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Mathieu Tonneau[⋆] *Gilles Regamey*[⋆] *Marie Ethvigot* [⋆]
[⋆]*EPFL*
PPH 335 Station 13, 1015 Lausanne, CH
matthieu.tonneau@epfl.ch · gilles.regamey@epfl.ch · marie.ethvignot@epfl.ch

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Abstract

The Lunar Global Navigation Satellite System (Lunar GNSS) and telecommunications constellation is envisioned as a transformative infrastructure to support humanity's growing ambitions on and around the Moon. By 2035, the mission aims to establish a fully operational constellation that provides high-precision navigation and moderate-bandwidth communication services across the lunar surface. This paper presents a comprehensive analysis of the mission design, leveraging a distributed constellation of SmallSats in low lunar orbit (LLO) to achieve scalability, cost-effectiveness, and operational resilience.

The proposed system integrates advanced GNSS payloads with Ka-band communication capabilities, supported by modular spacecraft platforms optimized for the harsh lunar environment. Propulsion systems utilizing high-efficiency Hall-effect thrusters ensure precise orbital adjustments and long-term station-keeping. The architecture adheres to stringent international regulatory standards and incorporates robust measures to mitigate risks associated with radiation, thermal extremes, and lunar dust. Stakeholder-driven requirements have been meticulously analyzed to align the technical capabilities of the mission with diverse user needs, including scientific research, commercial activities, and international collaboration.

By addressing these challenges and opportunities, the Lunar GNSS project aims to establish a critical enabler for sustained human and robotic presence on the Moon. This initiative not only advances the frontier of space exploration but also sets a benchmark for collaborative and sustainable space infrastructure development.

1. Introduction

The Moon has reemerged as a focal point for global space exploration, driven by scientific curiosity, commercial ambitions, and the prospect of establishing a sustainable human presence. As missions evolve from isolated landings to long-term operations, the need for reliable navigation and communication infrastructure has become critical. Current reliance on Earth-based systems presents significant limitations, including high latency, limited coverage, and diminished precision in the lunar environment. To overcome these barriers, the Lunar Global Navigation Satellite System (Lunar GNSS) and telecommunications constellation offers a transformative solution.

This paper outlines the development of a distributed constellation of SmallSats in low lunar orbit designed to deliver continuous, high-precision GNSS and moderate-bandwidth communication services. The system architecture prioritizes affordability and scalability, leveraging modular spacecraft platforms equipped with advanced payloads, including dual-band GNSS transmitters and Ka-band communication systems. These satellites are supported by high-efficiency propulsion systems capable of performing complex orbital maneuvers and maintaining long-term operational stability.

The mission design is rooted in a comprehensive systems engineering methodology, integrating inputs from a diverse array of stakeholders such as commercial operators, international regulators, and research institutions. By addressing stakeholder requirements for technical excellence, financial sustainability, and regulatory compliance, the Lunar GNSS project aims to enable a broad spectrum of applications. These include scientific exploration, commercial ventures, and international collaboration, all while setting new standards for sustainability and innovation in space.

The introduction examines the motivations and objectives behind the mission, detailing the environmental and operational challenges inherent to the lunar context. It also highlights the unique technical and strategic innovations embedded in the project, such as modular spacecraft design, integrated risk mitigation strategies, and a commitment to end-of-life sustainability. Through these efforts, the Lunar GNSS and telecommunications constellation seeks to establish a cornerstone for the future of humanity on the Moon, enabling a new era of exploration and discovery.

2. Mission Statement

By 2035, establish a fully operational lunar Global Navigation Satellite System and telecommunications constellation around the Moon to provide high-precision navigation and continuous, moderate bandwidth communication services. This infrastructure will enable advanced lunar exploration, scientific research, commercial activities, and international collaboration, marking a significant step toward sustained human presence on the Moon.

This mission statement is given here as a preamble to the following analysis in an effort to provide the reader with more context as to what this document is about. More detailed, quantifiable goals and objectives will be provided further down as they flow from the stakeholder analysis.

3. Systems Engineering Methodology

In an effort to help the reader understand the reasoning behind the structure of the following document, the systems engineering methodology of the project is broken down here and presented in figure 3. For readers more knowledgeable about the general systems engineering process for space applications, this will merely feel like a reminder. It is by no means intended to be a state-of-the-art demonstration of what systems engineering is –or is not– and more of an aggregate of what the authors learned and have seen throughout the development of the project. Some practices are derived from NASA's Systems Engineering Handbook[3] while others follow the European way of doing things[1]. In any case, its is hoped that the process demonstrated here helps the reader understand the philosophy of the project.

4. Stakeholders and Stakeholder Analysis

4.1 Stakeholder List

With the first step of systems engineering process being the identification of the project stakeholders, a significant effort was put into listing and classifying them, this list can be seen in table 8. With this list as baseline, the goal is to identify what type of interaction each stakeholder has with the project and how it influences the mission.

4.2 Stakeholder Analysis

4.2.1 Clustering Methodology

It is without doubt that some stakeholder needs are aligned whereas others may be opposed. In that sense, organizing them into groups, clusters, helps to get a better grasp of their implications. Among the many possibilities, two approaches are elected here:

- **Impact-Based Classification:** Stakeholders evaluated by *type of impact*:
  - **Financial:** Funding or risk mitigation.
  - **Goods/Services:** Tangible products or services.
  - **Client:** Reliance on mission services.
  - **Influence/Support:** Compliance, advocacy, or operational guidance.
- **Influence/Criticality-Based Classification:** Stakeholders evaluated by their ability to shape the mission *(influence)* and the importance of their contributions *(criticality)*.

4.2.2 Clustering Strategies

Both strategies provide good insights into stakeholder management and, in fact, sometimes overlap highlighting most relevant aspects of this foundation of the project. A comparison of both approaches is presented in figure 4.

4.2.3 Key Insights

- **Impact-Based Clustering:** Focuses on stakeholder roles, simplifying engagement strategies. Highlights functional roles. Provides a role-centric view. The result of that approach can be seen in table 9.
- **Influence/Criticality-Based Clustering:** Prioritizes stakeholders based on their strategic importance. Guides resource allocation and engagement prioritization. The result of that approach can be seen in table 10.

4.2.4 Final Stakeholder Classification

The final clusters are adjusted using both strategies to optimize engagement strategies and group them based on their type of interaction with the project. This was only done from a project perspective and does not take stakeholder interconnection into account.

- **Supporting Institutions:** National Organizations, International Organizations and Regulators, Governments and Policymakers.
- **Commercial Suppliers:** Ground Segment Providers, Launch Providers, Suppliers.
- **Client stakeholders:** Commercial Operators, Universities and Research Institutions.
- **Financial stakeholders:** Insurance and Risk Management Entities, Investors and Financial Institutions.

4.2.5 Stakeholder Engagement

With the stakeholder identified, classified and clustered with regards to their effect on the project, it is now justified to identify what the project can do for them, in a sense, reversing the initial top-down approach. At an initial glance, this takes the form of engagement strategies that are presented in table 11.

4.2.6 Stakeholder Interfaces

Figure 5 highlights the main interfaces and connections between the stakeholders. Along with the stakeholder value network (figure 6), we can use it to derive key insights to ensure that stakeholders needs are met and translated into actionable elements.
We can also identify that the stakeholder relationships are reflected in an almost integral matrix[2], this entails that there is a strong interdependence and that an impact on any stakeholder will be noticed throughout the network.
To ensure the mission's success, the project team must act as a central hub, harmonizing the flows of data, goods, funding, and regulations across all stakeholder groups. Effective coordination between stakeholders is essential to enable seamless operations and maintain alignment with mission objectives.
The involvement of supporting institutions from the early stages of the mission is critical for minimizing the risk of non-compliance with policies and standards. Their regulatory guidance and influence provide a strong foundation for policy alignment and international credibility.
The performance of commercial suppliers is vital to the mission, as their timely delivery of goods and services ensures the project stays on schedule and meets operational requirements. Incentives and regular performance reviews are necessary to maintain supply chain robustness and mitigate potential delays.
Building confidence in return on investment through transparent financial reporting is key to securing sustained support from financial stakeholders. Clear communication of financial metrics ensures alignment with stakeholder expectations and helps attract long-term funding for the mission.
Finally, the engagement of client stakeholders ensures the mission meets user needs effectively. Regular feedback loops provide insights that drive service-level improvements and foster innovation, ensuring the mission remains adaptable and valuable to its end users.

4.3 Stakeholder-driven Requirements

The stakeholder-driven requirements are presented in table 12 containing their specific identification (labeled REQ-SK-00), title, description, rationale, verification method and, if applicable, key performance indicator (KPI). This is done to ensure the results of the stakeholder analysis performed above are indeed taken into account as requirements for the rest of the project.
KPIs are used where relevant to establish a clear assessment metric complementing the verification method and allows to track the requirement throughout the project. They can be found in full, for all requirements, in table 13. The justification or rationale ensures that each requirement makes sense as part of the mission.

5. Goals and Objectives

Goals represent the broad, high-level aims of the mission, such as achieving regulatory compliance or technical excellence, while objectives define specific, measurable actions to achieve these aims, like maintaining >95% service uptime or integrating stakeholder feedback within 30 days. This distinction ensures clarity, traceability, and alignment with stakeholder expectations while providing actionable steps tied to requirements. Separating goals and objectives enables scalability and precision, balancing strategic vision with operational execution.

5.1 Mission Goals

1. **Reliable GNSS/Telecom Coverage:** Deliver GNSS/telecom services with an uptime of >95% to meet operational needs of lunar stakeholders. *Relevant Requirements:* REQ-SK-01, REQ-SK-02.

2. **Regulatory Compliance:** Ensure full compliance with international and national standards for lunar missions, including ITU and COSPAR guidelines. *Relevant Requirements:* REQ-SK-03, REQ-SK-04.

3. **Financial Sustainability:** Maintain transparency in ROI assessments and develop risk mitigation strategies to ensure financial stability. *Relevant Requirements:* REQ-SK-05, REQ-SK-06.

4. **Technical Excellence:** Achieve a component failure rate of <2% and on-time delivery rate of >95% from suppliers to meet system reliability benchmarks. *Relevant Requirements:* REQ-SK-07, REQ-SK-08.

5.2 Mission Objectives

1. **Deploy and Operate a Multi-Satellite Constellation:** Establish a constellation with >95% coverage of the lunar surface to provide continuous GNSS and telecom services. *Relevant Requirements:* REQ-SK-01, REQ-SK-02.
2. **Maintain Transparent Communication:** Provide regular updates to stakeholders, including periodic reporting and risk assessments. *Relevant Requirements:* REQ-SK-05, REQ-SK-06.
3. **Adapt to Stakeholder Feedback:** Implement a process for integrating stakeholder feedback into operational improvements within a response time of <30 days. *Relevant Requirements:* REQ-SK-09, REQ-SK-10.
4. **Adhere to International Standards:** Ensure compliance with ITU regulations for spectrum allocation and COSPAR standards for planetary protection. *Relevant Requirements:* REQ-SK-03, REQ-SK-04.

6. Timeline

One final aspect we ought to touch upon is the project timeline. One of the key stakeholder requirements is in fact the alignment of our tentative timeline and their own expectations. Ensuring a proper match between the two ensures that such a mission actually makes sense and that such a system is in fact an answer to a market demand. The milestones presented in table 14 allow to assess this projected timeline while ensuring that the project follows a state-of-the-art process by going rigorously through all mission phases as defined in industry standards[1].

7. Mission Statement

From the obtained mission goals, objectives and timeline, the mission statement provided in section 2 can be derived. Combined with the stakeholder-driven requirements this allows to create a baseline for future development of the mission concept.

8. System Engineering

8.1 Functional Analysis

Now that a baseline for the mission objectives is a set, we can start to decompose that even further and look into what function need to be performed by the system.
From figure 7 we can see how each function is connected to one or more subsystems. This approach ensures that each key aspect of the mission is covered and that, from a high-level viewpoint, the subsystem choices are efficient.
From the functional decomposition, a new set of requirements can be derived. They are presented in table 12 and labeled based on their respective subsystems (LA: Launch, PA: Propulsion and attitude control, GS: Ground Segment, CD: Command and Data handling, PL: Payload, TH: Thermal, AR: Architecture). As before, a dedicated set of performance metrics are provided in table 13.

8.2 Interface Analysis

With the various sub-systems defined and a preliminary baseline for their roles set, we can look further into their relationship and interfaces. This will help us derive new requirements relative to how the architecture of the spacecraft is structured. This can be seen in the design structure matrix (DSM) in figure 8 (and with the corresponding legend in figure 9).
The DSM presented above gives many subsystem-level insights that we shall discuss hereunder. From a system-level perspective however we can also gather some key information. As expected the structure subsystem is a strong source of bus-type modularity[2], same goes for the power system. Many subsystems also exchange information, yet this information rarely skips a direct neighbor, hence from an information perspective, our architecture can be considered modular within reason.
Subsystem inter-dependencies play a critical role in the mission's success. The Payload and Command/Data Handling subsystems are central to generating mission outputs and exhibit significant inter-dependencies with all other subsystems. Propulsion and Attitude Control are equally crucial, as they directly impact positioning, orbit stability, and the effective functioning of the Payload and Ground Segment subsystems.
Supporting subsystems provide essential stability and operational support. The Thermal subsystem ensures that the Payload and Command/Data Handling systems operate within safe temperature ranges. Although not a direct driver of mission outputs, a failure in the Thermal subsystem could have cascading effects across all systems. Similarly, the Ground Segment subsystem supports mission operations by managing telemetry, command, and data links, primarily acting as a downstream receiver.

