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Selection of the Propulsion System for the LUMIO Mission: an Intricate Trade-Off Between Cost, Reliability and Performance

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Abstract

The Lunar Meteoroid Impact Observer (LUMIO), one of the two winning concepts of the SysNova Lunar CubeSats for Exploration call by ESA, is a mission designed to observe, quantify, and characterize the meteoroid impacts on the Lunar far side by detecting the flashes generated by the impact. While Earth-based Lunar observations are restricted by weather, geometric and illumination conditions, a Lunar-based observation campaign can improve the detection rate and, when observing the Lunar far side, complement in both space and time the observations taken from Earth.

The mission, which has successfully completed its Phase A in March 2021, is based on a 12U CubeSat that carries the LUMIO-Cam, a custom-designed optical instrument capable of detecting light flashes in the visible spectrum. The spacecraft is placed on a halo orbit about the Earth–Moon L2 point, where permanent full-disk observation of the Lunar far side can be performed with excellent quality, given the absence of background noise due to the Earth.

The propulsion system is one of the most crucial design choices for the LUMIO spacecraft. It accomplishes various functions: orbital transfer from the initial Lunar orbit to the final halo orbit around L2, station keeping, reaction wheel desaturation, end of life disposal manoeuvres. The total required Delta-V budget for orbital transfer and station keeping is 201.8 m/s, plus an additional total impulse for reaction control tasks ranging from 110 Ns to 170 Ns, depending on the type of reaction control system that is selected.

This paper presents a detailed summary of the phase A selection and design of the LUMIO propulsion system, based on the full list of requirements generated by the mission analysis. The main challenges of this process and the way they have been tackled are presented and discussed, including: use of two separate systems as opposed to an integrate one for main propulsion and reaction control tasks; availability of sufficiently reliable European propulsion options, to reduce the general mission costs; feasibility of replacing a chemical/cold gas system with electric propulsion; possible need for custom changes to the design of the selected COTS option (e.g. due to tank sizing).

Keywords: LUMIO, CubeSats, Meteoroid impacts, ESA SysNova challenge. Micro-Propulsion

1. Introduction

LUMIO (LUnar Meteoroid Impacts Observer) is a CubeSat mission to a halo orbit at Earth–Moon L_2 that shall observe, quantify, and characterize meteoroid impacts on the Lunar farside by detecting their flashes, complementing Earth-based observations on the Lunar nearside, to provide global information on the Lunar Meteoroid Environment and contribute to Lunar Situational Awareness.

LUMIO was one of the proposals submitted to the SysNova LUnar CubeSats for Exploration (LUCE) call by the European Space Agency (ESA), a challenge intended to generate new and innovative concepts and to verify quickly their usefulness and feasibility via short concurrent studies [1]. After the first phase of the challenge (open call for ideas), LUMIO was one of the four proposals selected for performing a pre-Phase 0 analysis, funded by ESA. During the final review and evaluation from ESA, the mission was then selected as one of the two ex-aequo winners of the challenge. As prize for the winners, ESA offered the opportunity to perform an independent study in its Concurrent Design Facility (CDF), to further assess the objectives, design and feasibility of the mission. The CDF study confirmed the feasibility and the scientific value of the mission [2], proposing a number of design iterations that, together with the initial design proposed by the LUMIO team in response to the SysNova challenge, contributed to form the Phase 0 study of the mission. Details on this Phase 0 study have been provided by the LUMIO team in numerous publications and presentations, see for example [3], [4], [5].

The LUMIO Phase A study, funded by ESA under the General Support Technology Programme (GSTP), through the support of the national delegations of Italy (ASI), the Netherlands (NSO) and Norway (NOSA), has been kicked off in March 2020 and has been completed in March 2021. The initial results of the Phase A have been presented by the LUMIO team in a previous paper [6], while the final Phase A design is illustrated in detail in a companion paper presented at the IAC 2021 [7].

This paper, after a short introduction of the scientific relevance and goals of LUMIO and its main mission analysis results, will discuss in detail the Phase A design of the propulsion system of the LUMIO spacecraft, which is one of the most crucial sub-systems for the correct accomplishment of all mission goals.

2. Scientific goal and mission details of LUMIO

A large amount of meteoroids and micrometeoroids continuously enter the Earth–Moon system. Recent observations from the Lunar Reconnaissance Orbiter Camera have shown how substantially their impacts can cause modifications of the Lunar surface. There are also various hypothesis and speculations on possible asymmetries in the spatial distribution of impacts across the Lunar surface, especially between the nearside and the farside, between the equatorial and the polar flux, and between the Lunar leading side (apex) and the trailing side (antapex).

Since an observer on Earth always sees the same portion of the Moon (the Lunar nearside), observations of Lunar micro-meteoroid impacts taken from the Earth are intrinsically limited to just half of the Lunar surface. The illumination of the Lunar nearside from the Sun also varies with time, and micro-meteoroid impact flashes can only be observed from ground on the Lunar nightside, when the nearside is less than 50% illuminated, and during the Earth night. A similar situation applies to observations of the Lunar farside, which however can be performed at time periods complementary to those when Lunar nearside observations can be taken. It is therefore clear that space-based observations of the Lunar farside are fully complementary to Earth-based observations, in both space and time.

