<Constellation Mission>

Title: MOTHS (**M**oon **O**bservation **T**hrough **H**yperspectral **S**atellites): 6U Lunar CubeSat constellation for the observation and analysis of Transient Lunar Phenomena

Primary Point of Contact (POC) : Michela Boscia

Email: boscia.1810681@studenti.uniroma1.it

Co-authors: Valentina Abagnale, Gabriele Agresti, Carlotta Amicone, Eleonora Casuscelli, Lorenzo Chiavari, Chiara De Maria, Alessia Di Giacomo, Angelo Fabbrizi, Chiara Falcone, Maria Carla Fiorella, Carolina Ghini, Sidhant Kumar, Gaia Lorenzi, Lorenzo Mazzetti, Linda Misercola, Alessandro Moretti, Asia Nicolai, Alessandro Piro, Angela Raffaele, Leonardo Scardella

Organization: Sapienza University of Rome

Need

For future human lunar missions, in the perspective of choosing appropriate Moon landing and outposts sites, it is relevant to conduct a deep analysis on TLP (Transient Lunar Phenomena) [1]. To detect the color-changing effects on the surface and to study a correlation between outgassing and moonquakes [2], a mission conducted with a constellation in lunar orbit is needed, in order to avoid possible distortion caused by Earth atmosphere and also have a coverage of the far side of the Moon. With a view to future Moon colonization, a technology demonstration mission on Lunar Navigation Satellite System (LNSS) is also needed for the purpose of enabling support navigation and positioning on the surface.

Mission Objectives

The MOTHS constellation consists of six 6U CubeSats with the following objectives:

- To detect color changes on the surface of the Moon in optical wavelengths, to locate the main affected sites and to establish, if present, the correlation with outgassing of Argon, Radon and Polonium.
- To investigate the Argon outgassing location as an indicator of seismic activity [3] with the perspective of using this data as a basis to determine landing sites for future human missions.
- To verify if the TLP observations conducted from Earth surface are affected by the atmosphere comparing, for the same event, the data acquired from lunar orbit and from Earth.
- To perform a technology demonstration of Lunar Navigation and Safety Systems (LNSS), validating its effectiveness and reliability for future lunar missions.

Concept of Operations

Figure 1 shows the mission concept of operation for one CubeSat in its nominal phase.

The CubeSat operations are composed of two main phases: the scientific data acquisition phase, which lasts for 2 minutes and 30 seconds per commanded acquisition, and then the downlink phase with a period of 1 hour and 30 minutes per acquired data set. Between the two phases, the satellite will perform on-board processing of the data.

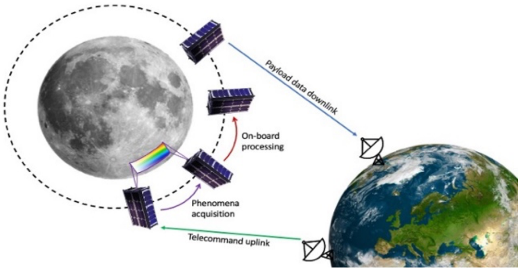


Figure 1: Concept of Operations

In a single orbit, the CubeSat will perform 4 acquisitions, where two of them will be executed on the dark side of the moon and the other on the visible part.

Key Performance Parameters

- To ensure TLPs detection the spatial resolution shall be below 20 m, considering that the phenomena has an extension between a few kilometers, up to 100 km
- To have a spectral characterization of the TLPs, the spectral band to be investigated shall be at least in the blue and red spectral region
- The GNSS receiver shall acquire, as a minimum set, the L1 GPS band and the E1 GALILEO band from Earth GNSS constellations

Space Segment Description

The satellite design is represented in Figure 2, where the view shows the mounting of the components.

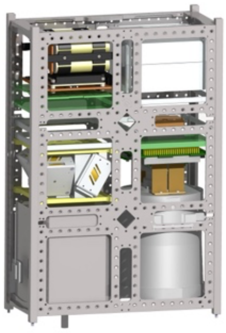


Figure 2: CAD design of the satellite

Payload

The selected primary payload is the Hyperscape100 from Simera Sense: this camera is a hyperspectral push-broom imager for CubeSat satellites. It is based on a CMOS image sensor and equipped with an optical filter in the visible and near-infrared (VNIR) spectral range. By considering the specifications reported in the datasheet [4], the main performances were computed as shown in Table 1.

