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The Radiation Environment and effects analysis of the LUMIO Mission.

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Abstract

The Lunar Meteoroid Impact Observer (LUMIO) is a mission designed to observe, quantify, and characterise the impacts of meteoroids by detecting their flashes on the far side of the moon. These Lunar-based observations offer the opportunity to perform longer data taking compared to Earth-based ones thanks to the fact that they are not limited by illumination, weather and geometry conditions. LUMIO is a 12U CubeSat, with a mass of less than 22 kg, which will be placed on a halo orbit about the Earth–Moon L2 point, where permanent full-disk observation of the Lunar far side can be performed in absence of background noise due to the Earth. Besides the principal instrument of the mission, the LUMIO-Cam, an optical instrument capable of capturing the light flashes in the visible spectrum, which is custom-designed, all other subsystems (e.g. On-board Computer, Propulsion System, Communications, Attitude Determination and Control System, Electrical Power System etc.) are heavily relying on COTS parts. Radiation effects represent already a great concern for any small satellite mission in Low Earth Orbit and in the case of a lunar mission such as LUMIO, it becomes of paramount importance to analyse the harsh radiation environment this mission will face in order to design a radiation-tolerant spacecraft. In this paper we will present the detailed radiation analysis performed during Phase A. A Monte Carlo simulation based on GEANT4 was performed which includes a simplified 2D model of the spacecraft and the predicted fluxes of trapped particles, solar particles and cosmic rays fluxes for the selected orbit. The analysis included Total Ionising Dose and Single Event Effects predictions for the most critical electronic components. Recommendations for the LUMIO system design were drawn and will be used as input for the Phase B spacecraft and mission detailed design.

Keywords: LUMIO, Interplanetary CubeSat missions, Lunar, Radiation environment, Radiation effects

1. Introduction

LUMIO (LUnar Meteoroid Impacts Observer) is a CubeSat mission to a halo orbit at Earth–Moon L2 to observe, quantify, and characterise meteoroid impacts on the Lunar far side 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 4 proposals selected by the European Space Agency (ESA) for the SysNova LUnar CubeSats for Exploration (LUCE) call, a challenge intended to generate new and innovative concepts and to verify quickly their usefulness and feasibility via short concurrent studies [1]. The four proposals, including LUMIO, carried out a pre-Phase 0 analysis, funded by ESA and during the final review and evaluation from ESA, LUMIO was 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. During the CDF study the preliminary mission design was further elaborated and the feasibility and the scientific value of the mission was confirmed. Details on this Phase 0 study have been published in numerous previous publications [2] and [3, 4, 5].

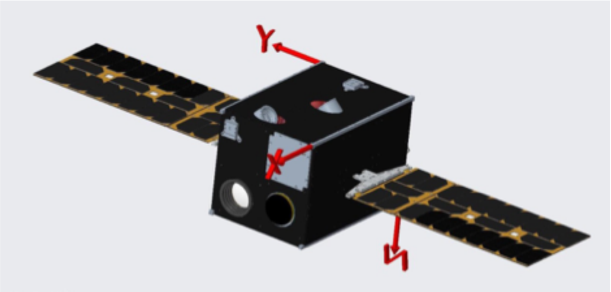

Fig. 1: Rendering of the LUMIO spacecraft configuration resulting from the Phase A study.

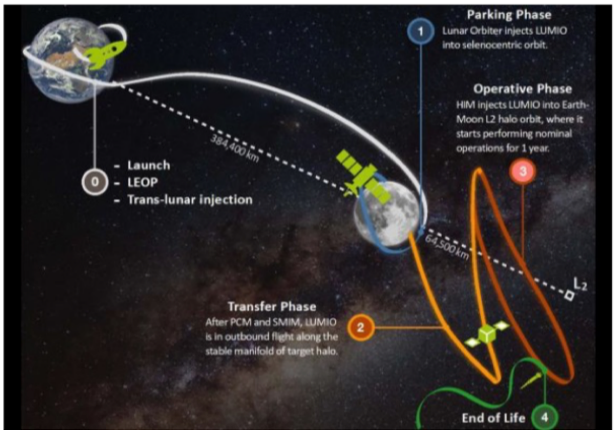

Fig. 2: LUMIO mission concept and phases.

The positive outcome of the Phase 0, resulted in a follow-up contract for the Phase A funded through the ESA General Support Technology Programme (GSTP), which was subscribed by the national delegations of Italy (ASI), the Netherlands (NSO) and Norway (NOSA). The Phase A was kicked off in March 2020 and concluded in February 2021. The first results of the Phase A have been presented in a dedicated paper [6]. This paper, after a short introduction of the LUMIO mission as defined at the end of Phase A, will present the radiation analysis carried out, which includes the radiation environment modelling, the expected Total Ionizing Dose (TID) and Single Event Effects (SEE) levels and the proposed strategy for the radiation hardness assurance of the mission.