The science question that the LUMIO mission intends to answer is: *what are the spatial and temporal characteristics of meteoroids impacting the Lunar surface?* The corresponding science goal will be to *advance the understanding of how meteoroids evolve in the cislunar space by observing the flashes produced by their impacts with the Lunar surface*.

LUMIO will make use of a 12U CubeSat equipped with 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 COTS CubeSat technologies, to serve as a pioneer in demonstrating how CubeSats can become a viable tool for interplanetary science and exploration. Figure 1 shows a simplified representation of the mission profile and phases.

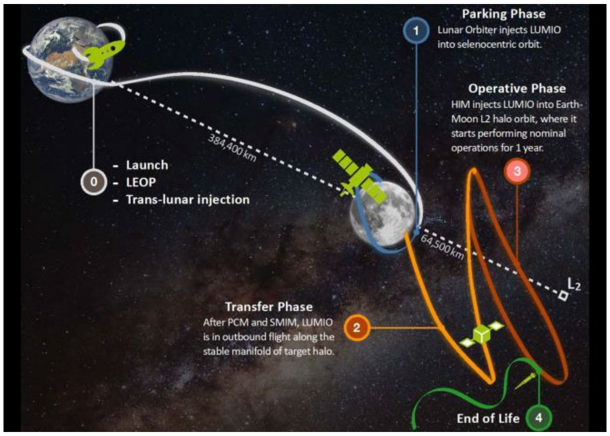


Fig. 1. LUMIO mission concept and phases.

As shown in Fig. 1, the mission is divided in 5 phases:

- **Earth-Moon transfer.** After the launch, the LUMIO spacecraft is carried inside its mothership to a Lunar parking orbit. During the transfer the spacecraft is switched off inside its deployer and the LUMIO batteries are kept charged by a power connection with the mothership.
- **Parking.** The LUMIO spacecraft is released in its Lunar parking orbit by the mothership. After de-tumbling and deployment of the solar arrays, the payload and all sub-systems are commissioned. The spacecraft stays in the parking orbit and, when necessary, performs station keeping and wheel desaturation manoeuvres.
- **Transfer.** The LUMIO spacecraft autonomously transfers from the Lunar parking orbit to the final operative orbit. The transfer is performed by means of a Stable Manifold Injection Manoeuvre (SMIM), two TCM manoeuvres, and a Halo Injection Manoeuvre (HIM). Also in this case, during the transfer, the spacecraft performs when necessary wheel desaturation manoeuvres.
- **Operative phase.** In this phase, expected to have a duration of at least 1 year, the LUMIO spacecraft accomplishes its scientific objectives. The phase is divided in two sub-phases: the science cycle, during which scientific data (images) are continuously acquired, processed and compressed; the navigation & engineering cycle, during which orbital navigation manoeuvres are performed and, eventually, station keeping and wheel desaturation manoeuvres are conducted. The science cycle takes place when Moon illumination allows for scientific observations, while

the navigation & engineering cycle takes place when scientific observations of the Lunar farside are not possible.

- **End-of-Life.** Finally, all spacecraft systems are de-commissioned, and the end of life manoeuvres are performed by the LUMIO spacecraft.

The trajectory proposed during Phase 0 for the transfer phase was based on an injection orbit of 200x15,000 km around the Moon, later modified during the CDF study to a 600x20,000 km orbit in order to reduce the magnitude of the SMIM manoeuvre. In the Phase A study, two alternative launch opportunities have been investigated: the Commercial Lunar Payload Services (CLPS) and Artemis-2, both from NASA, with the latter representing the worst-case scenario for the transfer phase and therefore being used for the determination of the Delta-V budget used for the selection and design of the propulsion subsystem.

The selected LUMIO operative orbit is a quasi-periodic halo orbit around Earth–Moon L_2, characterised by a Jacobi constant Cj = 3.09. One important advantage offered by this orbit is the absence of any eclipse periods during the complete 1-year nominal mission lifetime.

The worst-case Delta-V budget for the LUMIO spacecraft, based on the Artemis-2 launch opportunity and an optimized transfer strategy from the corresponding release orbit, includes the set of deterministic and stochastic manoeuvres as reported in Table 1. In this case, since the LUMIO spacecraft would be released in a trans-Lunar orbit, a completely different transfer strategy has been defined than the one used for the Phase 0 study and for the CLPS case studied during Phase A. In this case, a set of 6 impulsive manoeuvres (Δv_0-Δv_5) are performed, followed by a single TCM manoeuvre and by the HIM.

Table 1. Current worst-case Delta-V budget for LUMIO (based on the Artemis-2 launch opportunity).

Maneuver	**Deterministic Δv [m/s]**	**Stochastic Δv, 3σ [m/s]**	**Margin**
Δv_0	8.3		5%
Δv_1-Δv_5	129.2		5%
TCM		18	100%
HIM	12.2		5%
1-year SK		4.3	5%
Disposal	2		100%
		Total, without margins [m/s]	174.0
		Total, margined [m/s]	**201.8**

The LUMIO spacecraft configuration resulting from the Phase A study is presented in in Fig. 2. Two internal views of the spacecraft are shown in Fig. 3 and Fig. 4, where it is possible to see the main propulsion subsystem (which will be discussed in detail in the next sections of this paper) highlighted in red.