8.2.1 Interface Requirements

From those insights we can derive interface requirements to ensure the proper management of critical interfaces, those are presented in table 12 and use the identifier IF and again follows a description of the performance tracking metrics which can be found in table 13.

8.3 Environmental Constraints and Requirements

Another great source of constraints for the mission is the harsh lunar environment. Those are summarized in table 15. From this set of constraints, we can derive a new set of requirements and their respective tracking metrics. They are presented, per usual, in table 12 and use the identifier EN. They are associated with a dedicated performance metric, when applicable, which can be found in table 13.

8.4 End-of-Life Strategy

Another strong engagement point for many stakeholder lies in the end-of-life strategy of the mission. The trade-off study presented in table 16 examines the most viable options within reach.

8.4.1 Conclusion

The relocation to direct retrograde orbit (DRO) and passivation strategy is strongly favored due to its:

- **Cost-effectiveness**: Low operational and long-term maintenance costs.

- **Sustainability**: Reduces orbital debris, ensuring compliance with COSPAR standards.
- **Technical Simplicity**: Eliminates complex operations like docking and refueling.

This strategy aligns with stakeholder priorities, including financial efficiency for investors, sustainability for regulatory and environmental organizations, and reduced technical risk for operators. Implementing this as the baseline approach for the mission's end-of-life phase ensures operational and compliance success.

8.5 Concept of Operations

With the mission now more clearly defined, it is time to look more in depth into what operations are required for a single spacecraft to reach its target orbit around the moon. The visuals in section 13.13 shall illustrate this expected sequence in the form of a Concept of Operations (CONOPS).

8.6 Verification and Validation

Verification and Validation (V&V) are distinct but complementary processes within the mission lifecycle and while both are essential, the following paragraphs shall focus on the former.
The verification methods typically used revolve around 4 main activities: inspection, testing, analysis and review and all requirements defined previously were assigned the most suitable one. Thus, since we know the "how", we shall now discuss the "when".

8.6.1 V&V Timeline

The general verification and validation timeline is presented in table 17 but a more detailed verification plan ordered chronologically is presented in table 18 along with the details of the verification activities to be performed. The objective of those timelines is to assess, at a relevant time during the project lifecycle, the right performance indicators and ensure compliance with the requirements.

8.7 Risk Analysis

Now that the mission is more defined from an architecture, interfaces, target, timeline and environment standpoint, we can more clearly establish the threats that endanger its success.
The risk analysis presented in table 19 shows how the different risks, evaluated at the time of writing, are presented with a dedicated mitigation strategy and evaluated based on their likelihood (P) and impact (I), yielding a total risk score (S). A post mitigation assessment is also provided based on the expected effects of the mitigation strategy. It is uncommon for the mitigation to reduce both the probability and impact of the risk, it is hence also mentioned witch aspect the mitigation strategy targets.
As the project moves further into development, the prior risk assessment serves as a baseline for an improved and more precise analysis. Yet, this preliminary version allows to inform critical design decisions, such as thermal shielding, propulsion system redundancy and radiation hardening. It also identifies high-priority areas (e.g., communication and control systems) where additional resources should be allocated to mitigate high-impact risks. Finally, this analysis demonstrates a proactive approach to risk management, which builds confidence among stakeholders and regulatory bodies.

9. Mission Study

9.1 Methodology

Different mission alternatives were analyzed to explore various configurations and identify the most effective and efficient solution that meets the mission objectives using different criterias such as the cost, the system resilience and the launch window availability.

9.2 Initial Mission Concept Alternatives

The three mission alternatives examined differ primarily in their configuration: the first one uses medium-sized satellites in an NRHO orbit, inspired by traditional GNSS systems; the second one adopts a distributed constellation of SmallSats in low lunar orbit, emphasizing scalability and affordability; and the third one, also inspired by traditional GMSS systems, employs a smaller constellation of large, modular satellites in an NRHO orbit, leveraging advanced technologies like laser inter-satellite links for higher performance and redundancy. The following table presents the three mission alternatives in more detail.

Attribute	Alternative 1	Alternative 2	Alternative 3
Payload	Dual-band GNSS, Ka-band, redundant	Compact GNSS, Ka-band, laser	High-power GNSS, Ka-band, laser
Spacecraft Bus	Medium-sized	SmallSat (200-300 kg)	Large modular
Ground Segment	Dedicated (US/EU)	Commercial (AWS)	High-capacity (DSN)
Operations	Ground-controlled	Semi-autonomous	Fully autonomous
Constellation	12 sats, NRHO, 3 planes	18 sats, HLO, multi-plane	12 sats, NRHO, laser links
Launcher	Falcon Heavy, 3 launches	Falcon 9, 6 launches	New Glenn, 3 launches
Estimated cost	\$1.8B	\$0.9B	\$2.5B

Table 1: Comparison of Mission Alternatives

Category	Traditional Constellation	Distributed SmallSat Constellation	Modular Large-Scale Constellation
R&D	\$400 million	\$200 million	\$600 million
Platform	\$300 million	\$150 million	\$400 million
Payload	\$250 million	\$100 million	\$500 million
Launch	\$300 million	\$120 million	\$400 million
Operations (7 years)	\$550 million	\$330 million	\$600 million
Total Budget (w/o contingencies)	\$1.8 billion	\$900 million	\$2.5 billion
Contingency	\$480 million	\$250 million	\$670 million
Total Budget (w/ contingencies)	\$2.28 billion	\$1.15 billion	\$3.17 billion

Table 2: Financial Budget Details for Mission Alternatives

Table 2 presents the budget breakdown for the three mission alternatives, detailing the costs associated with R&D, platform and payload development, launch, and seven years of operations. Contingency factors were applied to account for uncertainties, with 50% for R&D, 20% for platform and payload, 10% for launch, and 25% for operations, resulting in adjusted total budgets.

9.3 Final selection criteria

The evaluation of the three mission alternatives was conducted using a Pugh matrix (provided in Table 20 in the Appendix), which provided a systematic framework for comparing each configuration based on weighted criteria. Key criteria, including cost, system resilience, payload redundancy, and launch requirements, were assigned the highest weights due to their critical impact on the mission's overall feasibility and success. This analysis identified the second alternative, a distributed constellation of SmallSats, as the most favorable option, offering an optimal balance of cost-effectiveness, scalability, and operational efficiency to meet the mission objectives.

10. Mission architecture

10.1 Orbital parameters

For accurate GNSS positioning, at least three satellites must be within line of sight (LoS) for latitude and longitude determination, and four are required to include altitude positioning. Lunar orbit configurations for GNSS satellites have been extensively studied, and we have chosen to base our constellation design on the work of Gordienko et al. (2016) . Specifically, we adopted their third satellite system configuration, which consists of three orbits with six satellites each.

This design ensures that at least three satellites are in LoS over the majority of the lunar surface, while benefiting from excellent passive orbital stability (with a worst-case stability of 503 days). This stability extends the operational lifetime and minimizes the cost of orbital maintenance maneuvers. Although the configuration is not fully redundant in the event of satellite failure, the majority of the lunar surface, especially at high latitudes, retains consistent coverage with minimal impact.

Satellite system Configuration Ver.3		
semi major axis a_0 = 4400 km		
inclinations i_0 = 113°		
Ω_1,°	Ω_2,°	Ω_3,°
30	150	270
u,°	u,°	u,°
0	20	40
60	80	100
120	140	160
180	200	220
240	260	280
300	320	340

Table 3: Orbital parameters of (**Gordienko**) Lunar Orbit Configuration Version 3

10.1.1 Maneuvers

To reduce cost and increase modularity of the constellation, each satellite is independent from each other when released from the rideshare vehicle in LEO and perform all maneuvers with its own propulsion system. Using high efficiency hall effect thrusters with liquid iodine as its propellant, one can expect an I_{sp} of 1244[sec] with a maximum continuous thrust of 17[mN] (see 11.1.6). Such high efficiency is required to reduce weight and volume usage inside the small-sat frame but limits us to long duration thrust spiral maneuvers instead of optimal short bursts Hohmann transfers for the LEO to LO voyage (Oberth effect). This problematic also affects inclination changes maneuvers but fortunately, by using a launcher (like a spaceX falcon Heavy) departing from the Kennedy space center to a LEO at an inclinations of 28.5, we only have 0.08 of correction in order to match the lunar orbital parameters[5].

$$\theta_{Eecl} + \phi_{Mecl} = \theta_{launch} + \theta_{corr}$$
$$23.44 + 5.14 = 28.5 + 0.08$$

ΔVComputation Spiral orbit raising burns at constant prograde low thrust can be approximated by summing infinitesimal circular orbits rises from LEO up to the moon Hill sphere of influence. Similarly, Lunar orbit insertion can be achieved with a retrograde spiral burn. the equation for spiral maneuvers ΔV is therefore:

$$\Delta V_{sp} = \left| \sqrt{\frac{\mu}{r_i}} - \sqrt{\frac{\mu}{r_f}} \right|$$

inclinations changes are notoriously costly and are computed with

$$\Delta V_{\theta} = 2sin\left(\frac{\theta}{2}\right)\sqrt{\frac{\mu}{r}}$$

Additionally, we have to periodically make orbit maintenance maneuvers to counteract solar radiations and orbital instability. Fortunately, our orbital configuration is stable and we estimated about 4[m/s] of ΔV for each year of operation. Table 4 shows the expected maneuver cost of each mission phases.

Propulsion Phase	Maneuver	ΔV [m/s]
A - LEO	Inclination change of 0.08 [deg]	10.629
B - TLO	spiral orbit raising from LEO to R_{sm}	5158.804
C - LO injection	spiral orbit lowering to LO	931.463
D - Operations	orbit maintenance	24
E - DRO injection	spiral injection to graveyard DRO	1054.6

Table 4: Satellite mission maneuvers and associated costs.

Propellant mass The propellant mass required for each maneuver is calculated using the Tsiolkovsky rocket equation and $m_p = m_o - m_f$, giving us

$$m_p = \frac{exp\left(\frac{\Delta V}{I_{sp} g_0}\right)}{m_f} - m_f$$

Where m_f is the mass of the spacecraft at the end of the maneuver. We can then work iteratively backward through the mission phases to get the total mass of the spacecraft at launch knowing the total dry mass of the satellite at the end of life. This calculation was automated for each iteration using a script (see 11.1).

10.2 Payload & Communication Systems

To fulfill the mission, our spacecraft needs four communication systems, namely Telemetry Tracking and control (TT&C), constellation communication system (CSS), GNSS beacon and Satellite ground telecoms (SGT). Table 5 shows the link budget obtained to answer each system performance requirements and by iterating over typical antennae and active gains for their signal path.

System	**TT&C**	**CCS**	**GNSS**	**SGT**
frequency [GHz]	2.2	$2.8 \cdot 10^8$	1.57	20
Average distance [km]	378022	4400	3352.5	3352.5
Path Loss [dB]	228.7	334.3	116.4	192.5
Sat. Ant. Gain [dB]	2.15	169.4	17.9	29.4
Rec. Ant. Gain [dB]	58.1	169.4	3	30.2
Polarization	circular	linear	circular	circular
Atm. & rain losses [dB]	1	0	0	0
Sat Rx Gain [dB]	10	0	-	16
Sat Tx Gain [dB]	10	10	10	16
link Rx Gain [dB]	24	0	-	10
link Tx Gain [dB]	24	10	-	10
Modulation	BPSK	QPSK	BPSK	QFSK
Correction code	Viterbi	-	-	Hamming
Typical baudrate [Mb/s]	1	$10 \cdot 10^3$	$5 \cdot 10^{-5}$	1000
Bandwidth [MHz]	1	$10 \cdot 10^3$	24	$1 \cdot 10^3$
Estim. Noise Floor [dB]	-150	-101.6	-128.4	-112.2
UpLink Margin [dB]	14.5	115.7	-	5.3
DownLink Margin [dB]	14.5	115.7	32.9	5.3

Table 5: Link budget of the communication systems

10.3 Mission modes

To determine a sensible power budget and simplify operation procedures we need to define the mission modes seen by the spacecraft. We devised 4 modes for the mission phases and particular events.

A - Maneuvers. In this critical mode, propulsion, AOCS and TT&C are privileged to ensure that the spacecraft follows the target trajectory and keeps radio link with GS. The payload and constellation communication systems are therefore completely turned off to save power. The OBC task is to be responsive to the GS and apply the trajectory control loop whilst coordinating the AOCS and Propulsion subsystems. This mode is used in all maneuvers, including orbit maintenance.

B - Operations. Once in the operation lunar orbit, the satellite can power down the propulsion system and rely on the AOCS to align the attitude for the payload antennas. The Payload is then fully powered to fulfill the mission goal. Nearly all systems on board are powered except propulsion. This mode is used during the operational phase and is hopefully only interrupted for orbit maintenance maneuvers.

C - Sleep. When the satellite is on hold, The payloads can be powered down as can the propulsion system. Full control of the satellite is kept in preparation for Operations with reduced power usage. This mode is reserved for operation periods lacking user usage and end of life.

D - Safe Mode. This mode is reserved only in case of a critical system failure. Only highly critical components are kept online to save power, including the EPS, TMU, attitude determination of the AOCS, TT&C and the OBC in low power mode to maximize vehicle recovery probability. This mode can triggered automatically by the OBC or requested from the control center but should ideally not be encountered in a nominal mission.

11. Baseline Design

11.1 Spacecraft Configuration

Figure 1 and 2 show the baseline configuration with all critical components high level interfaces and possible spacial emplacement. The overall size is under about 1 x 1 x 2 m. The placement of the separation mechanism is to be compliant within an XL full plate on spaceX Smallsat Rideshare Program[4].