2. The LUMIO mission

The LUMIO mission is conceived to address the following science question: What are the spatial and temporal characteristics of meteoroids impacting the lunar surface? In order to answer this question the LUMIO will provide in-situ measurements which will allow to understand of how meteoroids evolve in the cislunar and characterise the flux of meteoroids impacting the lunar surface. The mission will use a 12U form-factor CubeSat which carries as main payload the LUMIO-Cam, an optical instrument capable of detecting light flashes in the visible spectrum to continuously monitor and process the data. See Fig.1 for the rendering of the satellite as defined in Phase A. 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 LUMIO spacecraft will be composed by the following subsystems: the mechanical subsystem (primary and secondary structure); the power generation, storage and distribution subsystem; the command and data handling subsystem (CDHS), the telemetry and communication subsystem; the payload Data Handling System (data storage and transmission) and the attitude determination and control subsystem (ADCS), and orbit determination subsystem.

The LUMIO mission will be divided into 5 phases as shown in Fig. 2.

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 detumbling and deployment of the solar arrays, the payload and all subsystems are commissioned. The spacecraft stays in the parking orbit and, when necessary, performs station keeping and wheel destination manoeuvres.

Transfer: LUMIO 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 Trajectory Correction Manoeuvre (TCM) manoeuvres, and a Halo Injection Manoeuvre (HIM). This phase will last 14 days.

Operational phase: In this phase, expected to last at least 1 year, LUMIO accomplishes its scientific objectives.

End-of-Life: Finally, all spacecraft systems are decommissioned, and the end-of-life manoeuvres are performed.

3. The LUMIO radiation environment analysis

During these phases the LUMIO spacecraft will encounter three different radiation sources, namely trapped particles, solar particles and galactic cosmic rays.

3.1 Trapped particles

Charged energetic particles can get trapped inside of Earth's magnetic fields, giving rise to toroidal shapes called radiation belts. Particle energies vary from several keV up to hundreds of MeV for protons, and from several eV to $\sim$ 10 MeV for electrons. The shape of the radiation belts is heavily distorted by the sun, comparable to the bow wave and wake of a solid moving through a fluid. There are also offsets due to the tilt of the magnetic axis and geological influences. One important distortion is the South Atlantic anomaly, where the inner radiation belt dips down to an altitude of 200 km, leading to an increase in flux of particles in that region. The majority of the trapped particles are either located in the inner or outer Van Allen belt, named after its discovery by James Van Allen. The inner radiation belt, reaching up to 2.5

Earth radii features a mix of energetic electrons and protons. The outer belt begins at about 3 Earth radii and extends up to 12 Earth radii. Mostly energetic electrons are found in the outer belt [7]. During the Earth-Moon transfer phase the Van Allen belts will be crossed and the TID will be dominated by trapped particles. However the fact that the avionics is un-powered reduces significantly the risk of damage.

3.2 Solar particles

Solar flares and coronal mass ejections (CME) produce large bursts of particles from the sun (solar energetic particles). A solar flare is a sudden flash of brightness observed near the Sun surface. Solar flares are classified based on their X-ray intensity measured in units of power per area, or Watts per meters squared. In coronal mass ejection, coronal material in the form of huge amount of plasma and electromagnetic radiation is ejected into space at high speeds. The key differences between the 2 phenomena are the spatial scale and the speed. Flares are local events as compared to CMEs which are much larger eruptions of the corona and solar flares are very fast, CMEs are usually relatively slow. These solar particle events can last for several days. The Earth's magnetic field provides a certain degree of geomagnetic shielding, but anyway solar particle events are so intense that they can damage electronics onboard of satellites and electrical networks at ground level. An example was the solar storm of the 29 October 2003, in which 47 satellites reported malfunctions, including the ADEOS/Midori-2 which was a total loss [8]. Different models are available to predict the solar particles fluxes. In this analysis the CREME-96 and ESP-PSYCHIC models available in SPENVIS [9] were used a shown in Fig.3, 4 and 5.