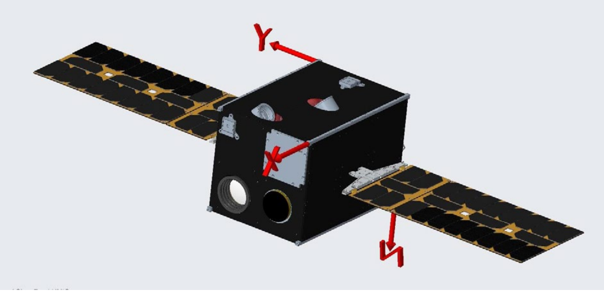


Fig. 2. Rendering of the LUMIO spacecraft configuration resulting from the Phase A study.

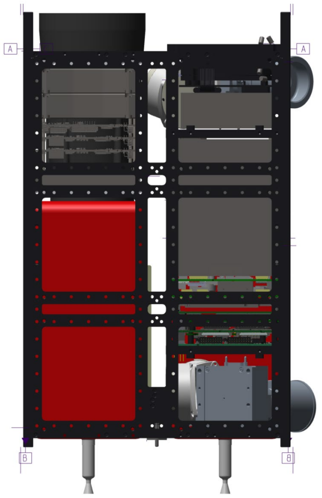


Fig. 3. Internal view of the LUMIO spacecraft as resulting from the Phase A study (-Y view).

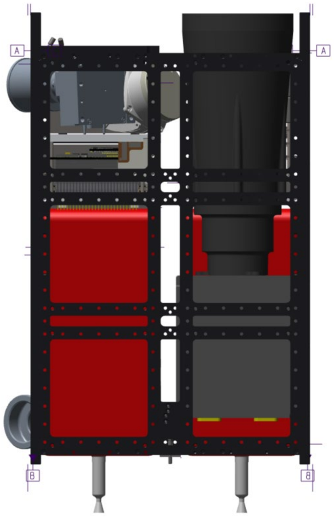


Fig. 4. Internal view of the LUMIO spacecraft as resulting from the Phase A study (+Y view).

The following sections of this paper discuss in detail the design of the propulsion subsystem of the LUMIO spacecraft, starting from its requirement and the main trade-off performed to define the system characteristics, highlighting in particular the differences between the design resulting from the Phase A study and those previously proposed during Phase 0.

3. LUMIO propulsion subsystem design

The propulsion subsystem is one of the most crucial design choices for LUMIO, given the various functions it accomplishes: orbital transfer from the initial Lunar orbit to the final halo orbit around L2, station keeping, reaction wheel desaturation, end of life disposal manoeuvres.

The initial propulsion system choice proposed by the team in the challenge response study was the VACCO Hybrid ADN MiPs system, which allowed to have in the same unit the main propulsion thruster (a 0.1 N mono-propellant) and four 10 mN cold gas thrusters in a "pyramid" configuration which, in that design, would have allowed for RCS manoeuvres (de-tumbling and wheel desaturation). The available COTS options for this system were not sufficient in terms of Delta-V budget, therefore a customization of the system in terms of tank size and propellant mass was foreseen.

The CDF study proposed an alternative solution, mainly to overcome the uncertainties related to the customization of the VACCO system. The propulsion design proposed by the CDF was 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 N mono-propellant thrusters at different locations, that could therefore be used for both main and RCS propulsion tasks, depending on the amount of activated thrusters and their activation strategy.

Based on the lessons learned from Phase 0, the first step taken in the Phase A study was to make a detailed trade-off between an "integrated" propulsion system (i.e., a system that accomplishes both main and RCS propulsion functions, similarly to the two solutions proposed during Phase 0), and an alternative solution in which two fully separate systems are considered for the main and RCS propulsion. The trade-off was conducted using as criteria the main expected requirements for the propulsion system: thrust level, mass, volume, power, cost, TRL/schedule, compliance to other requirements. The results of this preliminary trade-off are presented in Table 2.

Although the trade-off does not have a fully clear winner, it shows a defined preference for the "separate systems" option. This option allows for more flexibility, a larger number of potential COTS systems offered by the market (especially in the European scenario), and the possibility of separately optimizing the performance of the two propulsion systems. For this reason, it was decided to proceed with this option. Therefore, the subsystem requirements were written separately for main and RCS propulsion, and the selection of the two systems was based on two fully separate trade-offs.

A selection of the most important requirements for the main propulsion system and the RCS propulsion system is presented in Table 3 and Table 4. These requirements represented the basis on which the following trade-offs were conducted (see next sub-sections).

4.1 Main propulsion system: type of propulsion

For the main propulsion system, based on the requirements presented in Table 3, an initial trade-off was performed to define which type(s) of propulsion would be the most suitable for the task. The trade-off criteria were similar to those used in the initial trade-off for integrated or separate systems: thrust level, mass, volume, power, schedule/TRL, cost, compliance to other requirements. The results of this trade-off are presented in Table 5.