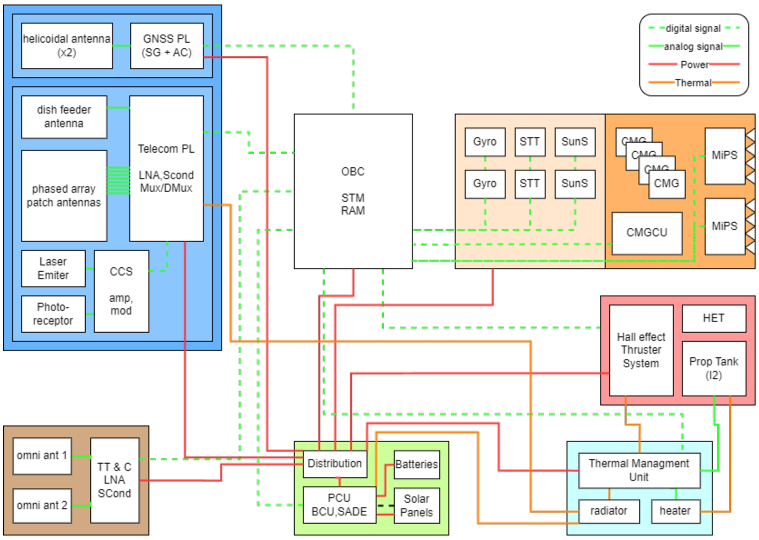

Figure 1: Spacecraft Configuration high level functional diagram.

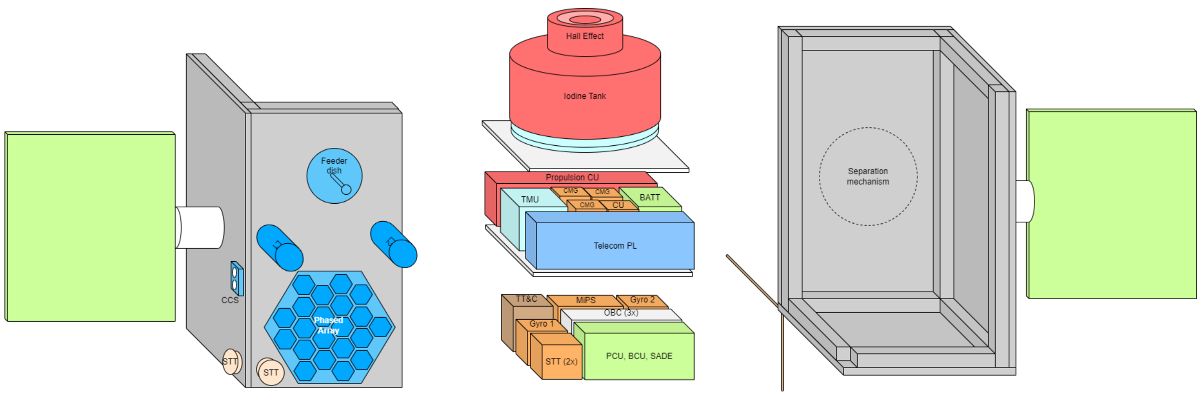

Figure 2: Satellite spacial configuration and placement of the subsystems. The color code is the same as in Fig 1.

Validation script To rapidly go over iterations, we devised a python script to virtually build our spacecraft and compute essential elements of the mission, see 11.1 for the complete code. The spacecraft is given all the mission flight phases as per the conops and each components containing relevant parameters are added. running the script gives us an overview of the critical elements of each flight phases along wet/dry mass and power budget estimations.

11.1.1 Structure

The satellite structure consists of honeycomb aluminum panels with CFRP face sheets panels supported by aluminum and carbon fiber struts. This design, which is widely used in small satellites, offers high modularity in component

Component	ref	system	dry mass [kg]
frame	custom AL/CFRP panels	Structure	3 ± 5%
Solar panel deployment mech.	sparkwing		0.8 ± 1%
Solar array drive mech.	KONGSBERG KARMA-4 SG		7.2 ± 1%
Launcher separation mechanism	RUAG PAS 381S		0.98 ± 1%
Solar panels	Sparkwing	Power	8.36 ± 1%
Battery	Titan 2 pack		3.7 ± 1%
PDU	Berlin space PCU-110		1.8 ± 1%
Hall Effect thruster	Busek BHT600	Propulsion	1.9 ± 1%
Iodine tank	-		10 ± 10%
Thruster system	Busek LCPPU		1.4 ± 5%
Atomic Clock	Microsemi CSAC SA.42s	Payload (GNSS)	0.1 ± 1%
Signal Generator	custom		1 ± 20%
helicoid Antenna	custom		0.4 ± 20%
Feeder dish Antenna	custom	Payload (Comms)	0.4 ± 20%
Tx Phased array	custom		1 ± 20%
CCS optical link	TeSat SCOT20		3.2 ± 1%
Transponder	custom		3 ± 20%
On Board Computer	STM NanoSatPro	Avionics	0.3 ± 1%
TT&C Transponder	L3Harris CXS-2000		3.9 ± 1%
TT&C Antenna	custom		0.2 ± 20%
StarTrackers(2x)	ST400	AOCS	0.56 ± 1%
CMG system	HoneyBee Microsat CMG Array		3.10 ± 1%
Coldgas MiPs	vaco X19039000-03		2.508 ± 1%
Gyros	STIM380H		0.12 ± 1%
Thermal Management Unit	custom	Thermal	2 ± 10%
radiator	custom		0.5 ± 10%
heater pad	custom		0.1 ± 10%
Misc.	-		*tot* ± 10%
total dry mass			67.67
resulting Iodine Propellant			48.373
Total spacecraft mass			**116.1**

Table 6: Spacecraft components and mass budget.

placement while maintaining a low weight. Additionally, structural components are designed to endure launch loads, thermal cycling, and radiation in space, ensuring the longevity of the satellite in the space environment. It allows for easy integration of subsystems and flexibility in layout adjustments during the design and testing phases.

11.1.2 Electrical Power System (EPS)

The choice of the PCU-110 is driven by its high adaptability and integration of multiple functionalities into a compact package, making it well-suited for small satellite platforms. Its ability to customize voltage levels and interfaces ensures compatibility with the satellite's power demands. it has more than enough power channels for our solar arrays and already integrate a battery management unit that is compatible with Titan 2 Lithium polymers packs.

Table 7 Shows that even with all component on the satellite active, the spacecraft can manage to produce enough power if properly lit by the sun. In fact we choose to have two large solar panels to even the weight and add redundancy to the power generation, only one solar panel is enough to complete the power needs of the non-thrusted operation phase. The battery serve as a buffer for power spikes and eclipse phases. They can sustain the spacecraft in safe mode for approximately 20 hours and in operational mode for 5 hours, much more than the 2.62 hours of the orbital period, meaning we do not need to fear the regular eclipses encountered.

11.1.3 Payload

The payload provides high-precision GNSS positioning and medium-bandwidth telecommunications for lunar operations. It includes:

Subsystem	Name	Power (W)	Contingency (W)
Power Generation			
Power	Solar Panels	+616.0	+6.16 (1%)
	Subtotal Generation	+616.0	+6.16
	Total Generation	**+622.16**	–
Power Consumption			
Propulsion	Hall Effect Thruster	-300.0	-75.0 (25%)
Thermal	Thermal Management Unit	-10.0	-2.5 (25%)
Avionics	Onboard Computer	-6.0	-1.5 (25%)
Payload	GNSS	-30.0	-7.5 (25%)
Payload	Atomic Clock	-0.1	-0.025 (25%)
Payload	Signal Generator	-10.0	-2.5 (25%)
Payload	Telecommunications	-20.0	-5.0 (25%)
Payload	Telecoms TX LNA	-40.0	-10.0 (25%)
Payload	Telecoms RX LNA	-40.0	-10.0 (25%)
Communication	TT&C	-20.0	-5.0 (25%)
Attitude Control	Star Trackers	-1.4	-0.35 (25%)
Attitude Control	Cold Gas System	-2.0	-0.5 (25%)
Attitude Control	Gyros	-3.6	-0.9 (25%)
	Subtotal Consumption	-483.1	-120.8
	Total Consumption	**-603.9**	–

Table 7: spacecraft high level power budget worst case scenario

- **GNSS Module:** 30 W signal generator, atomic clock (< 1 ns accuracy), and a medium-gain circularly polarized antenna ($L1$: 1575.42 MHz, $L2$: 1227.60 MHz).
- **Telecommunications Module:** 20 W MUX-DMUX router, medium-gain parabolic feeder antenna, and phased-array user antenna (28 dB gain) supporting 50 Mbps data rates.

11.1.4 Command & Data Handling

On-Board Computer The on-board computer (OBC) is designed to operate in a space-qualified environment, ensuring robust performance under extreme conditions. To guarantee mission success, the system incorporates fault tolerance and redundancy, with a total of three OBCs deployed. we choose STM's NANOSATPRO because it satisfies all aforementioned conditions whilst weighting only 300 grams and consuming 4.5 W of power. Leveraging an FPGA-based logic synthesis implementation of a RISC-V architecture. This approach allows for optimized performance and flexibility in handling mission-specific tasks. Memory includes 32 MB of SDRAM and 128 MB of SPI Flash, enabling in-orbit software updates. Additionally, the system includes a BIOS stored on ROM for bootstrapping and critical operations. It is also able to handle many protocols: SPI, I2C, CAN, RS485, UARTS and GPIO 3.3V logic natively, which covers all current needs for sensor and control units.

Databus The satellite employs a distributed bus architecture to provide greater flexibility in interfacing with various subsystems. To manage high data demands efficiently, the telecommunications subsystem is allocated a dedicated bus, offloading its data handling from the primary system. The mission requires a nominal data rate budget of 6 kbps, assuming a 1 Hz measurement rate with 32-bit precision, well below the 1Mbps ensured by telemetry radio link.

11.1.5 Telemetry and Control

Telemetry Telemetry packets are generated by the OBC, compiling sensor status, mission data, and precise position and attitude estimations. These packets are transmitted every half hour or upon request from the control station, ensuring timely monitoring of the satellite's status.

Control By default, the satellite operates autonomously for both attitude and orbit maintenance. This autonomy reduces the need for continuous ground intervention, enhancing mission efficiency for constellation mission while maintaining precise operational control. Nevertheless, a ground support team is essential for monitoring, system adjustments, and is necessary in case of failure resolution while the spacecraft is in safe mode.

11.1.6 Propulsion System

The satellite is equipped with a Hall Effect Thruster (BHT-350) from Busek, which uses liquid iodine as a propellant. This choice is advantageous as it eliminates the need for high-pressure tanks, although it requires heating for propellant feeding management. The thruster is paired with a motor driver, also provided by Busek, to generate high voltage and control propulsion operations. The system's high specific impulse (I_{sp}) makes it ideal for trans-lunar maneuvers, and its high reliability and easy cycling capabilities ensure efficient orbital maintenance.

11.1.7 Attitude Orientation Control System

Attitude Determination Attitude determination is achieved through a combination of sensors designed to ensure reliable operation in the lunar environment. Two star trackers are included to provide precise orientation, with redundancy to address potential sun-blind issues. Additionally, two sun sensors and two mechanical gyroscopes, which are less susceptible to drift, further enhance attitude determination. The main OBC synthesizes precise position and attitude data from these sensors, enabling accurate control.

Control Moment Gyroscopes The satellite utilizes a tetrahedral configuration of Control Moment Gyroscopes (CMGs) to ensure robust attitude control. While lunar gravitational gradients and solar radiation pressure are relatively mild, they can still cause CMGs to reach their angular momentum limits. To mitigate this, Micro Propulsion Systems (MPS) are employed for angular momentum desaturation.

Micro Propulsion Systems Micro Propulsion Systems complement the CMGs by facilitating rapid maneuvers and desaturating their angular momentum, ensuring sustained attitude control and operational flexibility.

11.1.8 Thermal Control system

The spacecraft experiences extreme temperature variations due to lunar orbit conditions. To ensure the design of a robust thermal subsystem, materials with appropriate thermal properties were selected and thermal flux calculations were performed using the following formula, to calculate the worst case temperatures the spacecraft would endure (full power during daylight or no power during eclipse):

$$T^4 = \frac{(A_\alpha \cdot J_{\text{sun}} + A_a \cdot J_a)}{A_\epsilon \cdot \sigma} \cdot \left(\frac{\alpha}{\epsilon}\right) + \frac{A_p \cdot J_p}{A_\epsilon \cdot \sigma} + \frac{P_{\text{internal}}}{\sigma \cdot A_\epsilon \cdot \epsilon}$$

where J_{sun} is the solar flux ($1361\,\text{W/m}^2$), J_{albedo} is reflected sunlight, and J_{IR} is planetary infrared radiation. Absorptivity (α) and emissivity (ϵ) depend on material properties.

The thermal analysis was performed on both the body of the spacecraft and the solar panels and the following materials were chosen for both parts of the spacecraft. The satellite body is covered in aluminum tape ($\alpha = 0.21$, $\epsilon = 0.04$) and the solar panels are in silicon ($\alpha = 0.75$, $\epsilon = 0.82$).
The results of the thermal analysis are the following: during daylight, the satellite body reaches **165**°C and the solar panels reach **120**°C, while during eclipse, the satellite body drops to **34**°C and the solar panels to **−60**°C.
The thermal control system requires a **radiator** to dissipate excess heat during daylight and prevent overheating, **heat transfer tubing** to efficiently redistribute heat to the radiator and avoid localized overheating, and **resistive heaters** to maintain critical components' functionality during the cold conditions of eclipses.