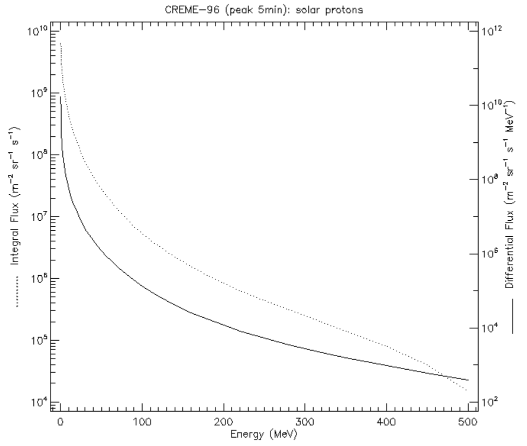

Fig. 3: Integral and differential flux of solar protons (CREME-96).

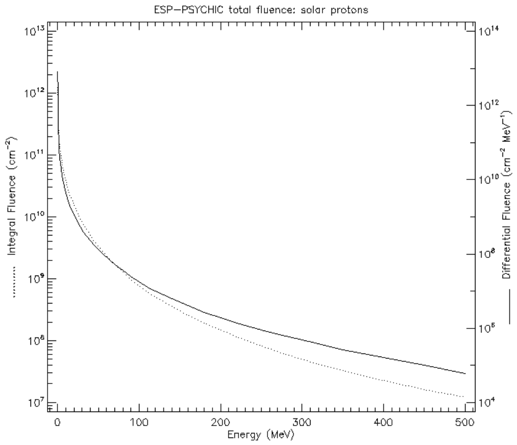

Fig. 4: Integral and differential flux of solar protons (ESP-PSYCHIC).

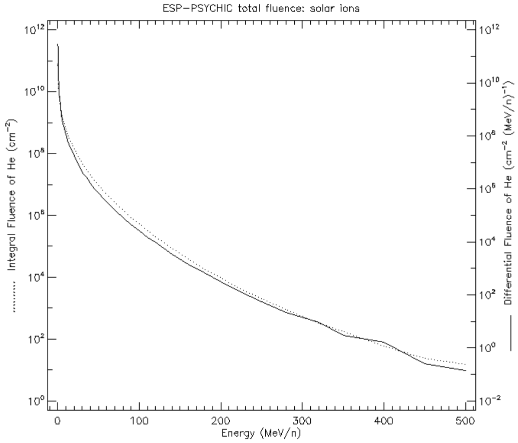

Fig. 5: Integral and differential flux of solar ions (ESP-PSYCHIC).

3.3 Galactic Cosmic Rays

Galactic cosmic rays are the primary source of cosmic rays, originating from outside of the solar system. They provide a constant low-flux or particles, comprised out of 85% protons, 14% alpha particles and 1% heavier nuclei with energies exceeding 1 GeV. The total flux of cosmic ray particles seen outside the magnetosphere at 1 AU is approximately $4cm^2/s$. The most accredited hypothesis is that Galactic Cosmic Rays (GCR) are produced by supernova explosions and travel through the galaxies where they get accelerated up to 10^{21} eV of energy. The flux of GCR is modulated by the solar activity: the strength and of the solar wind affects the levels of galactic cosmic rays reaching the Earth which is at its lowest at solar maximum and at its highest at solar minimum. Cosmic rays are responsible for Single Event Effects in sensitive devices. It

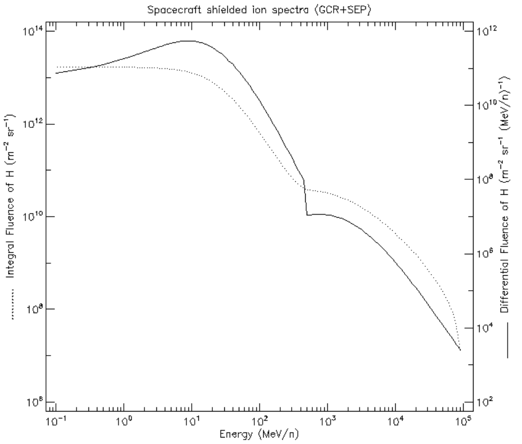

Fig. 6: The shielded flux of GCR and solar ion.

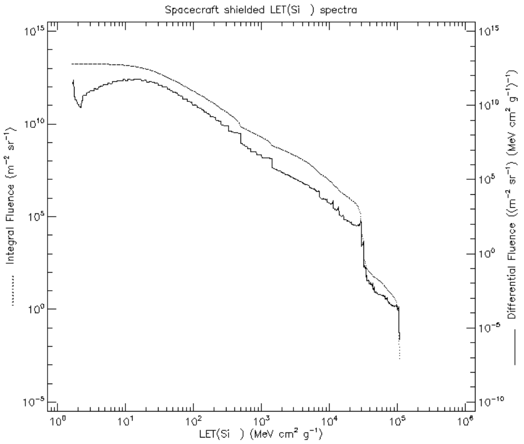

Fig. 7: The LET spectrum.

is assumed that only one particle (protons or heavy ion) can induce an event by striking a sensitive volume in circuits. For heavy ions interaction, the energy deposition is described in terms of Linear Energy Transfer (LET). In this work the model ISO-15390 has been used as shown in Fig. 6 and 7. In the LUMIO mission in the parking, transfer and operational orbit phases, galactic cosmic rays will dominate the environment together with solar particles. The segments of the orbit have been assumed to be near-Earth interplanetary at 1 AU in the SPENVIS simulation. The transfer phase will last 14 days, while the duration of the operational phase has been assumed to be 545 days. The end-of-life phase has not been taken into consideration in the radiation analysis.