The trade-off did not leave many options open for the main propulsion system, with mono-propellant as the only type of propulsion capable to meet, at least on paper, all given requirements. Bi-propellants might have been an option in principle, but their typical thermal control constraints (due to their higher operational temperatures) would probably prove to be an issue for the burning times expected by LUMIO, thus posing additional limitations also on the response time and number of burns. Electric propulsion options were ruled out after the preliminary results obtained by the mission analysis team, mainly as a combination of their power consumption and thrust level, the latter yielding cumbersome flight dynamics operations. Cold gas and electrothermal propulsion are not an option too, mainly due to their low specific impulse and, consequently, expected non-compliance to the given mass and volume requirements.

As a consequence of these trade-off results, the current space micro-propulsion market was investigated for available COTS mono-propellant systems, giving special priority to the European market. Based on the given requirements, two candidates were selected and investigated more in detail: the NanoAvionics EPSS system and a (partially customized) system developed by Bradford-ECAPS, based on their HPGP 1 N thruster.

4.2 Main propulsion system: candidates

The EPSS mono-propellant system from NanoAvionics is offered with a modular design and several options for scalability. The propellant is ADN-based, with an average vacuum specific impulse of 220 s. The system is blowdown, with an initial thrust level of 1 N and a final thrust of 0.25 N, corresponding to a chamber pressure decreasing from 25 bar to 5.5 bar.

Three COTS configurations are offered, with a volume of respectively 1.5U, 2U and 3U. The 2U configuration has a wet mass of 2.6 kg and offers a maximum total impulse of 1700 Ns. The system has already proven flight heritage, having been tested and validated during the LituanicaSAT-2 mission and subsequently used in several other spacecraft. It is radiation qualified, with a proven tolerance of 20 krads [8]. A picture of the 1.5U version of the system is shown in Fig. 5.

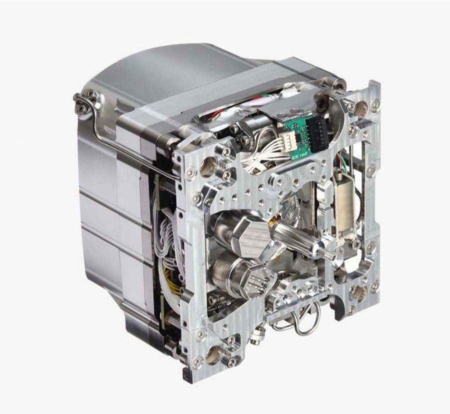


Fig. 5. 1.5U-version of the NanoAvionics EPSS [8].

To meet the specific requirements of LUMIO, NanoAvionics has proposed a slightly modified version of their EPSS 2U system, with two separate units (each with one thruster), having a cumulative volume of 5.5U and mass of 6.6 kg. In this way, a Delta-V budget of 221 m/s can be achieved, compatible to the LUMIO requirements.

Bradford, in collaboration with ECAPS, offers a wide range of mono-propellant thruster options in their HPGP (High Performance Green Propulsion) line, characterized also in this case by an ADN-based propellant. Among them, the HPGH 1 N thruster meets the general requirements of LUMIO and has a proven flight heritage, having been qualified in several space missions. This thruster has a vacuum specific impulse in the range from 204 to 231 s, with a proven life of 60000 pulses at a propellant throughput of 24 kg [9]. A picture of the HPGP 1 N thruster is shown in Fig. 6.

Fig. 6. Picture of the HPGP 1 N thruster from Bradford-ECAPS [9].

Bradford does not offer just the separate thrusters, but also full systems, designed to tailor specific applications and missions. Examples of such systems, based on the HPGP 1 N thruster, have been designed and flown in the Prisma satellite and in the Planet CubeSat constellation.

The system proposed by Bradford to meet the specific requirements of LUMIO is based on the heritage of their COMET system (already flown in 7 spacecraft in orbit), adapted to the HPGP 1 N thruster and its specific valves and flow control elements. Also in this case, two separate propulsion units with one thruster each are foreseen, with a wet mass of 2.984 kg per unit (5.968 kg in total) and a volume of exactly 1x1x2.5U per unit.

Both identified candidates for the LUMIO main propulsion system meet the requirements as presented in Table 3 and, as such, are suitable to be used for the mission. A final selection between these two candidates will be performed at the beginning of Phase B.

4.3 RCS propulsion system: type of propulsion

Also for the RCS propulsion system, similarly to what has been done for the main propulsion system, an initial trade-off has been performed to define which type(s) of propulsion would be the most suitable for the task. The trade-off criteria were again similar to those used in the previous trade-offs: thrust level, mass, volume, power, schedule/TRL, cost, compliance to other requirements. The results of this trade-off are presented in Table 6.

From this trade-off, several types of propulsion seem to be suitable for the RCS system. Only two options are clearly ruled out, mainly due to their typical thrust level: mono-propellant and bi-propellant systems. Cold gas is clearly the most promising option, scoring good or excellent in all trade-off criteria; however, electric and electrothermal propulsion cannot be ruled out yet and are still left open for consideration.