12. Conclusion

The Lunar GNSS and telecommunications constellation represents a critical enabler for the future of lunar exploration, scientific research, and commercial activities. By providing reliable navigation and communication infrastructure, the project supports a broad range of stakeholders and enhances the feasibility of sustained human and robotic presence on the Moon.

Through the innovative use of a distributed SmallSat constellation, advanced propulsion systems, and modular spacecraft design, the mission achieves a balance of technical robustness, cost-efficiency, and environmental sustainability. The integration of stakeholder requirements and adherence to international standards further strengthens the mission's foundation, ensuring its relevance and long-term viability.

As humanity looks beyond Earth, the Lunar GNSS project not only meets the immediate needs of lunar exploration but also establishes a scalable framework for future space infrastructure development. This initiative lays the groundwork for a collaborative and sustainable future in space exploration, marking a significant milestone in the journey toward a permanent human presence on the Moon and beyond.

References

[1] European Cooperation for Space Standardization (ECSS). *Space Project Management: Cost and Schedule Management*. Last accessed: January 13, 2025. 1996. URL: `https://ecss.nl/wp-content/uploads/standards/ecss-m/ECSS-M-30A19April1996.pdf`.

[2] Katja Hölttä, Eun Suk Suh, and Olivier de Weck. "Tradeoff between modularity and performance for engineered systems and products". In: *Proceedings of the International Conference on Engineering Design (ICED)*. International Conference on Engineering Design (ICED). Melbourne, Australia, Aug. 2005.

[3] National Aeronautics and Space Administration (NASA). *NASA Systems Engineering Handbook*. Rev 2. National Aeronautics and Space Administration. Washington, DC, 2016. URL: `https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook.pdf`.

[4] *Rideshare Payload User's Guide*. Space X. Sept 2024. URL: `https://storage.googleapis.com/rideshare-static/Rideshare_Payload_Users_Guide.pdf`.

[5] Dr. David R. Williams. *Moon Fact Sheet*. URL: `https://nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html`. NASA Goddard Space Flight Center.

13. Appendix

13.1 Systems Engineering Methodology

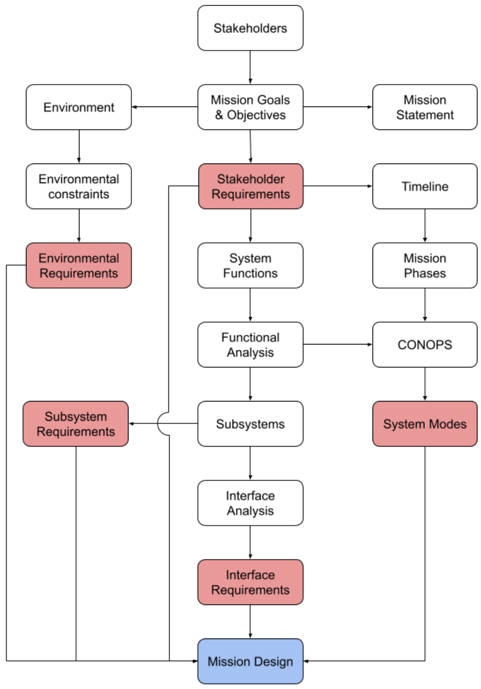

Figure 3: Flow Diagram of the General Systems Engineering Methodology for the project

13.2 Stakeholder List

Stakeholder	Role/Interest	Examples
Suppliers	Provide components, materials, and spacecraft bus.	Airbus, Lockheed Martin, Blue Canyon
Launch Providers	Deliver the spacecraft to its designated orbit.	SpaceX, ULA, Arianespace, Rocket Lab
Commercial Operators	Use GNSS/telecom services for Earth-based and lunar operations, including navigation, communication, and data services.	Amazon, SpaceLink, Astrobotic, iSpace, Intelsat
Investors and Financial Institutions	Fund the mission and expect returns on investment.	Morgan Stanley, Goldman Sachs, Space Angels
Ground Segment Providers	Operate ground stations for communication and data relay.	AWS Ground Station, Kongsberg, KSAT
Mission Control	Manage satellite operations and ensure system functionality.	NASA Deep Space Network, ESA ESTRACK
International Organizations and Regulators	Set global standards and ensure compliance.	UNOOSA, ITU, COSPAR

National Organizations	Oversee mission compliance and funding.	NASA, ESA, DoD, JAXA
Governments and Policymakers	Provide policies, regulations, and partial funding for space missions.	US Congress, European Commission, CNSA
Universities and Research Institutions	Conduct scientific research and provide technical support.	MIT, Caltech, EPFL
Environmental and Ethics Organizations	Advocate for sustainable practices and ethical operations.	The Planetary Society, Union of Concerned Scientists
Public and Media	Shape public opinion and disseminate information about the mission.	BBC, Space.com, Popular Science
Insurance and Risk Management Entities	Provide financial coverage against mission risks.	Marsh, AXA XL, Allianz

Table 8: Stakeholder List

13.3 Stakeholder Clustering

Cluster	Stakeholders
Financial	Investors and Financial Institutions, Insurance and Risk Management Entities, Governments/Policymakers
Goods/Services	Suppliers, Launch Providers, Ground Segment Providers
Client	Commercial Operators, Public and Media
Influence/Support	Mission Control, International Organizations and Regulators, National Organizations, Universities/Research Institutions, Environmental and Ethics Organizations

Table 9: Stakeholder Impact-based Clustering

Cluster	Stakeholders
High Influence, High Criticality	Investors and Financial Institutions, National Organizations, Governments/Policymakers, Mission Control, International Organizations/Regulators
High Influence, Low Criticality	Environmental and Ethics Organizations, Public and Media, Insurance and Risk Management Entities
Low Influence, High Criticality	Suppliers, Launch Providers, Ground Segment Providers
Low Influence, Low Criticality	Universities/Research Institutions, Commercial Operators

Table 10: Stakeholder Influence vs. Criticality Clustering

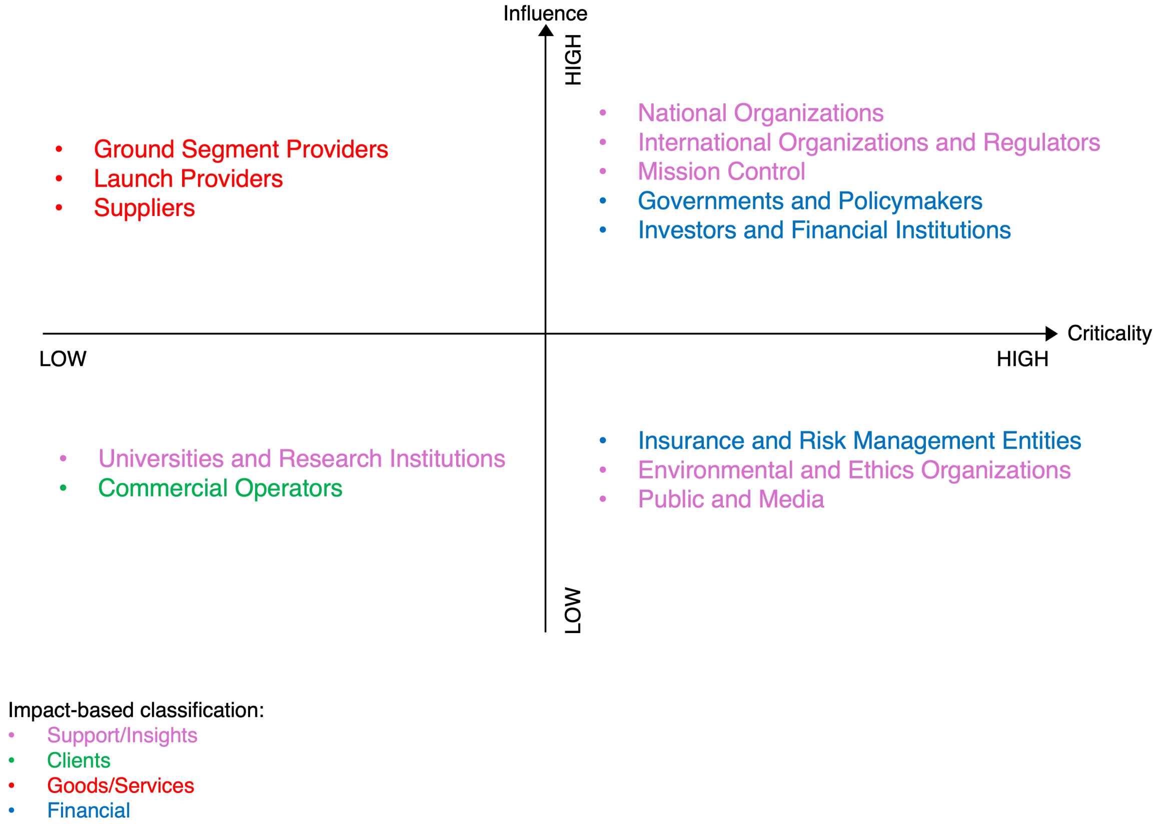

Figure 4: Overview of both stakeholder clustering methods

13.4 Stakeholder Engagement

Stakeholder Cluster	Engagement Strategies
Supporting Institutions	• Early and continuous engagement for compliance and alignment with regulations. • Collaboration on national and international mission priorities. • Clear communication of mission objectives, strategic goals, and economic or scientific benefits. • Provide periodic reporting and transparent updates on progress and compliance. • Leverage their influence to secure broad policy support and ensure global standards adherence.

Commercial Suppliers	• Establish detailed contracts with clear terms for performance, delivery timelines, and penalties. • Coordinate pre-launch and operational testing to ensure system compatibility. • Conduct regular performance reviews to assess alignment with mission goals. • Offer incentives for exceeding quality or delivery benchmarks. • Provide clear communication channels for issue resolution during procurement and operations.
Client Stakeholders	• Develop service-level agreements (SLAs) tailored to client-specific needs. • Maintain open channels for feedback and support during operations. • Provide training sessions or technical support for end-users of GNSS and telecom services. • Foster collaboration through joint research initiatives with universities. • Ensure transparent pricing and guaranteed uptime for mission-critical services. • Align with their timeline and expected activities.
Financial Stakeholders	• Offer comprehensive risk assessments and mitigation plans. • Regular updates on financial metrics, mission progress, and potential ROI. • Adhere to compliance and reporting standards to build confidence. • Foster trust through transparent communication about risks and operational contingencies. • Highlight the long-term strategic value of the mission to attract sustained financial support.

Table 11: Stakeholder Engagement Strategies

13.5 Stakeholder Interfaces

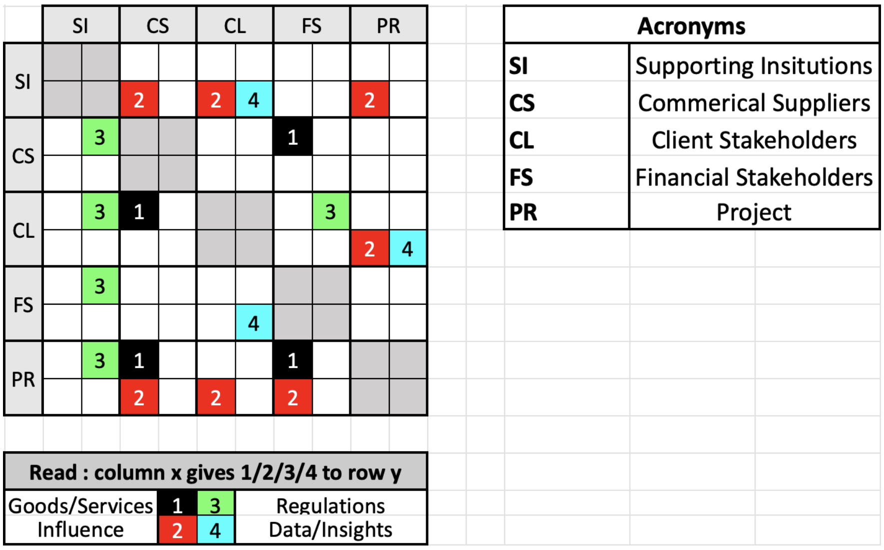

Figure 5: DSM of the Main Stakeholder Cluster's Interfaces

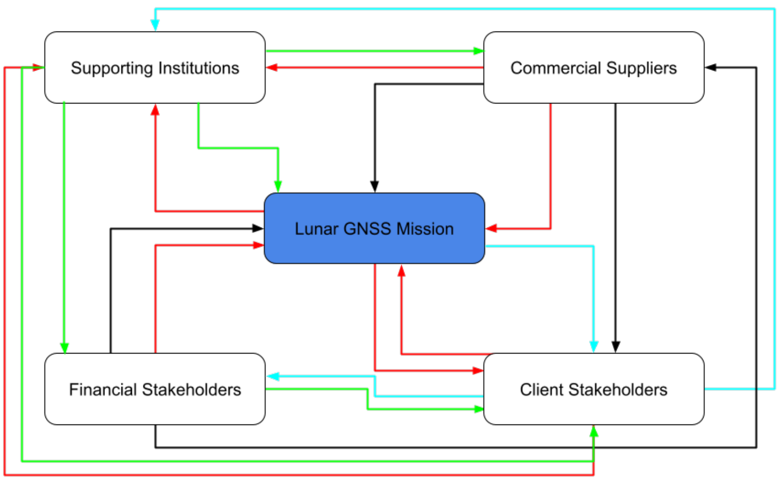

Figure 6: Stakeholder Value Network

13.6 Complete Requirements Table

ID	Title	Description	Justification	Verification Method	KPI
REQ-SK-01	Regulatory Compliance	Ensure compliance with international and national standards for lunar missions.	Mandated by Supporting Institutions for policy alignment.	Inspection	None

