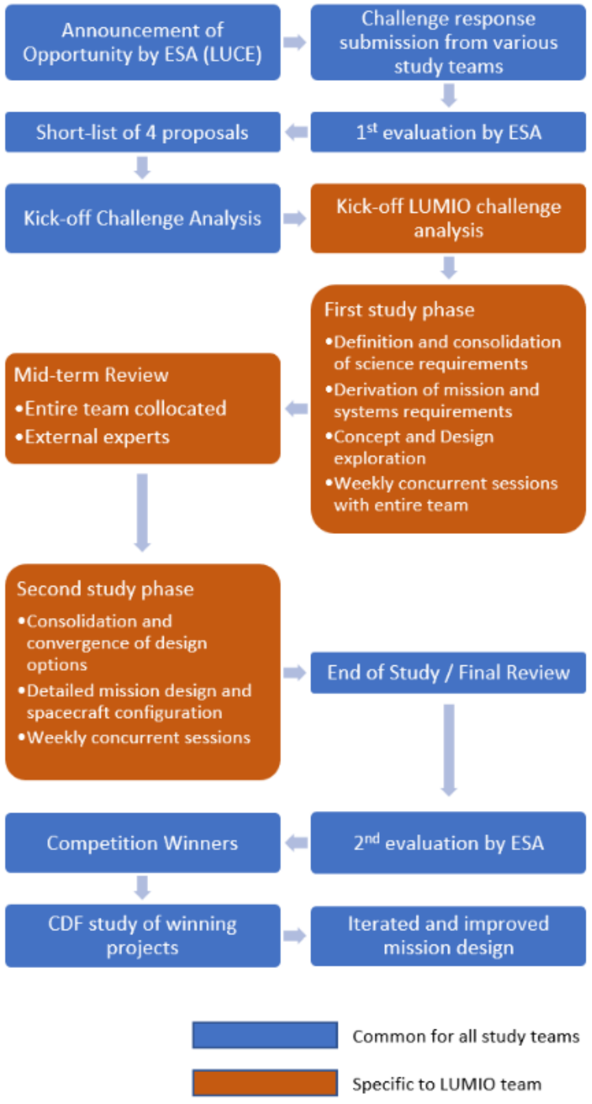


Fig. 1. SysNova LUCE and LUMIO sequence of events

LUMIO was selected as one of the four proposals that could proceed with the challenge analysis. Following an ESA evaluation and final review, LUMIO was selected as one of the two winners of the challenge.

As a prize for the winner, ESA provided the opportunity for a collaborative assessment of the LUMIO mission at ESA's Concurrent Design Facility (CDF). The aim of this paper is to present a summary of the LUMIO spacecraft design highlighting the key features. The results and conclusions of the ESA CDF study, with respect to the spacecraft design, are then discussed. The major design changes between the baseline LUMIO spacecraft and the CDF design are summarised and discussed.

Four documents form the main source of information in this paper:

- The SysNova announcement of opportunity [1]
- The Challenge Response by the LUMIO team [2]
- The Challenge Analysis by the LUMIO team [3]
- The CDF study of the LUMIO mission by ESA [4]

2. Science and mission design

The LUMIO mission is one of the four proposals that were funded by ESA for a six month feasibility study and the aim of the mission was to observe, quantify, and characterize the meteoroid impacts by detecting the impact flashes on the lunar farside. This will complement the knowledge gathered by Earth-based observations of the lunar nearside, thus synthesizing a global information on the lunar meteoroid environment.

The mission is designed to observe meteoroid impacts on the lunar farside for a continuous period (up to 14 consecutive days) to improve the existing statistic on meteoroids close to Earth. The Moon can be used as an impact target to measure the statistic but Earth-based observations of lunar impact flashes are restricted to periods when the lunar nearside is illuminated between 10-50%. The observation on the night side of the Moon can be carried out when the illumination is less than 50% and this happens for half of the lunar orbit. To achieve this, it was required to select an orbit that would maximize the visibility on the night side of the Moon (see Fig. 2) The key science and mission objectives along with the observation strategy are listed in Table 1.

The mission implements a sophisticated orbit design: LUMIO is placed on a halo orbit about Earth–Moon L_2 where permanent full-disk observation of the lunar farside is made. The mission concept along with the different phases are illustrated in Fig. 3.