Based on these preliminary results, also in this case the current space micro-propulsion market was investigated for available COTS systems, giving special priority to the European market. A particularly important criterion followed in this case, was to find existing systems in which an already fully integrated configuration of reaction control thrusters is offered. Based on this criterion and on the RCS propulsion requirements, two candidates were selected and investigated more in detail: the GomSpace NanoProp 6DOF cold gas system, and a (partially modified) version of the Aurora ARM water resistojet system.

4.4 RCS propulsion system: candidates

GomSpace offers various types of RCS systems based on their cold gas micro-thruster technology. The baseline thruster characteristics provide a thrust level that can be selected among two options, 1 mN or 10 mN. The NanoProp 6DOF module, in particular, is designed to offer complete control authority along all 3 translation and 3 rotation directions. It includes 6 MEMS thrusters integrated with two propellant tanks, one plenum tank, valves, heaters, filters, sensors and electronics. Its standard version uses Butane as propellant and provides a total impulse up to 100 Ns, with a dry mass of 682 g, a size of 200 x 100 x 55 mm and a vacuum specific impulse of 50 s [10]. A picture of the NanoProp 6DOF module is shown in Fig. 7.

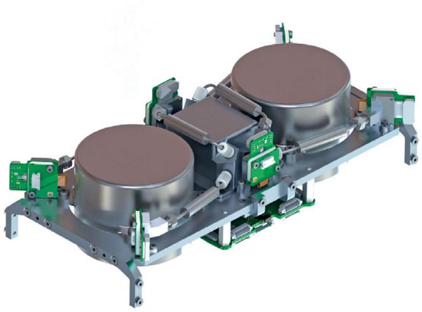


Fig. 7. GomSpace NanoProp 6DOF module [10].

The solution proposed by GomSpace to meet the specific RCS requirements of LUMIO is based on two units of the NanoProp 6DOF module, with thrusters providing a thrust level of 1 mN each and a minimum impulse bit of 25 μNs. The estimated wet mass is 802 g per module, with an available total impulse of 120 Ns (60 Ns per module).

Aurora Propulsion technologies offers several attitude and orbital control COTS modules, based on their water micro-resistojet thruster technology. The ARM-A module, as an example, is based on 6 thrusters with a thrust level in the range of 0.6 to 4 mN each. It is offered in several versions ranging from 0.35U to 2U, with a wet mass in the order of 1 kg/U. The thrusters have an estimated vacuum specific impulse of 100 s, and require an adjustable input power in the range from 3 to 5 W/mN, with a standby power consumption of 50 mW [11]. A complete in-orbit demonstration of the system is expected before the end of 2021 on board the AuroraSat-1 satellite. A picture of the ARM-A module is shown in Fig. 8.

To meet the specific RCS propulsion requirements of LUMIO, Aurora proposed a slightly tailored version of their ARM-A system, based on a configuration with 6 thrusters placed at a corner of the module with different orientations. The thrust level per thruster can be selected among two options: either 1 mN or 2 mN. The available total impulse is 150 Ns, for a wet mass of 800 g and a volume of 1x1x0.5U.

Fig. 8. The Aurora ARM-A resistojet module [11].

Also in the case of the RCS propulsion system, both identified candidates are suitable for use in the LUMIO spacecraft, and a final selection between them will be performed at the beginning of Phase B..

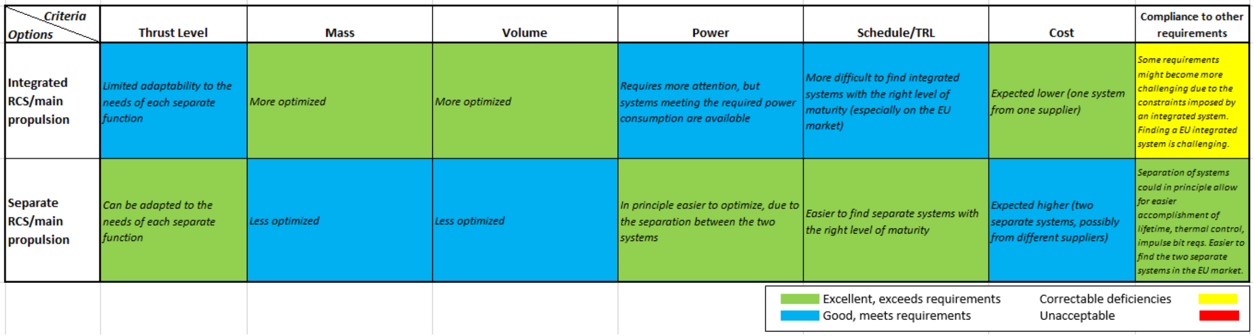
4. Conclusions

The LUMIO mission, one of the winners of the ESA SysNova LUCE challenge, has as primary science goal the observation and characterization of meteoroid impacts on the Lunar farside. The mission will allow to significantly improve the current meteoroid 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.

The LUMIO spacecraft is a 12U CubeSat equipped with the LUMIO-Cam, an optical instrument capable of detecting impact flashes while continuously monitoring and processing the image data. One of the most crucial subsystems for the success of the LUMIO mission is propulsion, given the various important functions it accomplishes: orbital transfer from the initial Lunar parking orbit to the final halo orbit around L2, station keeping, reaction wheel desaturation, end of life disposal manoeuvres.