REQ-SK-02	Periodic Reporting	Provide periodic updates to Supporting Institutions.	Builds trust and ensures alignment with mission objectives.	Review	None
REQ-SK-03	Quality Assurance	All components and services must meet defined quality benchmarks.	Critical to mission success and supply chain robustness.	Test	Component Failure Rate
REQ-SK-04	Timely Delivery	Deliver components and services on schedule.	Prevents delays in mission timeline.	Inspection	Delivery Timeliness Index
REQ-SK-05	Service Uptime Guarantee	Ensure GNSS/telecom services have >95% uptime.	Required to meet client operational needs.	Test	Service Availability
REQ-SK-06	Client Feedback Integration	Regularly gather and integrate feedback from clients.	Ensures mission usability and continuous improvement.	Review	Feedback Response Rate
REQ-SK-07	ROI Transparency	Provide regular ROI assessments to Financial Stakeholders.	Builds confidence and attracts sustained financial support.	Analysis	None
REQ-SK-08	Risk Mitigation Strategies	Present comprehensive risk mitigation plans.	Required for financial backing and confidence.	Analysis	Risk Assessment Accuracy
REQ-SK-09	Stakeholder Coordination	Maintain active coordination across all stakeholder clusters.	Ensures alignment of mission flows and operations.	Inspection	None
REQ-SK-10	Operational Adaptability	Adapt operations to evolving stakeholder requirements.	Enhances responsiveness to external conditions.	Test	Adaptability Metric
REQ-SK-11	Timeline	Develop a mission that fits within the client stakeholder's needs and expectations while ensuring implications from other stakeholders are met	Maintains good client/supplier relationship while ensuring that other stakeholders remain satisfied and engaged.	Review	None
REQ-LA-01	Launch System	The spacecraft shall be compatible with Falcon 9 and Falcon Heavy launch vehicles.	Ensures compatibility with current launch options.	Inspection	None
REQ-PA-01	Propulsion Subsystem	The spacecraft shall include a propulsion system capable of providing at least 2,000 m/s delta-v for transfer, station-keeping, and end-of-life maneuvers.	Required for orbital transfer, constellation stability, and disposal.	Test	Delta-v Reserve
REQ-PA-02	Attitude Control Subsystem	The spacecraft shall include an attitude control system capable of achieving pointing accuracy of $\pm$ 0.1 [deg] and stability of $\pm$ 0.05 [deg/s].	Ensures precise positioning and GNSS/telecom performance.	Test	Attitude Stability Index

REQ-GS-01	Ground Segment	The mission shall include a ground segment with global coverage and secure data handling for real-time command, control, and telemetry.	Ensures robust and secure mission operations.	Inspection	Communication Uptime
REQ-CD-01	Command and Data Handling	The spacecraft shall feature an onboard command and data handling system capable of supporting 10 Mbps inter-satellite links and data processing.	Required for GNSS synchronization and client services.	Test	Data Processing Rate
REQ-PL-01	GNSS Payload	The spacecraft shall include a GNSS payload capable of delivering positioning accuracy of <1 meter (3-sigma) and signal strength suitable for lunar shadowed regions.	Critical for client operations and mission success.	Analysis	Positioning Accuracy
REQ-PL-02	Telecom. Payload	The spacecraft shall include a secure telecom payload capable of a minimum data rate of 50 Mbps to the lunar surface.	Ensures reliable communication with clients.	Test	Data Rate Stability
REQ-TH-01	Thermal Subsystem	The spacecraft shall include a thermal subsystem capable of maintaining internal temperatures within -20 [C] to +40 [C] in a lunar environment (-120 [C] to +120 [C] external).	Ensures subsystem reliability under extreme conditions.	Test	Temperature Stability
REQ-TH-02	End-of-Life Passivation	The thermal subsystem shall support passive energy dissipation and shutdown during end-of-life operations.	Prevents thermal and energy hazards post-mission.	Analysis	None
REQ-AR-01	Modular Design	The spacecraft architecture shall support modular upgrades for payload replacement or enhancement.	Increases mission scalability and adaptability.	Inspection	None
REQ-IF-01	Payload-Command Data Interface	The Payload (PL) and Command/Data Handling (CD) subsystems shall enable bi-directional data exchange at a minimum rate of 10 Mbps.	Ensures synchronization for GNSS and telecommunication services.	Test	Data Exchange Rate

REQ-IF-02	Payload-Propulsion Interface	The Payload (PL) subsystem shall provide feedback to the Propulsion/Attitude Control (PR) subsystem for orbit and pointing corrections.	Enables accurate positioning and alignment for GNSS services.	Analysis	Positioning Accuracy
REQ-IF-03	Thermal-Payload Interface	The Thermal Subsystem (TH) shall provide active and passive thermal management for the Payload (PL) to maintain operational temperatures (-20 [C] to +40[C]).	Ensures Payload functionality under extreme lunar temperatures.	Test	Thermal Performance
REQ-IF-04	Thermal-Command Data Interface	The Thermal Subsystem (TH) shall provide thermal regulation for the Command/Data Handling (CD) subsystem under nominal and extreme conditions (-20[C] to +40[C]).	Maintains subsystem reliability for continuous data handling.	Test	Temperature Stability
REQ-IF-05	Command Data-Ground Interface	The Command/Data Handling (CD) subsystem shall enable secure uplink/downlink with the Ground Segment (GS) at a minimum data rate of 1 Mbps.	Supports real-time command and telemetry data exchange.	Analysis	Com.on Uptime
REQ-IF-06	Ground-Payload Interface	The Ground Segment (GS) shall provide remote control and telemetry for the Payload (PL) with latency not exceeding 2 seconds.	Ensures timely adjustments and monitoring of GNSS operations.	Test	Control Latency
REQ-IF-07	Propulsion-Ground Interface	The Propulsion/Attitude Control (PR) subsystem shall support telemetry for orbital transfer and maneuver planning with a maximum delay of 5 seconds.	Enables real-time feedback for precision orbit adjustments.	Analysis	Telemetry Accuracy
REQ-IF-08	Propulsion-Thermal Interface	The Thermal Subsystem (TH) shall provide thermal protection to the Propulsion/Attitude Control (PR) subsystem during transfer and station-keeping maneuvers.	Ensures propulsion functionality under varying thermal loads.	Test	Thermal Load Tolerance

REQ-IF-09	Inter-Satellite Communication	The Payload (PL) and Command/Data Handling (CD) subsystems shall support inter-satellite communication with latency <1 second for GNSS synchronization.	Ensures consistent GNSS accuracy across the constellation.	Test	Com. Latency
REQ-IF-10	Modular Connections	All subsystem interfaces shall be modular and standardized to allow for upgrades or replacements without redesign.	Increases scalability and simplifies maintenance.	Inspection	None
REQ-IF-11	Thermal-Ground Interface	The Ground Segment (GS) shall monitor the thermal subsystem status to detect anomalies in real-time.	Allows pre-emptive action against thermal failures.	Analysis	Thermal Anomaly Detection
REQ-IF-12	Payload-Payload Interface	Inter-satellite payload interfaces shall allow seamless GNSS synchronization for constellation-level accuracy.	Critical for global lunar coverage.	Test	Sync. Latency
REQ-IF-13	Command-Telecom. Interface	The Command/Data Handling (CD) subsystem shall prioritize telecom data when bandwidth exceeds 90% utilization.	Maintains critical communication links.	Analysis	Bandwidth Utilization
REQ-IF-14	Propulsion-Command Interface	The Propulsion/Attitude Control (PR) subsystem shall communicate real-time orbital adjustments to the Command/Data Handling (CD) subsystem.	Ensures precise control and telemetry updates.	Test	Adjustment Latency
REQ-IF-15	Propulsion-Payload Interface	The Propulsion/Attitude Control (PR) subsystem shall adjust satellite orientation based on payload operational needs within 1 second.	Maintains GNSS and telecom service reliability.	Test	Orientation Stability
REQ-IF-16	Command-Payload Interface	The Command/Data Handling (CD) subsystem shall update Payload (PL) parameters in under 0.5 seconds during operational adjustments.	Ensures real-time responsiveness to mission changes.	Test	Update Response Time

REQ-IF-17	Command-Thermal Interface	The Command/Data Handling (CD) subsystem shall actively control thermal subsystem adjustments to maintain subsystem health.	Prevents overheating or undercooling of critical components.	Analysis	Thermal Adjustment Rate
REQ-IF-18	Ground-Ground Interface	The Ground Segment (GS) shall include inter-ground station communication with latency <2 seconds for global redundancy.	Ensures smooth handovers between ground stations.	Analysis	Ground Redundancy
REQ-IF-19	Cybersecurity Interface	All subsystems shall integrate with the Command/Data Handling (CD) subsystem for active threat detection and mitigation within 1 second.	Prevents mission disruptions due to cyberattacks.	Analysis	Threat Mitigation Time
REQ-EN-01	Thermal Tolerance	The spacecraft shall withstand lunar surface temperatures ranging from -120[C] to +120[C].	Ensures functionality in extreme lunar thermal environments.	Test	Thermal Performance
REQ-EN-02	Internal Temperature Control	The spacecraft shall maintain internal subsystem temperatures within -20[C] to +40[C] during all operations.	Protects internal components and ensures reliable operation.	Test	Temperature Stability
REQ-EN-03	Radiation Protection	The spacecraft shall withstand Total Ionizing Dose (TID) up to 100 krad and Single Event Effects (SEE) with LET threshold >15 MeV cm^2/mg.	Prevents radiation damage to critical electronics.	Analysis, Test	Radiation Hardening Index
REQ-EN-04	Microgravity Operations	The spacecraft shall operate effectively in low-gravity lunar orbital conditions (1.62 m/s^2).	Ensures stability and performance of subsystems in microgravity.	Simulation	Operational Stability
REQ-EN-05	Vacuum Compatibility	All spacecraft materials shall be vacuum-rated for operation in $<10^{-12}$ bar pressure.	Prevents outgassing and material degradation in vacuum.	Inspection	Material Compliance
REQ-EN-06	Debris Impact Resistance	The spacecraft shall withstand impacts from debris with velocities up to 10 km/s and sizes >1 cm.	Reduces risk of mission failure from debris collisions.	Simulation	Impact Resistance
REQ-EN-07	EMI Shielding	The spacecraft shall protect sensitive electronics from EMI with a frequency range of 1 kHz to 10 GHz and peak field strength up to 200 V/m.	Prevents interference with critical communication and GNSS systems.	Test	EMI Shielding Effectiveness

REQ-EN-08	Acoustic Load Resistance	The spacecraft shall tolerate acoustic loads up to 140 dB during launch.	Ensures structural integrity during launch.	Test	Acoustic Endurance
REQ-EN-09	Vibration Load Resistance	The spacecraft shall withstand vibration levels of 5 to 100 Hz at 0.1 g^2/Hz during launch.	Prevents damage to subsystems during ascent.	Test	Vibration Resistance

Table 12: Full Requirements List

13.7 Complete Key Performance Indicators Table

Title	Description	Threshold
Component Failure Rate	Measures the percentage of delivered components that fail during testing or early operation.	< 2% failure rate
Delivery Timeliness Index	Measures the ratio of components/services delivered on time to the total deliveries.	> 95% on-time delivery
Service Availability	Measures the uptime of GNSS/telecom services provided to clients.	> 95% availability
Feedback Response Rate	Measures the percentage of client feedback addressed within a set period (e.g., 30 days).	> 90% response rate
Risk Assessment Accuracy	Measures the percentage of risks that were correctly predicted and mitigated as per assessments.	> 85% accuracy
Delta-v Reserve	Measures the propulsion system's ability to perform all required maneuvers.	≥ required mission delta-v
Attitude Stability Index	Measures the pointing accuracy and stability of the attitude control subsystem.	±0.1 [deg] pointing accuracy, ±0.05 [deg/s] stability
Communication Uptime	Tracks the percentage of time real-time communication is available.	≥ 95%
Data Processing Rate	Measures the onboard data handling capacity for inter-satellite links.	≥ 10 Mbps
Positioning Accuracy	Measures the GNSS payload's positioning accuracy.	≤ 1 meter (3-sigma)
Data Rate Stability	Tracks the stability of the telecom payload's data rate.	≥ 50 Mbps
Temperature Stability	Ensures operational stability of subsystems.	Internal: -20 [C] to +40 [C]; External: -120 [C] to +120 [C]
Data Exchange Rate	Measures bi-directional data transfer rate between Payload (PL) and Command/Data Handling (CD).	≥ 50 Mbps
Thermal Performance	Tracks the Thermal Subsystem's (TH) ability to maintain Payload (PL) and Command/Data Handling (CD) operational temperatures.	-20 [C] to +40 [C] (internal)
Temperature Stability	Assesses the Thermal Subsystem's (TH) regulation in extreme lunar conditions.	-120 [C] to +120 [C] (external)
Control Latency	Measures latency for Ground Segment (GS) commands to Payload (PL).	≤ 2 seconds
Telemetry Accuracy	Tracks precision of telemetry data received by Ground Segment (GS) from Propulsion/Attitude Control (PR).	≥ 99%
Thermal Load Tolerance	Evaluates Thermal Subsystem's (TH) performance under varying loads for Propulsion/Attitude Control (PR).	No operational degradation
Communication Latency	Measures latency of inter-satellite communication between Payload (PL) and Command/Data Handling (CD).	≤ 1 second
Synchronization Latency	Tracks delay in synchronization between constellation satellites.	≤ 1 second