3. LUMIO spacecraft design

In this section, the spacecraft requirements, a summary of the design, platform configuration and mass budget and conclusions with respect to the baseline LUMIO design are presented.

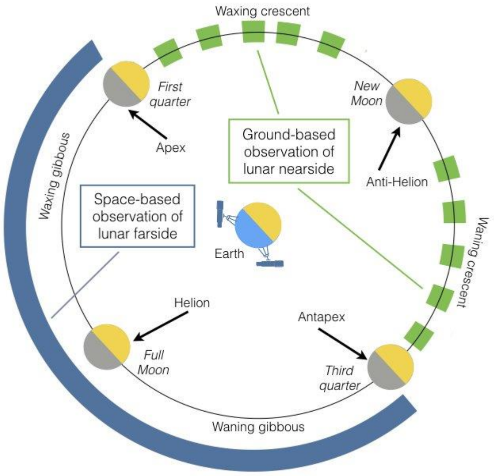


Fig. 2. Moon phases and the geometry of Earth and space-based observations. The dashed green line represents the portion of the Moon orbit where Earth-based observations of the nearside can be made. The solid blue line indicates the portion of the Moon orbit where space-based observations of the farside can be made (Reproduced from LUMIO Challenge Analysis [3])

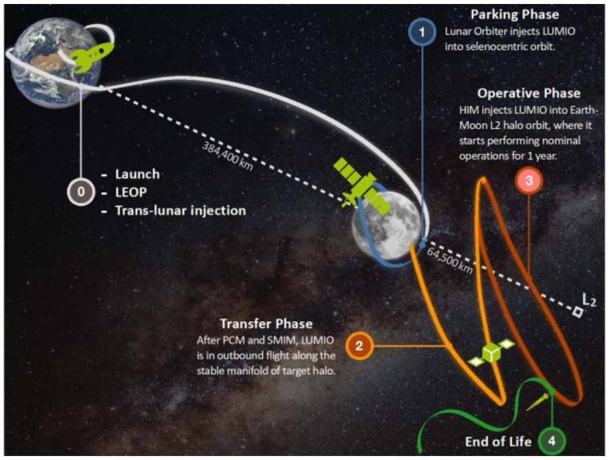


Fig. 3. LUMIO mission concept and mission phases (Reproduced from LUMIO Challenge Analysis [3])

Table 1. Summary of science and mission objectives along with observation strategy. (Adapted from LUMIO Challenge Analysis [3])

Key Science Question	What are the spatial and temporal characteristics of meteoroids impacting the lunar surface?
Science Objectives	• Advance the understanding of how meteoroids evolve in the cislunar space by observing the flashes produced by their impacts with the lunar surface. • Characterize the flux of the meteoroids impacting the lunar surface. • Refine current meteoroid models that are useful in multifarious applications.
Mission Objectives	• Conduct observations of the lunar surface to detect meteoroid impacts and characterize their flux, magnitudes, luminous energies, and sizes. • Complement observations achievable via ground-based assets in terms of space, time, and quality to provide a better understanding of the meteoroid environment. • Demonstrate deployment and autonomous operation of a CubeSat in the lunar environment.
Observation Strategy	• Remote observation of light flashes to detect lunar meteoroid impacts. • Observation of lunar far-side during darkness, ~15 days, from a quasi-halo orbit about EM L_2. • Lunar full disk observation with high resolution by utilizing a 6° FOV. • Required SNR obtained by analyzing the noises and setting the detector’s amplification factor (gain) of the incoming signals with respect to distance from the Moon.

3.1 Main requirements

The key requirements and constraints that drive the spacecraft design are listed in Table 2.