GSD @ (750 km)	SWATH @ (750km)	Data Rate @ (32 bands)
7 m	27 km	0.4 GB/s

Table 1: HyperScape100 main performance @ 750 km

To accomplish a full spectrum characterization the selected filter allows to investigate 32 bands in a range of 442-884 nm with a hyperspectral resolution of 0.2 nm. The on-board processing through the binning and the CCSDS 122.0-B-2 Lossy/Lossless compression procedures reduce data weight by 50%, providing a Data Rate acquisition of 0.2 GByte/s. An additional system composed of a GNSS receiver and a patch antenna was considered as a secondary payload. This system supports global positioning and navigation for the future lunar mission, following the NASA and JAXA concepts of lunar LNSS mission [5], [6]. The selected receiver is the SGR LIGO, which will operate at the GPS L1 band (C/A code), GALILEO E1 band, and GLONASS G1 band. The selected antenna is the EXA GCA01, a compact GNSS active patch antenna solution that has a wide-band operation over GPS/GLONASS/Galielo/BeiDou systems from 1561MHz to 1606MHz.

Subsystems Description

The selected on-board computer for the mission is the Proton400KTM, which is a Radiation-hardened multi-core Single Board Computer (SBC) that can endure an amount of Total Ionizing Dose up to 100 krads. The storage capability of 256 GB provides crucial support for the payload work in storing scientific observations and analyzing information during the mission.

To allow the proper acquisition of the data, the ADCS shall provide stabilization on three axes, to keep the satellite in nadir pointing. Therefore, the attitude determination can be performed by a set of fine sun sensors, and the Inertial Measurement Unit Sensonor STIM300. The attitude control can be provided by four reaction wheels, in particular the NanoTorque GSW-600 which are organized in a pyramidal setup. Each wheel provides a 1.5 mNm torque, and it is desaturated through a set of thrusters, such as the VACCO ArgoMoon MiPS.

The CubeSat will be equipped with X-Band communication, which is used for Direct-to-Earth (DTE) communication, and S-Band communication, which is used for Inter-Satellite-Link (ISL) communication in case of the former communication failure. The transceivers and antennas by IQspacecom shall be used for X-Band and S-Band communications. Link Budgets, both for DTE communication (X-Band) and for ISL communication (S-Band), are reported in a short version in Table 2, where for DTE communications the specifications of the Goldstone Deep Space Communications Complex by NASA are considered, whereas for ISL communication a realistic evaluation of future Lunar Relays specifications has been done.

Feature	Downlink	Uplink
DTE X-Band communication		
Total Losses (dB)	231.7143	231.7143
Eb/N0 (dB)	21.6588	60.9726
Link Margin (dB)	3.6588	42.9726
ISL S-Band communication		
Total Losses (dB)	189.3451	189.3451
Eb/N0 (dB)	37.5659	59.2418
Link Margin (dB)	19.5659	41.2418

Table 2: Communications Link Budget

The full Link Budget will be reported in the final paper, both for X-Band and S-Band communications.

The solar panels considered for the satellite are the NANOPower Tracking Solar 2030-3P, which consists of 3 panels connected in series. The solar panels generate a total power of 55 W, as reported in Table 3. The Nano Power BPX is chosen as the main battery with 8 cells with configuration of 8S1P. The chosen power distribution unit is the NanoPower P60 System, with a high-capacity power supply. Table 3 shows the Energy budget and the Deep of Discharge for one CubeSat orbit. At the end of each orbit, the battery is fully recharged. The full power and energy budget will be reported in the full-text version of the paper.