Positioning Uptime	Tracks real-time positioning data availability from Payload (PL) to the lunar surface.	$\geq$ 95%
Bandwidth Utilization	Measures bandwidth usage prioritization for telecom data.	$\leq$ 90%
Adjustment Latency	Tracks response time for Propulsion/Attitude Control (PR) orbital adjustments.	$\leq$ 5 seconds
Orientation Stability	Evaluates satellite orientation maintenance based on Payload (PL) needs.	$\leq$ 0.1 [deg] deviation
Update Response Time	Measures Command/Data Handling (CD) response time for Payload (PL) parameter updates.	$\leq$ 0.5 seconds
Thermal Adjustment Rate	Monitors thermal adjustments controlled by Command/-Data Handling (CD).	$\leq$ 1 second
Ground Redundancy	Tracks latency for inter-ground station communication.	$\leq$ 2 seconds
Threat Mitigation Time	Measures time for cybersecurity threat detection and mitigation.	$\leq$ 1 second
Radiation Hardening Index	Evaluates the effectiveness of radiation shielding and resistance to SEE.	$\geq$ 100 krad TID, LET >15 MeV cm^2/mg
Operational Stability	Assesses spacecraft performance in low-gravity environments.	$\geq$ 95% stability during operations
Material Compliance	Ensures all materials are vacuum-rated and resistant to outgassing.	100% compliance with ECSS standards
Dust Resistance Index	Evaluates the system's resistance to lunar dust infiltration.	$\leq$ 5% degradation in moving parts or optics
Impact Resistance	Measures the spacecraft's ability to withstand debris impacts.	No critical damage from impacts up to 10 km/s
EMI Shielding Effectiveness	Tracks the effectiveness of EMI protection for sensitive electronics.	$\geq$ 95% shielding efficiency
Acoustic Endurance	Assesses spacecraft tolerance to acoustic loads during launch.	$\leq$ 5% structural degradation at 140 dB
Vibration Resistance	Measures the spacecraft's ability to withstand vibration during launch.	No critical damage at 5 to 100 Hz

Table 13: Key Performance Indicators (KPI) Full Table

13.8 Timeline

Phase	**Years**	**Milestone Summary**
Phase 0: Mission Concept & Feasibility	2024 to 2026	Mission concept, feasibility studies, stakeholder requirements, risk assessment, preliminary objectives, architecture options, initial cost estimates, funding allocation.
Phase A: Preliminary Design & Requirements Definition	2027 to 2028	Requirements definition, preliminary design review (PDR), early prototyping, initial ground segment design, risk mitigation planning, interface assessment.
Phase B: Detailed Design & Development	2029 to 2030	Design freeze, critical design review (CDR), payload and platform development, prototype finalization, system integration testing, ground segment setup.
Phase C: Assembly, Integration & Testing	2031 to 2032	Satellite assembly and integration, end-to-end testing, software deployment, final testing, launch readiness review (LRR), operational readiness check.
Phase D: Launch & Deployment	2033 to 2034	First satellite launch, initial constellation deployment, early orbit testing, full constellation deployment, calibration, final handover to operations.

Phase E: In-Orbit Operations & Maintenance	2035 to 2041	Regular monitoring and diagnostics, data processing, mid-mission performance review, constellation performance assessment (2038).
Phase F: Mission Life Assessment	2041	7-year assessment: Mission termination and EOL procedures or extension with satellite replacement.

Table 14: Mission Timeline

13.9 Functional Decomposition

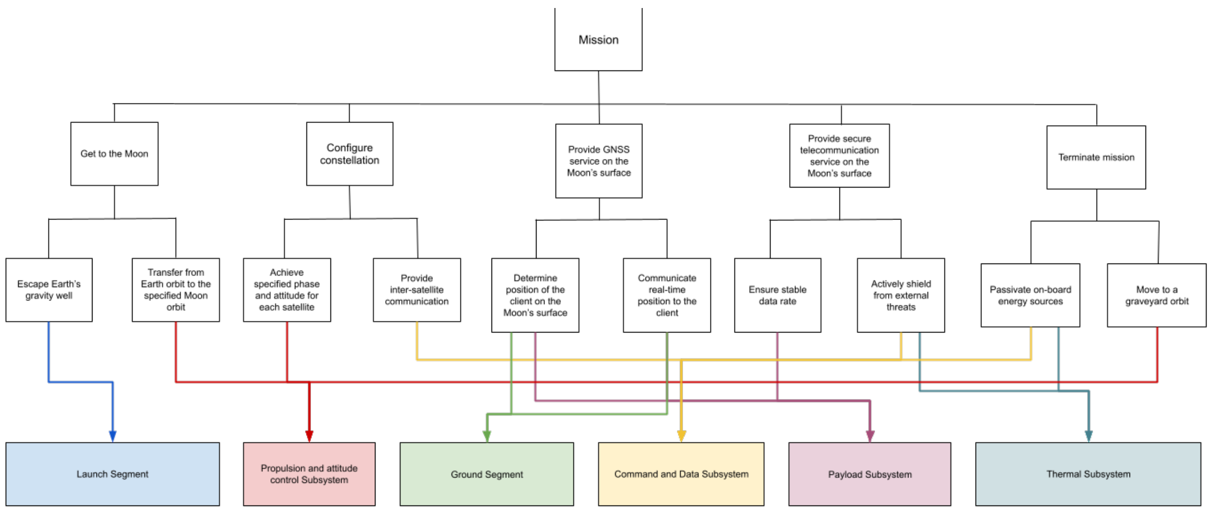

Figure 7: Functional Decomposition of the Mission

13.10 Subsystem interfaces

	ST	PR	GS	CD	PL	TH	PW
ST		1, 3, 2		1	1	1, 3	1
PR	1, 3, 2			4			3
GS				4	4		
CD	1	4	4		4	3	3
PL	1		4	4		3	3
TH	1, 3			3	3		3
PW	1	3	3	3	3	3	

Figure 8: DSM of the different subsystem interfaces

Read : column x gives 1/2/3/4 to row y			
Physical	1	3	Energy
Mass	2	4	Information

Figure 9: DSM flux description

With the following abbreviations found in the preceding DSM:

- **ST:** Structure
- **PR:** Propulsion
- **GS:** Ground Segment
- **CD:** Command and Data Handling
- **PL:** Payload
- **TH:** Thermal
- **PW:** Power

13.11 Environmental Constraints

Constraint	Description	Source
Thermal Environment	The spacecraft must withstand lunar surface temperatures ranging from -120[C] to +120[C] and maintain internal subsystem temperatures between -20[C] to +40[C].	COSPAR guidelines, ITU specifications
Radiation	Exposure to cosmic radiation and solar energetic particles in lunar orbit, with Total Ionizing Dose (TID) up to 100 krad and Single Event Effects (SEE) threshold >15 MeV cm^2/mg LET.	NASA handbook, ECSS standards
Microgravity	Operate effectively in low-gravity lunar orbital conditions, with lunar gravity at 1.62 m/s^2.	ESA lunar guidelines
Vacuum	Operate in hard vacuum with pressure $<10^{-12}$ bar.	ECSS materials standards
Debris Mitigation	Risk of collisions with orbital debris in cis-lunar space, with impact velocities up to 10 km/s and critical debris size >1 cm.	ITU debris mitigation standards
Electromagnetic Interference (EMI)	Exposure to EMI in the lunar environment, with frequency range of 1 kHz to 10 GHz and peak field strength up to 200 V/m.	ECSS standards, ITU regulations
Launch Environment	High vibrational and acoustic loads during launch, with vibration levels of 5 to 100 Hz at 0.1 g^2/Hz and acoustic loads up to 140 dB.	Launch vehicle provider specifications

Table 15: Environmental Constraints

13.12 End-of-Life Trade-off Study

Aspect	Life Extension through Refueling	Relocation to DRO + Passivation
Technical Complexity	High: Requires docking, refueling, and hardware upgrades.	Low: Uses proven relocation and passivation techniques.
Operational Risk	Elevated: Risk of docking failures and hardware degradation.	Minimal: Stable orbit with reduced intervention.
Cost	High: Significant CAPEX for servicing missions.	Low: Limited to relocation fuel overhead and passivation operations.
Sustainability	Moderate: Delays resource depletion but increases traffic.	High: Reduces debris and frees orbital slots.
Environmental Impact	Negative: Increased resource usage for servicing missions.	Positive: Reduces debris and requires no active propulsion.
Regulatory Compliance	Complex: Greater challenge to meet COSPAR debris guidelines.	Simple: Fully complies with international standards.