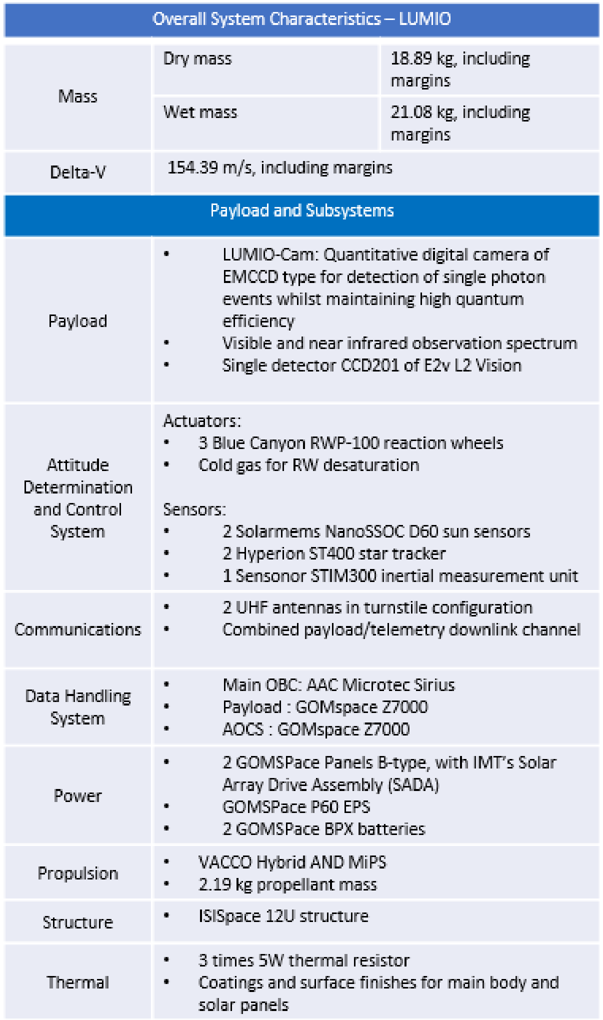
Table 2. Key System and Subsystem requirements [3]

OVRSYS-001	The mass of the spacecraft shall be no greater than 24 kg
OVRSYS-002	The spacecraft volume shall not exceed that of a 12U CubeSat
OVRSYS-003	The system shall operate in a standalone mode for a period of 10 days without any communication
PROP-001	The propulsion system shall provide a minimum ΔV =154.39 m/s for station keeping, orbital transfer, end-of-life disposal, and a minimum total impulse of 72.91 Ns for de-tumbling and wheel desaturation maneuvers
PROP-002	The maximum thrust of the propulsion system shall be 500 mN
PROP-003	The propulsion system shall have maximum thrusting time of 8 hours per orbital transfer maneuver
ADCS-001	After the separation from the Lunar Orbiter, the ADCS shall de-tumble the spacecraft from tip-off rates of, up to 30 deg/s in each axis
ADCS-003	The ADCS shall point with an accuracy of less than 0.1 deg during science and navigation phases
ADCS-005	The ADCS shall provide minimum pointing stabilization of 79.90 arcsec/s during the science phase
ADCS-006	The ADCS shall provide a maximum slew rate of 1 deg/s
EPS-002	The EPS shall supply 22 W average and 36 W peak power to the subsystems in parking orbit phase
EPS-004	The EPS shall supply 23 W average and 39 W peak power to the subsystems during transfer phase
EPS-006	The EPS shall supply 27 W average and 46 W peak power to the subsystems in science mode
EPS-008	The EPS shall supply 22 W average and 42 W peak power to the subsystems in navigation mode
EPS-013	The EPS shall have a mass of no more than 3 kg
COMMS-001	The spacecraft shall receive Telecommands from the Lunar Orbiter in the frequency range of 390-405 MHz
COMMS-002	The spacecraft shall send Telemetry to the Lunar Orbiter in the frequency range of 435-450 MHz
COMMS-003	The spacecraft shall send payload data to the Lunar Orbiter in the frequency range of 435-450 MHz
COMMS-007	The maximum available time limit for communication between the spacecraft and the Lunar Orbiter shall be 1 hour per day
PDLPROC-01	The payload processor shall receive and process a maximum 15 images per seconds from payload
PDLPROC-02	The payload processor shall store a maximum of 13 MB of payload data per 29 days period to the COMMS for transmission to Lunar Orbiter

3.2 Design Summary

The main features of the LUMIO spacecraft are summarised in Table **3**.