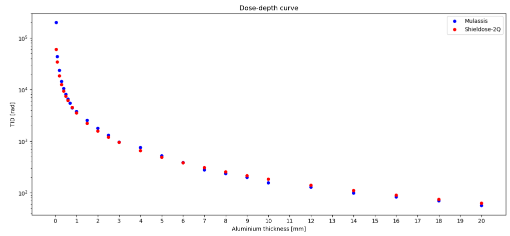

Fig. 8: Comparison between Shieldose-2Q and Mulassis.

4. The Total Ionising Dose analysis

In SPENVIS it is possible to model simple geometry using SHIELDOSE-2Q, an updated version of SHIELDOSE-2 which includes higher energy electrons and different shielding and target materials [9]. It is also possible to use MULASSIS, a multi layered, 1-dimensional shield which is based on Geant-4 toolkit and thus using Monte-Carlo simulation to transport radiation through simple geometry [10]. The 2 methods were compared for verification as shown in Fig.8. Although as discussed in 3.1, it is expected that the radiation damage caused by trapped particles during the Earth-Moon transfer will be negligible, the dose-depth curve of this mission phase has also been estimated assuming a near-Earth phase of maximum 15 days, as expected in the launch scenario baseline with the NASA Commercial Lunar Payload Services (CLPS)*. The dose-depth curve can be found in Table1. Assuming a minimum of 3 mm of shielding (1.5 mm provided by the Cubesat structure and 1.5 mm provided by the deployer) the additional TID experienced by LUMIO will be of only 287.3 rad in 15 days, which corresponds to $\sim$ 20 rad/day. This is considered a very conservative assumption since the launcher adapter interface will also provide additional shielding. Moreover, unpowered electronics is known to be far less sensitive to radiation effects compared to the powered mode of a factor which depends on the type of device and of course the radiation environment considered. Different studies indicated a delay of several tens of krad with respect to the powered mode before seeing TID events [11]. Most of the TID will be received during the operational phase. For this preliminary analysis it is assumed that the structure and solar panels will provide an Aluminium equivalent shielding of 1.5 mm in all sides. A refined analysis will be performed when a detailed design of the satellite structure will be available. For the calculation of the TID the following input parameters were assumed:

- Solar Particle Model ESP-PSYCHIC (total fluence)

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*see "Peregrine Lunar Lander Payload User's Guide" at https://www.astrobotic.com/peregrine with 95% confidence level.

- Orbit parameters: near-Earth interplanetary
- Start date: 28-02-2024
- Mission duration: 393 days and 545 days
- Geometry: solid sphere of 1.5 mm
- Target: Silicon detector of 0.1 mm
- Number of particles: 1000000

Although the nominal duration of the operational phase is one year, due to the uncertainty related to the launch and the transfer to the LUMIO moon-halo orbit approach, we have considered also a worst case scenario in which LUMIO will spend 6 months in the transfer/parking orbit. The solid sphere configuration is used for conditions where components are shielded to a finite level over all solid angles. This approach as indicated by ECSS-E-10-12 this is considered a valid first-order estimate of the influence of shielding, since it represents a worst-case analysis. For a detailed estimation, sector shielding analysis will be used with the final geometry models. The version of Mulassis used was v.01.26.

The estimated values are reported in

As expected, an increase of the duration of the parking + transfer to operative orbit phase will result in an increase of the Total Ionising Dose. This increase is on average 18 rad/day in interplanetary orbit. Spending 5 extra months which is considered a worst case in the mission analysis would thus mean an additional TID of 3.5 krad. This calculation will be updated once the final mission profile will be known and will be taken into account in the overall LUMIO radiation hardness assurance strategy.

Table 1: Dose-depth curve for the Earth-Moon transfer of 15 days

Depth [Al mm]	Dose [rad]
0.05	166600
0.1	77610
0.2	34620
0.3	19770
0.4	12780
0.5	8910
0.6	6551
0.8	4010
1	2740
1.5	1351
2	768.9
2.5	463
3	287.3
4	118.3
5	51.36
6	24.08
7	12.97
8	8.41
9	6.49
10	5.52
12	4.54
14	3.97
16	3.59
18	3.33
20	3.07

Table 2: Total Ionising Dose .