Table 16: End-of-Life Trade-off Evaluation

13.13 Enlarged Concept of Operations

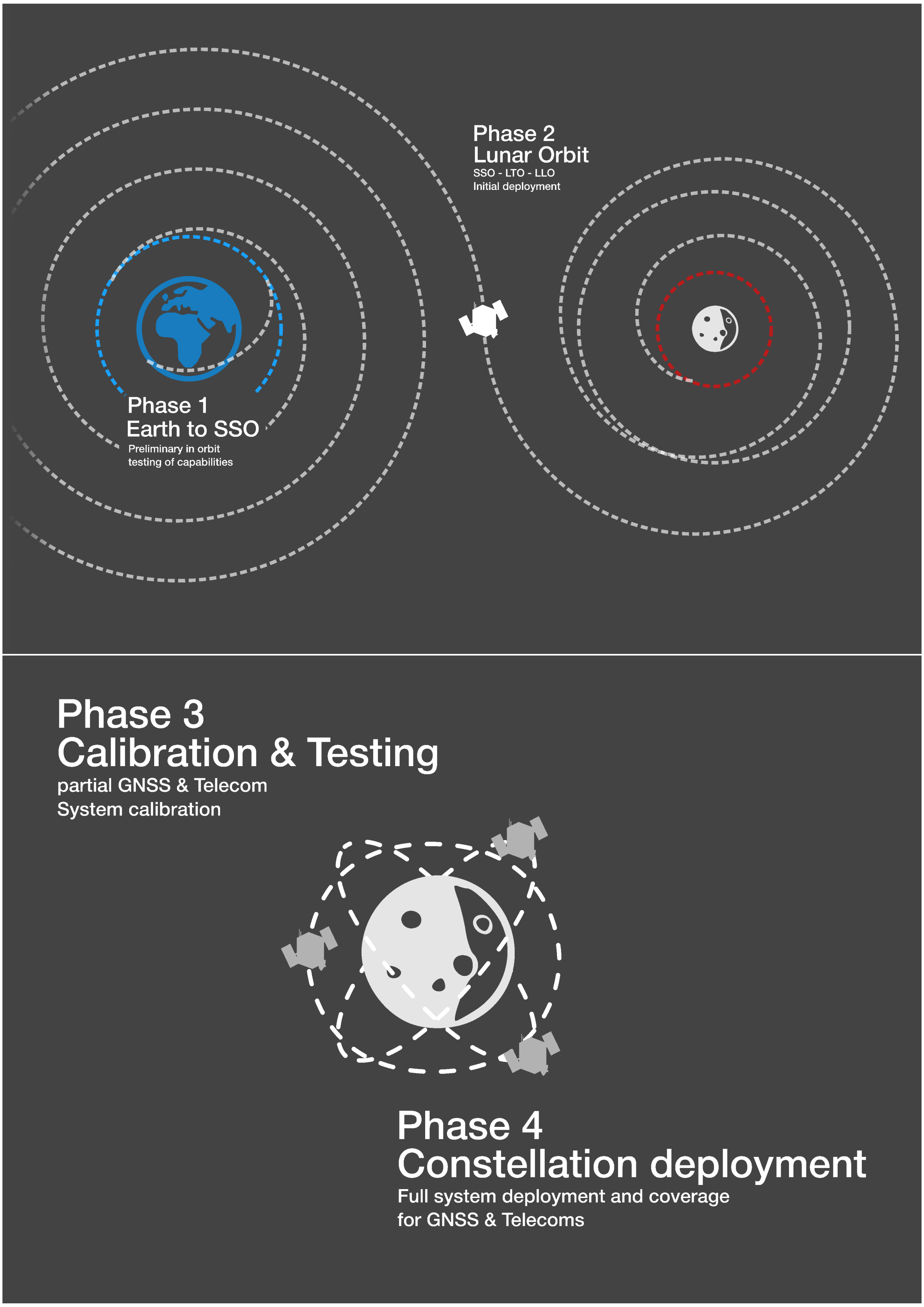

Figure 10: Phases 1,2,3 & 4 of the CONOPS

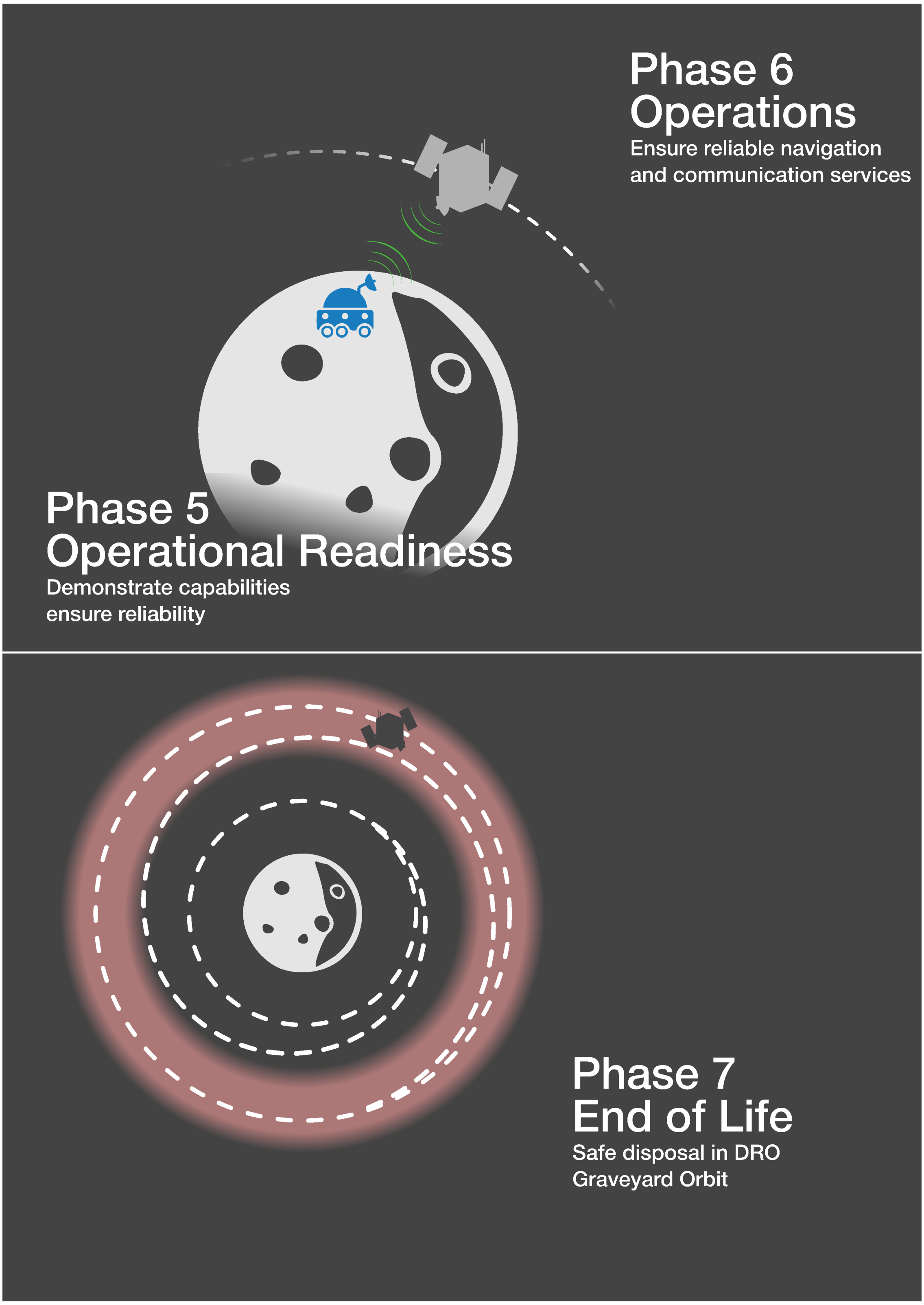

Figure 11: Phases 5,6 & 7 of the CONOPS

13.14 Verification and Validation Timeline

Phase	Years	Activities	Deliverables
Phase 0	2024 to 2026	Stakeholder alignment, mission feasibility, and concept definition.	Requirements document, feasibility study.
Phase A	2027 to 2028	Preliminary design validation and trade studies.	Preliminary Design Review (PDR) report.
Phase B	2029 to 2030	Subsystem development and testing, interface design validation.	Subsystem validation reports, test results.
Phase C	2031 to 2032	Integration testing, environmental testing, and end-to-end simulations.	Integration readiness report, simulation data.
Phase D	2033 to 2034	System validation during launch and deployment, pre-launch reviews.	Launch Readiness Review (LRR), validation reports.
Phase E	2035 to 2041	Operational validation, in-orbit diagnostics, and mid-mission assessments.	Performance reports, mid-mission review.
Phase F	2041	End-of-life compliance validation (passivation, deorbit maneuvers).	EOL compliance report, mission evaluation.

Table 17: Project Phase Timeline

13.15 Verification Plan

KPI	Description	Threshold	Verification Activity	Phase
Delivery Timeliness Index	Ratio of components/services delivered on time to total deliveries.	> 95% on-time delivery	Inspection and schedule tracking	Phase A
Risk Assessment Accuracy	Percentage of risks predicted and mitigated correctly.	> 85% accuracy	Analysis of historical data	Phase A
Component Failure Rate	Percentage of components failing during testing or operation.	< 2% failure rate	Testing during validation phase	Phase B
Dust Resistance Index	Resistance to lunar dust infiltration.	≤ 5% degradation in optics or parts	Dust simulation tests	Phase B
Impact Resistance	Capability to withstand debris impacts.	No critical damage at 10 km/s	Impact simulation tests	Phase B
Material Compliance	Compatibility of materials with vacuum conditions.	100% compliance with ECSS standards	Inspection and material testing	Phase B
Delta-v Reserve	Propulsion system's capability to perform maneuvers.	≥ required mission delta-v	Simulation and subsystem testing	Phase C
Attitude Stability Index	Pointing accuracy and stability of attitude control subsystem.	±0.1[deg] accuracy, ±0.05[deg/s] stability	Attitude control subsystem tests	Phase C
Data Processing Rate	Onboard capacity for inter-satellite links.	≥ 10 Mbps	Subsystem performance tests	Phase C
Synchronization Latency	Delay in synchronization between constellation satellites.	≤ 1 second	GNSS synchronization tests	Phase C
Threat Mitigation Time	Cybersecurity threat detection and mitigation time.	≤ 1 second	Cybersecurity stress testing	Phase C
Thermal Performance	Thermal subsystem's ability to maintain operational temperatures.	-120[C] to +120[C]	Thermal cycling tests	Phase C

Temperature Stability	Ensures subsystem stability in extreme environments.	-20[C] to +40[C] internal; -120[C] to +120[C] external	Thermal monitoring tests	Phase C
Radiation Hardening Index	Effectiveness of radiation shielding and SEE resistance.	≥ 100 krad TID, LET >15 MeV cm^2/mg	Radiation testing	Phase C
EMI Shielding Effectiveness	Protection of sensitive electronics from EMI.	≥ 95% shielding efficiency	EMI shielding tests	Phase C
Acoustic Endurance	Tolerance to acoustic loads during launch.	≤ 5% degradation at 140 dB	Acoustic testing	Phase C
Vibration Resistance	Capability to withstand launch vibrations.	No critical damage at 5 to 100 Hz	Vibration tests	Phase C
Positioning Accuracy	GNSS payload's positioning accuracy.	≤ 1 meter (3-sigma)	GNSS tests during in-orbit validation	Phase D
Data Rate Stability	Stability of telecom payload's data rate.	≥ 50 Mbps	Data transmission tests	Phase D
Communication Uptime	Real-time communication availability.	≥ 95% uptime	Telemetry tracking and analysis	Phase E
Service Availability	Uptime of GNSS/telecom services provided to clients.	> 95% availability	Operational diagnostics	Phase E
Feedback Response Rate	Percentage of client feedback addressed within 30 days.	> 90% response rate	Review of client feedback logs	Phase E
Bandwidth Utilization	Prioritization of telecom data under bandwidth constraints.	≤ 90% utilization	Bandwidth tracking during operations	Phase E
Ground Redundancy	Latency in inter-ground station communication.	≤ 2 seconds	Operational diagnostics	Phase E

Table 18: Verification Plan

13.16 Risk Analysis

Risk	**Description**	**P**	**I**	**S**	**Mitigation**	**P**	**I**	**S**	**Mitigation Effect**
Launch Vehicle Failure	Failure of launch system during deployment	5	5	25	Use proven launchers	2	5	10	Reduced Probability
Collision with Space Debris	Impact with orbital debris	4	4	16	Active collision tracking and avoidance	2	4	8	Reduced Probability
Fuel Depletion	Insufficient fuel to meet lifetime	5	5	25	Monitor fuel usage, add margins	3	5	15	Reduced Probability
Radiation Damage	Damage to electronics from radiation	4	5	20	Shield components, redundancy	4	4	16	Reduced Impact
Power System Degradation	Decline in power generation	4	4	16	Monitor batteries, ensure margins	2	4	8	Reduced Probability
Communication Signal Loss	Loss of communication with satellites	3	5	15	Dual communication links, backups	1	5	5	Reduced Probability
Thermal Instability	Fluctuations in system temperature	4	3	12	Optimize thermal shielding	2	3	6	Reduced Probability
Payload Data Processing Failure	Failure in data handling	3	4	12	Redundant processing units	1	4	4	Reduced Probability

Delayed Satellite Phasing	Delay in achieving orbital positioning	4	3	12	Accurate deployment sequences	2	3	6	Reduced Probability
Propulsion System Failure	Anomaly in propulsion systems	3	5	15	Redundancy, thrust monitoring	2	5	10	Reduced Probability
Ground Segment Failure	Loss of ground station connectivity	3	4	12	Backup stations, regular tests	1	4	4	Reduced Probability
Software Glitches	Bugs in flight software	4	3	12	Software validation, regular updates	2	3	6	Reduced Impact
Structural Fatigue	Long-term structural degradation	3	4	12	Use advanced materials, stress testing	2	4	8	Reduced Probability
Solar Panel Degradation	Reduced efficiency over time	2	3	6	Use durable panel materials	1	3	3	Reduced Probability
GNSS Signal Accuracy Degradation	Reduced positioning accuracy	4	4	16	Frequent recalibration, signal checks	3	4	12	Reduced Probability
Loss of Mission Control	Inability to send commands	3	5	15	Redundant control systems	1	5	5	Reduced Probability
Vibrational Stress	Damage during launch vibrations	3	4	12	Pre-launch vibration testing	2	4	8	Reduced Probability
Late Payload Deployment	Delay in deploying instruments	4	4	16	Mechanical validation tests	2	4	8	Reduced Probability
Environmental Noise	Signal interference in communications	4	3	12	Improve signal-to-noise ratio	2	3	6	Reduced Impact
Data Latency Issues	Delays in real-time operations	4	3	12	Optimize data relay paths	2	3	6	Reduced Impact

Table 19: Risk Analysis

13.17 Pugh Matrix: Mission Trade-Off Analysis

Criteria	Weight	Alt 1 Base	Alt 1 Weighted	Alt 2 Base	Alt 2 Weighted	Alt 3 Base
Cost	5	4	20	5	25	3
Platform lead time	3	4	12	5	15	3
Number of launches	3	4	12	3	9	4
Minimal launches for operability	3	4	12	3	9	5
Payload redundancy	4	3	12	2	8	5
Ground station extensiveness	2	3	6	4	8	2
System resilience	5	4	20	5	25	3
Operational complexity	3	3	9	4	12	2
Orbit regularity	3	2	6	5	15	2
Launch window availability	4	2	8	4	16	2
Scalability	3	3	9	4	12	3
Space debris potential	4	3	12	4	16	2
Technology heritage	3	5	15	2	6	5
Total Weights	**45**	**44**	**153**	**50**	**176**	**142**
Grade (%)		**67.69%**	68%	**78.22%**	67.69%	**63.08%**