Table 3. Specifications of the LUMIO spacecraft based on the baseline design provided by the LUMIO team [3]

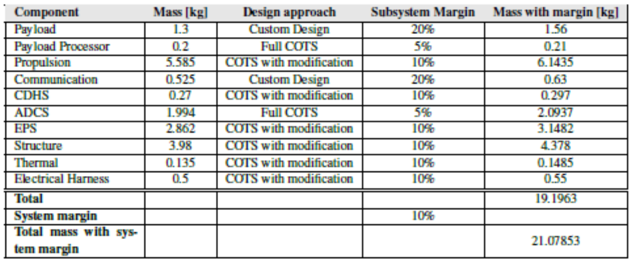


Overall System Characteristics – LUMIO		
Mass	Dry mass	18.89 kg, including margins
	Wet mass	21.08 kg, including margins
Delta-V	154.39 m/s, including margins	
Payload and Subsystems		
Payload	• LUMIO-Cam: Quantitative digital camera of EMCCD type for detection of single photon events whilst maintaining high quantum efficiency • Visible and near infrared observation spectrum • Single detector CCD201 of E2v L2 Vision	
Attitude Determination and Control System	Actuators: • 3 Blue Canyon RWP-100 reaction wheels • Cold gas for RW desaturation Sensors: • 2 Solarmems NanoSSOC D60 sun sensors • 2 Hyperion ST400 star tracker • 1 Sensonor STIM300 inertial measurement unit	
Communications	• 2 UHF antennas in turnstile configuration • Combined payload/telemetry downlink channel	
Data Handling System	• Main OBC: AAC Microtec Sirius • Payload : GOMspace Z7000 • AOCS : GOMspace Z7000	
Power	• 2 GOMSPace Panels B-type, with IMT's Solar Array Drive Assembly (SADA) • GOMSPace P60 EPS • 2 GOMSPace BPX batteries	
Propulsion	• VACCO Hybrid AND MiPS • 2.19 kg propellant mass	
Structure	• ISISpace 12U structure	
Thermal	• 3 times 5W thermal resistor • Coatings and surface finishes for main body and solar panels	

3.3 Mass Budget

Table **4** shows the mass budget of the LUMIO spacecraft for the design summarized in the last section. The pie chart in Fig. **4** shows the relative contribution of the different subsystems to the CubeSat total mass. Based on the design approach, a consistent subsystem margin of 5, 10 or 20% is included. An overall system margin of 10% is also provided. Even with all the margins taken, the final estimated LUMIO mass is well below the maximum allocated mass of 24 kg, showing the effectiveness and feasibility of the design choices made. It is therefore expected that, in the next project phases, significant improvements can be made in terms of both spacecraft mass and volume.

Table 4: Mass budget of the LUMIO spacecraft including subsystem level and system level margins (Reproduced from LUMIO Challenge Analysis [3])



Component	**Mass [kg]**	**Design approach**	**Subsystem Margin**	**Mass with margin [kg]**
Payload	1.3	Custom Design	20%	1.56
Payload Processor	0.2	Full COTS	5%	0.21
Propulsion	5.585	COTS with modification	10%	6.1435
Communication	0.525	Custom Design	20%	0.63
CDHS	0.27	COTS with modification	10%	0.297
ADCS	1.994	Full COTS	5%	2.0937
EPS	2.862	COTS with modification	10%	3.1482
Structure	3.98	COTS with modification	10%	4.378
Thermal	0.135	COTS with modification	10%	0.1485
Electrical Harness	0.5	COTS with modification	10%	0.55
Total				19.1963
System margin			10%	
Total mass with system margin				21.07853

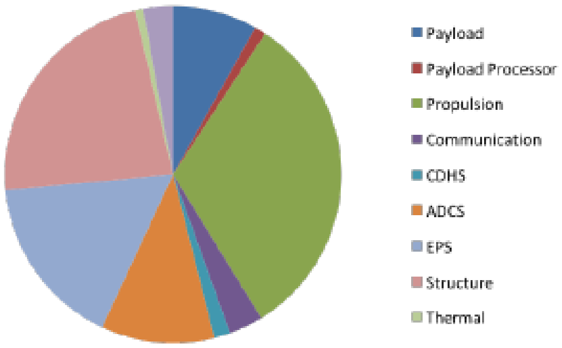


Fig. 4. Relative mass contribution of the different subsystems to the LUMIO spacecraft [3]

3.4 Spacecraft Configuration

Here, the final configuration of LUMIO is presented through 3D drawings of the spacecraft developed in SolidWorks. The spacecraft configuration with and without panels is shown in Fig **5**.

3.5 Conclusions and Recommendations

The preliminary system design conducted during this Challenge Analysis has shown the feasibility of the LUMIO mission with a spacecraft largely made of COTS (or COTS-based) sub-systems and components. Even after all the necessary margins required at this early design stage, the mass budget (See Table **4**) shows a total system mass significantly lower than the maximum allocated 24 kg.