In this paper, the most important requirements for the propulsion subsystem of LUMIO have been presented and discussed, followed by an extensive presentation of the trade-offs and current choices adopted for both the main and RCS propulsion systems. A final decision on the actual systems that will be used in the LUMIO spacecraft is expected at the beginning of Phase B, which is expected to start at the end of 2021 or at the beginning of 2022.

Table 2. Trade-off integrated vs. separate main/RCS propulsion system.



Criteria / *Options*	**Thrust Level**	**Mass**	**Volume**	**Power**	**Schedule/TRL**	**Cost**	**Compliance to other requirements**
Integrated RCS/main propulsion	🟦 *Limited adaptability to the needs of each separate function*	🟩 *More optimized*	🟩 *More optimized*	🟦 *Requires more attention, but systems meeting the required power consumption are available*	🟦 *More difficult to find integrated systems with the right level of maturity (especially on the EU market)*	🟩 *Expected lower (one system from one supplier)*	🟨 *Some requirements might become more challenging due to the constraints imposed by an integrated system. Finding a EU integrated system is challenging.*
Separate RCS/main propulsion	🟩 *Can be adapted to the needs of each separate function*	🟦 *Less optimized*	🟦 *Less optimized*	🟩 *In principle easier to optimize, due to the separation between the two systems*	🟩 *Easier to find separate systems with the right level of maturity*	🟦 *Expected higher (two separate systems, possibly from different suppliers)*	🟩 *Separation of systems could in principle allow for easier accomplishment of lifetime, thermal control, impulse bit reqs. Easier to find the two separate systems in the EU market.*

🟩 Excellent, exceeds requirements
🟦 Good, meets requirements
Correctable deficiencies 🟨
Unacceptable 🟥

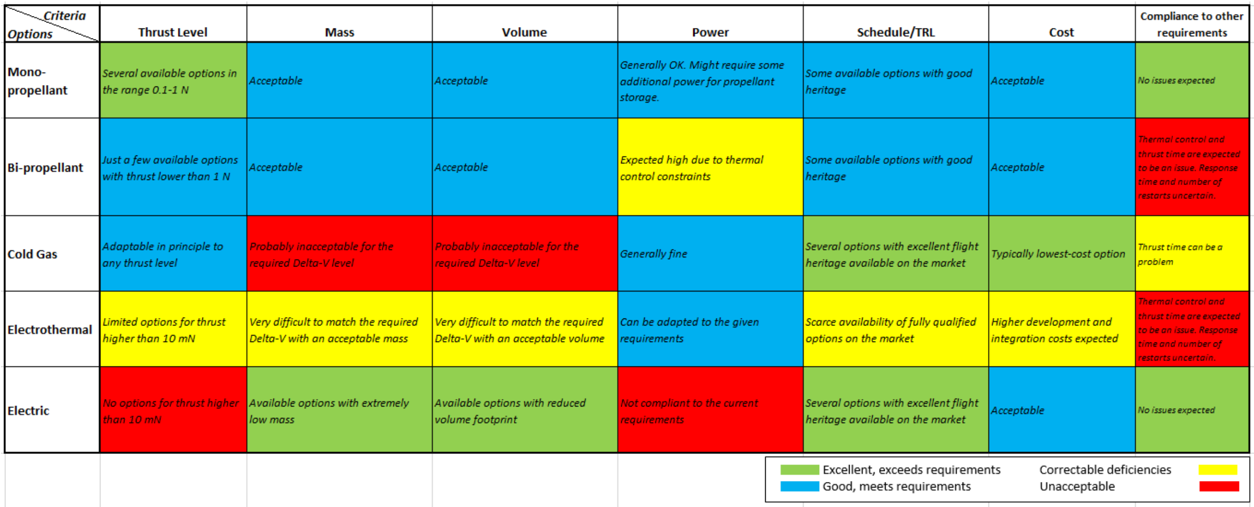
Table 3. Selection of the most important LUMIO propulsion subsystem requirements (main propulsion).

Req. ID	Requirement	*Rationale*
PROP.010	The propulsion system shall provide a minimum Delta-V = 202 m/s for station-keeping and orbital transfer	*From Delta-V budget (including all dictated margins as per ESA margin policy)*
PROP.020	The propulsion system shall allow for a minimum Delta-V = 3 m/s to remain available at the end of the mission for EOL manoeuvres	*From DeltaV budget and EOL strategy*
PROP.050	The thrust delivered by each thruster shall be no more than 1000 mN	*For minimising transfer time without undesired unbalancing effects (Phase 0, CDF study)*
PROP.051	The number of main thrusters shall be 2, placed symmetrically with respect to the spacecraft principal axis of inertia	*To allow for compensation of misalignment effects*
PROP.052	Each thruster shall be throttleable within a range of no less than ±10% of the nominal thrust	*To facilitate compensation of undesired torques (such as those caused by misalignment effects)*
PROP.053	The thrust delivered by each thruster shall be more than 100 mN	*To allow for quasi-impulsive manoeuvres (from Phase 0 and CDF study)*
PROP.070	The propulsion system shall have an operational life in space of at least 1.5 years	*Operational lifetime constraints*
PROP.100	The propulsion system shall have a maximum volume of 5U (CubeSat form factor)	*From spacecraft volume budget*
PROP.110	The propulsion system shall have a wet mass of no more than 6 kg	*From spacecraft mass budget*
PROP.120	The propulsion system shall require a total power of no more than 10 W during firing, 25 W for preheating, and 1 W during standby	*From spacecraft power budget*
PROP.160	The pressure in all components of the propulsion system shall be no more than 50 bar	*From launch and safety constraints*
PROP.190	The propellants shall not include any substance that is classified as toxic according to the REACH regulations	*From safety constraints*

Table 4. Selection of the most important LUMIO propulsion subsystem requirements (RCS propulsion).