Duration [days]	TID [rad]	Error [rad]
393	8.5473e+03	1.4614e+03
545	1.1676e+04	1.8252e+03

5. Strategy for Radiation Hardness Assurance

For the LUMIO mission, a "careful COTS" radiation hardness assurance approach will be taken, as proposed in in [12], [13], and [14]. This means that key COTS will be screened and tested (e.g. in the payload) while the rest of spacecraft will be designed such as to avoid single-point failures due to radiation induced effects. The LUMIO radiation environment will be dominated by solar particles and Galactic Cosmic Rays. Trapped

particles in the Van Allen belts will not affect the LUMIO spacecraft since all subsystems will be off until injection into the lunar orbit. The Total Ionizing Dose over the mission lifetime was evaluated with a Monte Carlo method (Mulassis v.1.26) and it is predicted to be 8.547 ± 1.461 kRad assuming a solid sphere Aluminium shielding of 1.5 mm which corresponds to the minimum shielding offered by the ISIS structure and solar panels. The TID includes solar particles modelled with ESP-PSYCHIC (total fluence with 95confidence level) and GCR (ISO 15390) in near-Earth interplanetary orbit, assuming a launch date on 28-02-2024.

Regarding Single Event Effects, the recommendation is to combine high-energy proton testing for the key components combined with the analysis of the radiation environment for the particle energies not covered by the proton testing. Former studies have shown that inelastic interaction between protons and the silicon composing typical electronic devices produces most likely LET in the range of $10-14 MeV cm^2 mg^{-1}$. However many modern COTS also contain high-Z materials such as copper and tungsten and as a result of the inelastic interaction taking place between impinging protons and these materials a much higher LET can be produced. For example a 200 MeV proton can produce up to 30 MeV cm 2 mg - 1 LET in tungsten [13]. By testing the LUMIO key COTS with proton beams, SEE cross-sections can be measured for a large range of the expected LETs. As an upper limit it is assumed that the cross-sections for the higher LETs not covered by the proton testing, will not be higher than the physical size of the considered device. In Phase A an extensive analysis of the LET spectrum expected in the LUMIO mission has been performed. A summary of the results is reported in Table. These results show that assuming a solar particle total fluence as predicted by the ESP-PSYCHIC model with 95% confidence, under a shielding of only 1.5 mm, an electric device measuring $10x10\ mm^2$ will see at worst 8 particles with a LET $> 14\ MeV cm^2 g^{-1}$ per day. This fluence is further reduced by a factor 3 by increasing the shielding to 2.5 mm.

Conclusions

The Lunar Meteoroid Impact Observer (LUMIO) mission has as primary goal to observe, quantify, and characterise the impacts of meteoroids by detecting their flashes on the far side of the moon. These Lunar-based observations will allow to significantly improve the current understanding of the meteoroid distribution fluxes. LUMIO will provide unique data, in both space and time, which will complement the Earth-based observations. LUMIO is a 12U CubeSat equipped with the LUMIO-Cam, an optical instrument capable of detecting impact flashes while continuously monitoring and processing the images. LUMIO will operate in a moon halo-orbit where it will be exposed to the harsh environment outside the protection of the Earth magnetosphere. The LUMIO design is heavily based on COTS which are generally not suited for harsh radiation environments. In this paper we have presented the preliminary radiation analysis which included the environment modelling, the TID and SEE analysis. The TID for the worst case of 18 months in lunar orbit is estimated to be 11.7 ± 1.8 krad assuming only 1.5 mm shielding. Regarding the LET flux caused by heavy ions, it is found that a device of $10x10\ mm^2$ will see at worst 8 particles with a $> 14\ MeV cm^2 g^{-1}$ per day. However the sensitivity of the mission critical COTS components will be tested to fully estimate the potential risk.

Table 3: Yearly fluences ($\#/cm^2$) at LET $>$ 14 and $30 MeV cm^2$ for different solar particles models.

Solar Particles Model	**Shielding [mm]**	**Fluence LET** $>$ $14\ [\#/cm^2]$	**Fluence LET** $>$ $30\ [\#/cm^2]$
ESP-PSYCHIC (total fluence)	1.5 2.5	3022 897.7	13.74 3.99
SAPPHIRE (worst fluence)	1.5 2.5	16831 869.5	83.59 3.89
SAPPHIRE (1 in 10000)	1.5 2.5	3704 3674	18.6 3.89

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