This saved mass could be used, in the next project phases, for one or more of the following:

- Reduce the spacecraft mass and volume and, consequently, the mission costs;
- Deviate from the zero-redundancy design strategy, by adding some additional components to avoid single points of failure for the most critical sub-systems (in particular ADCS and navigation);
- Include additional propellant for extending the mission lifetime and/or for alternative End Of Life strategies;
- Accommodate additional payloads for implementing one or more secondary mission objectives.

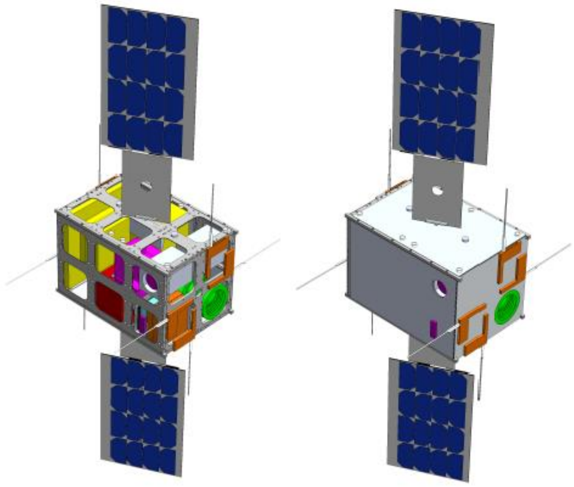


Fig 5. LUMIO spacecraft with deployed solar panels, isometric projection. Left side: Through view to show internal configuration. Right side: Covered with panels (Reproduced from LUMIO Challenge Analysis [3])

Based on the spacecraft design, a number of recommendations arise:

- The current trade-offs have led to the selection of several non-European components (in particular the propulsion sub-system and the ADCS reaction wheels). A more in-depth investigation for European alternatives shall be conducted.
- Most of the COTS components currently selected for the LUMIO spacecraft are not qualified yet for the Lunar environment. Attention shall be paid in ensuring they can be safely used for the proposed mission.
- The LUMIO propulsion sub-system design is currently based on the use of two different types of propulsion (mono-propellant for station keeping and orbital maneuvers; cold gas for RCS, detumbling and wheel de-saturation), with consequent mass and volume inefficiencies due to the presence of two tanks, two feeding lines etc. Alternatives based on performing all required functions with the same propulsion type (mono-propellant or eventually resistojet) shall be investigated and better assessed. In addition, further optimization would be required on the placement of the smaller (cold gas) thrusters, currently exclusively based on the selected COTS option, in order to make them more efficient for the

de-tumbling and de-saturation maneuvers. Placing the thrusters further away from the central axis of inertia (which would also allow for better interfacing of the spacecraft with the QuadPack deployer) and reducing, or completely eliminating, the net force generated when firing a pair of thrusters are two of the available options in this respect.

- The EPS design shall be further optimized by investigating solutions for a more uniform distribution of the power requirements through the different mission phases and, therefore, allowing for size and mass reduction of solar arrays and batteries.
- The antenna choice for the communication sub-system shall be carefully revisited, based on the expectable short-term developments on the UHF patch.
- The current LUMIO design including active thermal control by means of relatively power-demanding COTS heaters (3 to 5 W) is driven by the results of a simplified single-node thermal analysis of the spacecraft. Active thermal control devices might prove to be unnecessary after a more in-depth characterization of the LUMIO environment and thermal properties by means of a multimodal analysis and, eventually, a more optimized design of the external coating for passive thermal control.
- The current data handling system has been designed with a rigid split in functions between the different components (the OBC and AOCS computer and the Onboard Payload Data Processor (OBPDP)) to simplify and modularize the design. Due to the anticipated complexity of the navigation and attitude control algorithms, it was decided to run them on a separate computer (AOCS computer) but, upon further investigation, such complexity may be reduced and the navigation and attitude control algorithms may be run on the OBC. This could further lower the mass and volume of the platform.

4. CDF Study

4.1 Process

The CDF study involved the following activities [4].

- Start with the Sysnova study baseline design as a basis.
- Focus on improving the baseline design in the identified weak areas in a collaborative concurrent working approach (external customer and ESA together as one study team).
- Possibly perform additional trade-offs and analyses as necessary to support the design updates (to be run during/between sessions).
- Use the CDF model (OCDT) and CAD model as a basis to track the design evolution incl. equipment list, budgets and configuration.