Req. ID	Requirement	***Rationale***
RCS.030	The RCS propulsion system shall provide a minimum Total Impulse for all RCS tasks of 110 Ns (if the Aurora ARM system is used), or 170 s (if the GomSpace 6DOF system is used)	*From Attitude control strategy (including all dictated margins as per ESA margin policy). The required total impulse depends on the specifics of the system used (thrust, position of thrusters etc.)*
RCS.050	The thrust delivered by each RCS thruster shall be in the range 1-10 mN	*To allow for an optimum RCS strategy*
RCS.051	The number of RCS thrusters shall be no less than 4	*Minimum number of RCS thrusters theoretically allowing for 3-axis operation*
RCS.070	The RCS propulsion system shall have an operational life in space of at least 1.5 years	*Operational lifetime constraints*
RCS.100	The RCS propulsion system shall have a maximum volume of 1U (CubeSat form factor)	*From spacecraft volume budget*
RCS.110	The RCS propulsion system shall have a wet mass of no more than 1 kg	*From spacecraft mass budget*
RCS.120	The RCS propulsion system shall require a power of no more than 25 W during operation, and no more than 0.5 W during standby	*From spacecraft power budget*
RCS.160	The pressure in all components of the RCS propulsion system shall be no more than 50 bar	*From launch and safety constraints*
RCS.190	The propellants shall not include any substance that is classified as toxic according to the REACH regulations	*From safety constraints*

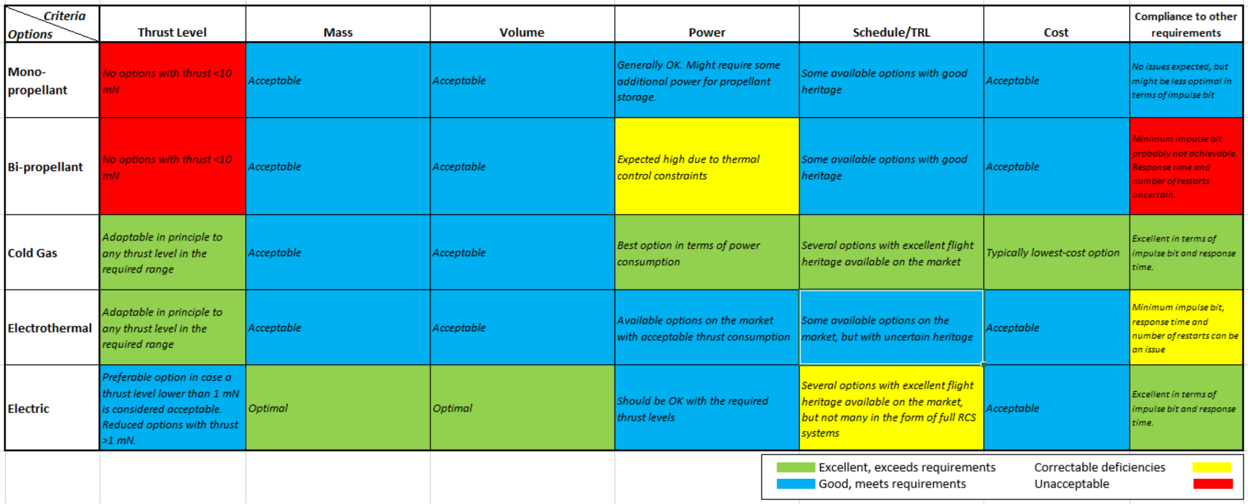
Table 5. Trade-off propulsion type (main propulsion system).



Criteria / *Options*	Thrust Level	Mass	Volume	Power	Schedule/TRL	Cost	Compliance to other requirements
Mono-propellant	🟩 *Several available options in the range 0.1-1 N*	🟦 *Acceptable*	🟦 *Acceptable*	🟦 *Generally OK. Might require some additional power for propellant storage.*	🟦 *Some available options with good heritage*	🟦 *Acceptable*	🟩 *No issues expected*
Bi-propellant	🟦 *Just a few available options with thrust lower than 1 N*	🟦 *Acceptable*	🟦 *Acceptable*	🟨 *Expected high due to thermal control constraints*	🟦 *Some available options with good heritage*	🟦 *Acceptable*	🟥 *Thermal control and thrust time are expected to be an issue. Response time and number of restarts uncertain.*
Cold Gas	🟦 *Adaptable in principle to any thrust level*	🟥 *Probably inacceptable for the required Delta-V level*	🟥 *Probably inacceptable for the required Delta-V level*	🟦 *Generally fine*	🟩 *Several options with excellent flight heritage available on the market*	🟩 *Typically lowest-cost option*	🟨 *Thrust time can be a problem*
Electrothermal	🟨 *Limited options for thrust higher than 10 mN*	🟨 *Very difficult to match the required Delta-V with an acceptable mass*	🟨 *Very difficult to match the required Delta-V with an acceptable volume*	🟦 *Can be adapted to the given requirements*	🟨 *Scarce availability of fully qualified options on the market*	🟨 *Higher development and integration costs expected*	🟥 *Thermal control and thrust time are expected to be an issue. Response time and number of restarts uncertain.*
Electric	🟥 *No options for thrust higher than 10 mN*	🟩 *Available options with extremely low mass*	🟩 *Available options with reduced volume footprint*	🟥 *Not compliant to the current requirements*	🟩 *Several options with excellent flight heritage available on the market*	🟦 *Acceptable*	🟩 *No issues expected*