Specification	Energy [Wh]
Total components Power demand	-107.554
Total demand + 10% of margin	-118.309
Power Generation (55 W for 140 minutes per orbit)	+ 128.333
Energy Margin per Orbit	**+10.0243**
DOD	**13.8 %**

Table 3. Energy budget and DoD calculations

The best choice for the structure is the 6U Nanosatellite structure by GomSpace, made of Al-7075. This structure is modular, allowing for great flexibility and multiple configurations for hardware mounting. The total mass of one satellite, including 10% of safety margin, is 8.59 kg. The full mass budget will be reported in the full text version of the paper.

Orbit/Constellation/Description

The constellation consists of six satellites divided in two different orbital planes spaced at 180° in Right Ascension of Ascending Node (RAAN). In Table 4 are reported the orbital parameters of one CubeSat. For both cases, $\Omega=0°$ and $\Omega=180°$, the other two CubeSats on the plane are spaced from the first of respectively

60° and 120° in True Anomaly.

e	a	i	Ω	Ω	ν
0	2847.4 km	80°	0°	0°	0°

Table 4: Orbital Parameters for one CubeSat

The ground track and a 3D view of two satellites on the two different planes are shown in Figure 3

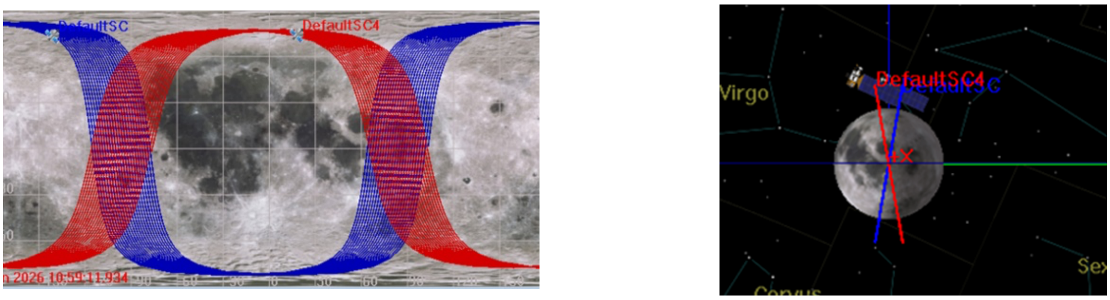


Figure 3: Ground track (left) and 3D view of the orbits (right)

The altitude has been set at 750 km, which allows for a satisfying swath (27 km) and resolution (7 m). The choice of a nearly polar orbit comes from the objective of covering almost the totality of the surface. Spacecraft will be properly spaced to not overlie the sensors' swaths and consequently increase the total coverage. In fact, the True Anomaly of each satellite has been decided to acquire simultaneous images from different and distant points. Contact time with Earth has been analyzed with X-band ground stations located at Goldstone (California), Malindi (Kenya), and Rome (Italy). The first one is currently operative with a diameter of 34 m, an Uplink Gain of 67.1 dBi, and a Downlink Gain of 68.2 dBi. The others are University ground stations supposedly developed for the mission, which are supposed with a diameter of 10 m and a G/T (in clear sky conditions) of 17.7 dB/K. Commercial X-band ground stations with similar features can be applied to the mission case if needed. The results show an everyday contact of nine hours (corresponding to one hour and a half continuously for passage) for every satellite of the constellation.

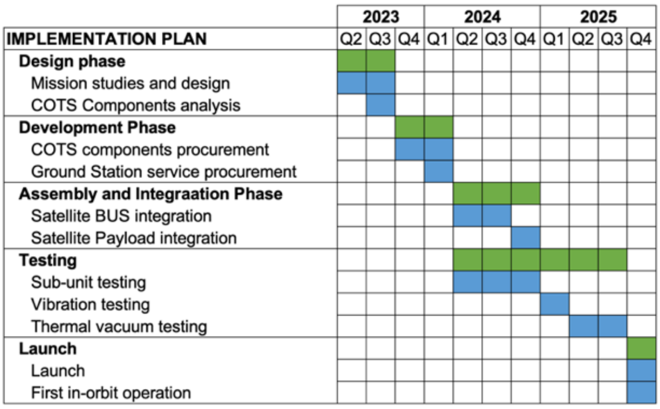
Implementation Plan

The MOTHS student team is composed of 21 students, studying for Master's and Bachelor's degrees in Aerospace engineering at the Sapienza University of Rome and part of the S5Lab student team.