The review of the baseline design was carried out in 5 sessions at the ESTEC CDF by an integrated team of ESA specialists from various ESA sites.

4.2 Iterated Design

The CDF study concluded with the iterated design, referred to as LUMIO_2.0, shown in Table **5**.

4.3 Conclusions and major design changes

The LUMIO mission concept proposed and studied by the LUMIO consortium (Politecnico Milano (Polimi), Delft University of Technology (TU Delft), Ecole Polytechnique Federale de Lausanne (EPFL), S[&]T Norway, Leonardo SpA and the University of Arizona (UoA)) for the Sysnova Challenge #4 “LUnar Cubesats for Innovation” has been selected by an ESA evaluation panel as a joint winner of the Challenge. As a winner of the competition, a concurrent review of the LUMIO study output has been performed in the CDF by an inter-disciplinary ESA study team. The team consisted of system engineering, mission analysis, ground segment & operations, subsystem, and cost/risk/programmatics disciplines. The LUMIO consortium have been integrated in the concurrent review process in the external customer role, and as the responsible for the payload design and performance.

The SysNova LUMIO study results have been assessed in terms of [4]:

- Mission and system requirements definition and analysis
- Mission, system and subsystem-level design trade-offs
- Conceptual design of the nano-satellite system and its predicted performance
- Launch, deployment, operation and maintenance of the satellite
- Programmatic aspects (incl. cost, schedule, risk).

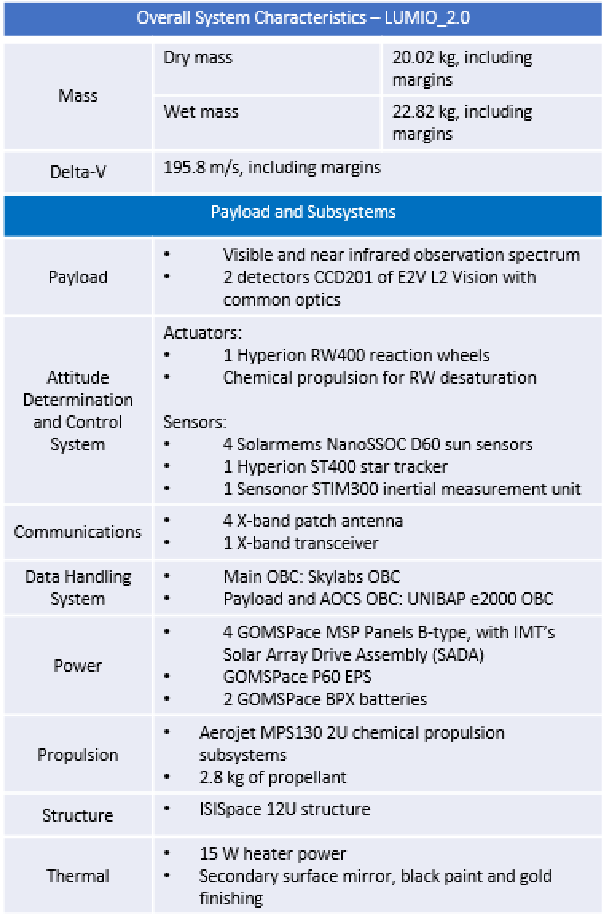
In this paper, the scope of the results is restricted to the spacecraft design. As part of the concurrent review process, critical issues have been identified and were further addressed by iterating the conceptual design in those weak areas, using the initial Sysnova design baseline as a starting point. The major design changes are listed in Table **6**.

On the platform, multiple design changes have been made [4];

- The delta-v budget has gone up in comparison with the original design. For this a change in the propulsion system baseline was required. Therefore, a liquid propulsion system was chosen. The current baseline employs two non-European thrusters each with four nozzles removing the need of a separate attitude control system.
- The total data generated has increased due to the extra payload on board. To transfer all this data the

communication system has changed to a direct–to–Earth link. This communication link also provides the possibility to monitor any critical orbital manoeuvres.