🟩 Excellent, exceeds requirements
🟦 Good, meets requirements
Correctable deficiencies 🟨
Unacceptable 🟥

Table 6. Trade-off propulsion type (RCS propulsion system).



Criteria / Options	Thrust Level	Mass	Volume	Power	Schedule/TRL	Cost	Compliance to other requirements
Mono-propellant	🟥 *No options with thrust <10 mN*	🟦 *Acceptable*	🟦 *Acceptable*	🟦 *Generally OK. Might require some additional power for propellant storage.*	🟦 *Some available options with good heritage*	🟦 *Acceptable*	🟦 *No issues expected, but might be less optimal in terms of impulse bit*
Bi-propellant	🟥 *No options with thrust <10 mN*	🟦 *Acceptable*	🟦 *Acceptable*	🟨 *Expected high due to thermal control constraints*	🟦 *Some available options with good heritage*	🟦 *Acceptable*	🟥 *Minimum impulse bit probably not achievable. Response time and number of restarts uncertain.*
Cold Gas	🟩 *Adaptable in principle to any thrust level in the required range*	🟦 *Acceptable*	🟦 *Acceptable*	🟩 *Best option in terms of power consumption*	🟩 *Several options with excellent flight heritage available on the market*	🟩 *Typically lowest-cost option*	🟩 *Excellent in terms of impulse bit and response time.*
Electrothermal	🟩 *Adaptable in principle to any thrust level in the required range*	🟦 *Acceptable*	🟦 *Acceptable*	🟦 *Available options on the market with acceptable thrust consumption*	🟦 *Some available options on the market, but with uncertain heritage*	🟦 *Acceptable*	🟨 *Minimum impulse bit, response time and number of restarts can be an issue*
Electric	🟦 *Preferable option in case a thrust level lower than 1 mN is considered acceptable. Reduced options with thrust >1 mN.*	🟩 *Optimal*	🟩 *Optimal*	🟦 *Should be OK with the required thrust levels*	🟨 *Several options with excellent flight heritage available on the market, but not many in the form of full RCS systems*	🟦 *Acceptable*	🟩 *Excellent in terms of impulse bit and response time.*

🟩 Excellent, exceeds requirements
🟦 Good, meets requirements
Correctable deficiencies 🟨
Unacceptable 🟥

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References

[1] European Space Agency, 2016, “SysNova: R&D Studies Competition for Innovation. AO#4: LUnar CubeSats for Exploration (LUCE)”, Statement of Work - Issue 1, Rev 0. TEC-SY/84/2016/SOW/RW

[2] European Space Agency, 2018, “LUMIO. Review of SysNova Award LUMIO Study”, CDF Study Report CDF R-36

[3] S. Speretta, et al., 2019, “LUMIO: an Autonomous CubeSat for Lunar Exploration”, in *Space Operations: Inspiring Humankind’s Future*, Springer nature Switzerland AG

[4] P. Sundaramoorthy, et al., 2018, “System Design of LUMIO: a CubeSat at Earth-Moon L2 for Observing Lunar Meteoroid Impacts”, IAF 69th International Astronautical Congress, Bremen, Germany

[5] F. Topputo, et al., 2018, “LUMIO: a CubeSat at Earth-Moon L2”, The 4S Symposium, Sorrento, Italy

[6] A. Cervone, et al., 2020, “Phase A Design of the LUMIO Spacecraft: a CubeSat for Observing and Characterizing Micro-Meteoroid Impacts on the Lunar Far Side”, IAF 71st International Astronautical Congress (Cyber Edition)

[7] A. Cervone, et al., 2021, “Design Challenges and Opportunities Offered by the LUMIO Spacecraft: a CubeSat for Observing and Characterizing Micro-Meteoroid Impacts on the Lunar Far Side”, IAF 72nd International Astronautical Congress, Dubai, United Arab Emirates

[8] https://nanoavionics.com/cubesat-components/cubesat-propulsion-system-epss/ (last accessed: 6/8/21)

[9] https://www.ecaps.space/products-1n.php (last accessed: 6/8/21)

[10] https://gomspace.com/shop/subsystems/attitude-orbit-control-systems/nanoprop-6u-propulsion.aspx (last accessed: 6/8/21)

[11] https://aurorapt.fi/products/#arm (last accessed: 6/8/21)