The top-level Gantt Chart, represented in Figure 4, reports the development, assembly, and testing of the first satellite of the constellation, which is expected to be launched in Q4 of 2025.

The launch opportunity and orbit insertion chances will be analyzed in the full version of the paper, with reference to the available information on the imminent Lunar exploration programmes and secondary missions launch opportunities.

Table 5 reports the cost of one satellite, by considering zero costs for AIV and testing, as if performed by the University students team. The total cost for two year operations for one satellite is around 7 million euros. Due to the high cost of the mission, possible



	2023			2024				2025			
IMPLEMENTATION PLAN	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Design phase	🟩	🟩									
Mission studies and design	🟦	🟦									
COTS Components analysis		🟦									
Development Phase			🟩	🟩							
COTS components procurement			🟦	🟦							
Ground Station service procurement				🟦							
Assembly and Integraation Phase					🟩	🟩	🟩				
Satellite BUS integration					🟦	🟦					
Satellite Payload integration							🟦				
Testing					🟩	🟩	🟩	🟩	🟩	🟩	
Sub-unit testing					🟦	🟦	🟦				
Vibration testing								🟦			
Thermal vacuum testing									🟦	🟦	
Launch											🟩
Launch											🟦
First in-orbit operation											🟦

Figure 4: Gantt Chart of the project

governmental endorsement should be considered, including the manpower for the AIV and testing activities within the total cost of the mission, which can equal almost 45% of the total costs, with a resulting total of around 11 million euros.

In order to improve the sustainability of the mission, after the end of the scientific analyses the satellites will be used as a support for the future lunar communication and navigation constellation. Then, the satellites will be disposed in a graveyard orbit, as the likely future guidelines defined by the IADC will propose.

Table 5: Cost for one satellite

Payload	80000 €
Subsystem components	200000 €
AIV and Testing	0 €
Launch	5 million €
Operation and disposal	1 million € per year

Top project risks

Risk description	Risk level	Mitigation action
Saturation of storage capacity due to incorrect processing and compression of data	Low	Telecommand from Earth to reschedule the acquisition and downlink strategy
Impossibility to send commands or receive data to/from the CubeSat in X band	Low	S band antenna and transceiver have been added in order to guarantee telecommunications
Impossibility to desaturate the wheels due to thruster malfunctions	Low	The thruster will be tested fully tested on the ground to guarantee its correct function before the launch
Development complexity of the mission for a student team	Low	Finding space agencies collaboration for technical support
Insufficient funding for the development of the mission	Medium	Finding governmental project or space agencies collaborations for funding opportunities

Table 6: Top project risks

References

The complete bibliography will be reported in the paper extended version, due to page limitations.

[1] B. M. Middlehurst and P. A. Moore, “Lunar Transient Phenomena: Topographical Distribution,” *Science*, vol. 155, no. 3761, pp. 449–451, Jan. 1967, doi: 10.1126/science.155.3761.449.

[2] A. P. S. Crotts and C. Hummels, “Lunar Outgassing, Transient Phenomena, and the return to the Moon. II. Predictions and tests for outgassing/Regolith interactions,” *Astrophys. J.*, vol. 707, no. 2, p. 1506, Dec. 2009, doi: 10.1088/0004-637X/707/2/1506.

[3] B. Sabot *et al.*, “Radon and Polonium as tracers of Lunar outgassing, volatiles and dust: goign back to the Moon?,” presented at the 51st Lunar and Planetary Science Conference, 2020.

[4] Satsearch and Simera Sense, “HyperScape100 technical details.” https://satsearch.co/products/simera-sense-hyperscape100 (accessed Jul. 09, 2023).

[5] L. Groswald, “A Small Satellite Lunar Communications and Navigation System,” Accessed: Jul. 09, 2023. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/8._palo_techexpo_slides_final.pdf

[6] M. Murata, “Lunar Navigation Satellite System (LNSS) and Its Demonstration Mission,” Accessed: Jul. 09, 2023. [Online]. Available: https://www.gps.gov/cgsic/meetings/2022/murata.pdf