Table 5. Specifications of LUMIO_2.0 spacecraft design, based on the CDF study. (Adapted from ESA LUMIO CDF Study[4])



Overall System Characteristics – LUMIO_2.0		
Mass	Dry mass	20.02 kg, including margins
	Wet mass	22.82 kg, including margins
Delta-V	195.8 m/s, including margins	
Payload and Subsystems		
Payload	• Visible and near infrared observation spectrum • 2 detectors CCD201 of E2V L2 Vision with common optics	
Attitude Determination and Control System	Actuators: • 1 Hyperion RW400 reaction wheels • Chemical propulsion for RW desaturation Sensors: • 4 Solarmems NanoSSOC D60 sun sensors • 1 Hyperion ST400 star tracker • 1 Sensonor STIM300 inertial measurement unit	
Communications	• 4 X-band patch antenna • 1 X-band transceiver	
Data Handling System	• Main OBC: Skylabs OBC • Payload and AOCS OBC: UNIBAP e2000 OBC	
Power	• 4 GOMSPace MSP Panels B-type, with IMT's Solar Array Drive Assembly (SADA) • GOMSPace P60 EPS • 2 GOMSPace BPX batteries	
Propulsion	• Aerojet MPS130 2U chemical propulsion subsystems • 2.8 kg of propellant	
Structure	• ISISpace 12U structure	
Thermal	• 15 W heater power • Secondary surface mirror, black paint and gold finishing	

- The increase in the data generation rate from the payload resulted in the need for a more performant data handling system, in particular in the on-board image processing capabilities
- The power budget increased and therefore the number of solar panels was increased accordingly, remaining compatible in stowed configuration with the CubeSat deployer constraints.
- Multiple options have been investigated in case some constraints come up in a later phase of the design.

5. Summary and Conclusions

The Lunar Meteoroid Impact Observer (LUMIO) is a CubeSat mission at Earth-Moon L2 to observe, quantify, and characterise meteoroid impacts by detecting their flashes on the lunar farside. These observations can complement ground-based observation to improve current meteoroid flux models. LUMIO is one of the two winners of ESA's LUCE (Lunar CubeSat for Exploration) SysNova competition, and as such is being considered by ESA for implementation in the near future subject to available flight opportunities and the related selection process for those opportunities. The sequence of events and milestones involved in the SysNova study is addressed in Chapter 1. In Chapter 2, the science objective and mission design are presented along with the observation strategy. The salient features of the LUMIO spacecraft design which was the outcome of the challenge analysis is highlighted in Chapter 3. The results of the ESA CDF study with respect to the platform design are summarised in Chapter 4. The design changes and refinements are outlined and the iterated design of LUMIO 2.0 is presented.

Table 6. Major design changes between baseline LUMIO and the outcome of the CDF study (Adapted from ESA LUMIO CDF Study [4])

Subsystem	**LUMIO**	**LUMIO_2.0 (CDF design)**
Payload	Single detector; Small baffle	Two detectors; Longer baffle
Propulsion	Custom VACCO propulsion system	Two Aerojet propulsion modules
ADCS	Low number of RW desaturations	Higher number of RW desaturations
Communications	Inter-satellite UHF link between LUMIO and lunar orbiter	Direct to Earth using X-band
Data handling	Independent computers for AOCS and payload processing	Combined AOCS and payload processing computer
Power	Deployable solar array with SADA	Increased power with double deployable solar array with SADA

The design of the LUMIO mission and the platform to enable this mission followed a very systematic and structured process. To enable a cohesive and consistent design, all subsystem leads participated in remote weekly concurrent design sessions. A mid-term review involving external reviewers was organized to identify bottlenecks in the design and to converge on the format of the required science products. This led to the baseline design that was presented in the Challenge Analysis and in the Final Review to ESA. LUMIO was awarded the prize of a CDF review and study by ESA for jointly winning the SysNova competition.

The design changes, with respect to the spacecraft configuration, resulting from the LUMIO CDF study by ESA have been summarised in this paper. This iterated design, referred to as LUMIO 2.0 in this paper, addresses key issues related to propulsion, power and communications among others that were identified during the review of the baseline LUMIO design. The CDF study and the iterated LUMIO 2.0 provide the LUMIO concept, to observe meteoroid impacts on the farside of the Moon from a CubeSat at Earth-Moon L2, a clear direction and impetus towards the next development phases in realizing such a mission.

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The input from of all the external experts during the mid-term review of LUMIO and throughout the design process has been extremely valuable and their role is highly appreciated.

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