Table 20: Pugh Matrix: Mission Trade-Off Analysis

13.18 Mission & baseline Design verification script

```
#   python 3.12.0
#   basic computation of spacecraft design
from enum import Enum
import numpy as np
from colorama import Fore, Back, Style

# constants
MU_EARTH = 3.986004418e14 # m^3/s^2
MU_MOON = 4.9028e12 # m^3/s^2
R_EARTH = 6378.137e3 # m
R_MOON = 1737.4e3 # m
RS_MOON = 66200000 # m
DIST_EARTH_MOON = 384400000 # m
SECPDAY = 86400 # s
GZERO = 9.81 # m/s^2
BOLTZ = 5.67e-8 # W/m^2K
TMOONAVG = 273 # K

class flightphase():
    def __init__(self,name,prevflightphase = None):
        self.name = name
        self.mass_at_start = 0
        self.mass_at_end = 0
        self.energy_at_start = 0
        self.energy_at_end = 0
        self.conspropmass = 0
        self.dv = 0
        self.duration = 0
        self.max_duration = 1e100
        self.constraints = []
        self.prevflightphase = prevflightphase

    def add_constraint(self,type,value):
        self.constraints.append((type,value))

    def compute_duration(self,thrust,mass):
        self.duration = self.dv*mass/thrust

    def compute_spiral_dV(self,mu,r0,r1):
        self.dv = np.abs(np.sqrt(mu/r0)-np.sqrt(mu/r1))

    def compute_hohmann_dV(self,mu,r0,r1):
        self.dv = np.abs(np.sqrt(mu/r0)*(np.sqrt(2*r1/(r0+r1))-1))

    def set_max_duration(self,duration):
        self.max_duration = duration

    def set_mass_end(self,mass):
        self.mass_at_end = mass

    def comp_mass_start(self,isp,chain = False):
        self.mass_at_start = self.mass_at_end*np.exp(self.dv/(isp*GZERO))
        self.conspropmass = self.mass_at_start - self.mass_at_end
        if self.prevflightphase is not None:
            self.prevflightphase.set_mass_end(self.mass_at_start)
            if chain:
                self.prevflightphase.comp_mass_start(isp,True)



#subsystems
class Subsystem(Enum):
    PROPULSION = "Propulsion"
    POWER = "Power"
    THERMAL = "Thermal"
    STRUCTURE = "Structure"
    AVIONICS = "Avionics"
    PAYLOAD = "Payload"
```

```
    COMMUNICATION = "Communication"
    ATTITUDE_CONTROL = "Attitude Control"

# spacecraft component class
class SCComponent():
    def __init__(self,name,subsystem,dry_mass,prop_mass,max_thrust,isp,pwr_active,pwr_passive):
        self.drymass = dry_mass
        self.propmass = prop_mass
        self.maxthrust = max_thrust
        self.isp = isp
        self.pwractive = pwr_active
        self.pwrpassive = pwr_passive
        self.name = name
        self.subsystem = subsystem
        self.activephases = []
        self.isgenertor = False
        if self.pwractive > 0:
            self.isgenerator = True
        self.max_energy_storage = 0

    def set_max_energy_storage(self,max_energy):
        self.max_energy_storage = max_energy

    def add_active_phase(self,phase):
        self.activephases.append(phase)

    def activate(self):
        self.active = True

    def deactivate(self):
        self.active = False

    def get_pwr(self,phase):
        for active_phase in self.activephases:
            if active_phase == phase:
                return self.pwractive
        return self.pwrpassive


# spacecraft class
class Spacecraft():
    def __init__(self):
        self.components = []
        self.mass = 0
        self.thrust = 0
        self.delta_v = 0
        self.pwrreq = 0
        self.dry_mass = 0
        self.prop_mass = 0
        self.max_energy_storage = 0
        self.area = 0
        self.absorbitivity = 0
        self.emissivity = 0.4
        self.inertia = [0,0,0]
        self.torque = [0,0,0]
        self.axis_accel = [0,0,0]
        self.flight_phases = []
        self.warnings = []


    def add_component(self,component):
        self.components.append(component)
        self.mass += component.drymass + component.propmass
        self.thrust += component.maxthrust
        self.dry_mass += component.drymass
        self.max_energy_storage += component.max_energy_storage

    def get_pwr(self,phase):
        pwr = 0
        for component in self.components:
            pwr += component.get_pwr(phase)
        return pwr
```

```
    def get_mass(self):
        return self.mass

    def get_dry_mass(self):
        return self.dry_mass

    def add_area(self,area):
        self.area += area

    def light_rad(self,radflux):
        return self.area*self.absorbitivity*radflux

    def add_flight_phase(self,phase):
        self.flight_phases.append(phase)

    def comp_propmass(self):
        for phase in self.flight_phases:
            self.prop_mass += phase.conspropmass

    def set_torque(self,torque):
        self.torque = torque

    def comp_axis_accel(self):
        self.axis_accel[0] = self.torque[0]/self.inertia[0]
        self.axis_accel[1] = self.torque[1]/self.inertia[1]
        self.axis_accel[2] = self.torque[2]/self.inertia[2]

    def inertia_estimate(self,shape):
        #shape is an array of the form [h,w,d] for boxe dimensions or [r,h] for cylinders
        if len(shape) == 3:
            height = shape[0]
            width = shape[1]
            depth = shape[2]
            Ixx = self.mass/12*(width**2 + depth**2)
            Iyy = self.mass/12*(height**2 + depth**2)
            Izz = self.mass/12*(height**2 + width**2)
        elif len(shape) == 2:
            radius = shape[0]
            height = shape[1]
            Ixx = self.mass/12*(3*radius**2 + height**2)
            Iyy = Ixx
            Izz = self.mass/2*radius**2

        self.inertia = [Ixx,Iyy,Izz]
        return [Ixx,Iyy,Izz]

    def compute_elec_energy(self,start_energy,fromphase):
        phases = []
        strtd = False
        for phase in self.flight_phases:
            if phase == fromphase:
                phases.append(phase)
                strtd = True
            elif strtd:
                phases.append(phase)

        for phase in phases:
            pwr = self.get_pwr(phase)
            if phase == fromphase:
                phase.energy_at_start = start_energy
            elif phase.prevflightphase is not None:
                phase.energy_at_start = phase.prevflightphase.energy_at_end
            else:
                print(Back.RED + Fore.BLACK + "Error: no previous phase to {}".format(phase.name))
                print(Style.RESET_ALL,end="")

            energ = phase.energy_at_start + pwr*phase.duration
            if energ > self.max_energy_storage:
                self.warnings.append("warning: energy storage exceeded at {} ({:.3}Wh)".format(
    phase.name,(energ-self.max_energy_storage)/3600))
                energ = self.max_energy_storage
```

```
            if energ < 0:
                self.warnings.append("warning: energy storage negative at {} ({:.3} Wh)".format(phase.name,energ/3600))
                energ = 0
            phase.energy_at_end = energ


    def print_info(self):
        print("##### Spacecraft Information #####")
        print("------------------------------------")
        print("# {:<20}:{:>10.3f} kg".format("total dry mass",self.mass))
        print("# {:<20}:{:>10.3f} kg ({:>2.1f}%)".format("total prop. mass",self.prop_mass,(100*self.prop_mass)/(self.mass+self.prop_mass)))
        print("# {:<20}:{:>10.3f} kg".format("total mass",self.mass + self.prop_mass))
        print("\n{:<22}:{:>13}{:>13}".format("subsys & name","dry mass","active pwr"))
        for subsys in Subsystem:
            print(Fore.BLUE + "{:<20}".format(subsys.value))
            print(Style.RESET_ALL,end="")
            for component in self.components:
                if component.subsystem == subsys:
                    print("- {:<20}:{:>10.3f} kg {:>10.3f} W".format(component.name,component.drymass,component.pwractive))
        print("------------------------------------")
        print("# {:<20}:{:>10.3f} N".format("nominal thrust",self.thrust))
        print("# {:<20}:{:>10.3f} Wh".format("elec capacity",self.max_energy_storage/3600))
        print("# {:<20}:{:>10.3f} m^2".format("total area",self.area))
        print("# {:<20}:{:>10.3f} rad/s^2".format("roll max acc",self.axis_accel[0]))
        print("# {:<20}:{:>10.3f} rad/s^2".format("pitch max acc",self.axis_accel[1]))
        print("# {:<20}:{:>10.3f} rad/s^2".format("yaw max acc",self.axis_accel[2]))

        print("------------------------------------")
        print("##### flight phases #####")
        for phase in self.flight_phases:
            print(Fore.WHITE + Back.LIGHTBLACK_EX + "--- {:^20} ---".format(phase.name))
            print(Style.RESET_ALL,end="")
            print("- {:<20}:{:>10.3f} kg".format("mass at start",phase.mass_at_start))
            pwr = self.get_pwr(phase)
            if pwr < 0 :
                print(Fore.LIGHTYELLOW_EX + "- {:<20}:{:>10.3f} W".format("power balance",pwr))
                print(Style.RESET_ALL,end="")
            else:
                print("- {:<20}:{:>10.3f} W".format("power balance",pwr))
            print("- {:<20}:{:>10.3f} m/s".format("maneuver dV",phase.dv))
            if phase.duration > phase.max_duration:
                print(Fore.RED + "- {:<20}:{:>10.3f} days".format("maneuver duration",phase.duration/SECPDAY))
                print(Style.RESET_ALL,end="")
            else:
                print("- {:<20}:{:>10.3f} days".format("maneuver duration",phase.duration/SECPDAY))
            print("- {:<20}:{:>10.3f} kg".format("consumed propellant",phase.conspropmass))
            print("- {:<20}:{:>10.3f} Wh".format("Battery energy start",phase.energy_at_start/3600))
        print("------------------------------------")
        print("##### warnings #####")
        for warning in self.warnings:
            print(Fore.RED + warning)
            print(Style.RESET_ALL,end="")

#### mission ####

myspacecraft = Spacecraft()

# flight phases
launch = flightphase("Launch",None)
leo = flightphase("LEO",launch)
tlo = flightphase("TLO",leo)
llo_inj = flightphase("LLO Injection",tlo)
operations = flightphase("Operations",llo_inj)
eol_burn = flightphase("End of Life Burn",operations)
endoflife = flightphase("End of Life",eol_burn)

```

```
# structure
frame = SCComponent("Frame",Subsystem.STRUCTURE,3,0,0,0,0,0)
myspacecraft.add_area(2*2*np.sin(np.pi/4))
mech_sp_deploy = SCComponent("solar deploy. mech.",Subsystem.STRUCTURE,0.4*2,0,0,0,0,0)
mech_sp_rotate = SCComponent("solar array drive mech.",Subsystem.STRUCTURE,3.7*2,0,0,0,4,0)

# propulsion
#busek BHT-350
# throttled to consume less power
halleffect = SCComponent("Hall Effect Thruster",Subsystem.PROPULSION,1.9,0,17e-3,1244,-300,0)
#halleffect = SCComponent("Hall Effect Thruster",Subsystem.PROPULSION,1.9,0,16e-3,1244,-286,0)
halleffect.add_active_phase(tlo)
halleffect.add_active_phase(llo_inj)
halleffect.add_active_phase(eol_burn)

lcppu = SCComponent("Thruster system",Subsystem.PROPULSION,1.4,0,0,0,0,0)

# for solid iodine propellant tank & system - dry =~ wet*0.2
tank = SCComponent("Propellant Tank",Subsystem.PROPULSION,50*0.2,0,0,0,0,0)

# power
solarpanels = SCComponent("Solar Panels",Subsystem.POWER,3.8*1.1*1*2,0,0,0,308*2,0)
solarpanels.add_active_phase(leo)
solarpanels.add_active_phase(tlo)
solarpanels.add_active_phase(llo_inj)
solarpanels.add_active_phase(operations)
solarpanels.add_active_phase(eol_burn)
solarpanels.add_active_phase(endoflife)
myspacecraft.add_area(1.1*1.0) # 1 panel 1.1m x 1m

batteries = SCComponent("Batteries",Subsystem.POWER,3.7,0,0,0,0,0)
batteries.set_max_energy_storage(260*3600*batteries.drymass) # 260 Wh/kg
batteries.add_active_phase(leo)
batteries.add_active_phase(tlo)
batteries.add_active_phase(llo_inj)
batteries.add_active_phase(operations)
batteries.add_active_phase(eol_burn)
batteries.add_active_phase(endoflife)

pcdu = SCComponent("Power Control Unit",Subsystem.POWER,0.5,0,0,0,-10,0)

launcher_gen = SCComponent("Launcher el",Subsystem.POWER,0,0,0,0,100,0)
launcher_gen.add_active_phase(launch)

# avionics
OBC = SCComponent("Onboard Computer",Subsystem.AVIONICS,0.300,0,0,0,-6,-1)
OBC.add_active_phase(leo)
OBC.add_active_phase(tlo)
OBC.add_active_phase(llo_inj)
OBC.add_active_phase(operations)
OBC.add_active_phase(eol_burn)
OBC.add_active_phase(endoflife)

# attitude control
#ST400
startrackers = SCComponent("Star Trackers",Subsystem.ATTITUDE_CONTROL,0.28*2,0,0,0,-0.7*2,-0.37*2)
startrackers.add_active_phase(tlo)
startrackers.add_active_phase(llo_inj)
startrackers.add_active_phase(operations)
startrackers.add_active_phase(eol_burn)
#4 cmgs + ctrl box
cmgs = SCComponent("CMGs",Subsystem.ATTITUDE_CONTROL,0.6*4 + 0.7,0,0,0,-1.5*4 + 8,-0.5)
cmgs.add_active_phase(leo)
cmgs.add_active_phase(tlo)
cmgs.add_active_phase(llo_inj)
cmgs.add_active_phase(operations)
cmgs.add_active_phase(eol_burn)

# STIM380H
gyros = SCComponent("Gyros",Subsystem.ATTITUDE_CONTROL,0.06*2,0,0,0,-1.8*2,-0.2*2)
gyros.add_active_phase(leo)
gyros.add_active_phase(tlo)
```

```
gyros.add_active_phase(llo_inj)
gyros.add_active_phase(operations)
gyros.add_active_phase(eol_burn)

# coldgas microsystem
# vaco X19039000-03 (x2)
mips = SCComponent("coldgas system",Subsystem.ATTITUDE_CONTROL,(0.557 + 0.697)*2,0,0,0,-1*2,0)
mips.add_active_phase(tlo)
mips.add_active_phase(llo_inj)
mips.add_active_phase(operations)
mips.add_active_phase(eol_burn)

#thermal
Qsol = myspacecraft.light_rad(1361)
Qmoon = myspacecraft.light_rad(1361*0.12) + myspacecraft.emissivity*BOLTZ*TMOONAVG**4

tmu = SCComponent("thermal management unit",Subsystem.THERMAL,3,0,0,0,-10,0)
tmu.add_active_phase(leo)
tmu.add_active_phase(tlo)
tmu.add_active_phase(llo_inj)
tmu.add_active_phase(operations)
tmu.add_active_phase(eol_burn)
tmu.add_active_phase(endoflife)
radiator = SCComponent("radiator",Subsystem.THERMAL,0.5,0,0,0,0,0)

#communcation
ttnc = SCComponent("TTNC",Subsystem.COMMUNICATION,4,0,0,0,-20,-2)
ttnc.add_active_phase(leo)
ttnc.add_active_phase(tlo)
ttnc.add_active_phase(llo_inj)
ttnc.add_active_phase(operations)
ttnc.add_active_phase(eol_burn)
ttnc.add_active_phase(endoflife)

gnss = SCComponent("GNSS",Subsystem.PAYLOAD,0.6,0,0,0,-30,-1)
gnss.add_active_phase(operations)

heli = SCComponent("Helical Antenna",Subsystem.PAYLOAD,0.2,0,0,0,-0,-0)
gnssSigGen = SCComponent("Signal generator",Subsystem.PAYLOAD,0.3,0,0,0,-10,-0)
gnssSigGen.add_active_phase(operations)

atomic_clock = SCComponent("Atomic Clock",Subsystem.PAYLOAD,0.1,0,0,0,-0.1,-0)
atomic_clock.add_active_phase(operations)

# 30Ghz high directivity antenna for 1Gbps
telecoms = SCComponent("Telecommunications",Subsystem.PAYLOAD,3,0,0,0,-20,0)
txLNA = SCComponent("telecoms TX LNA",Subsystem.PAYLOAD,0.1,0,0,0,-40,-0)
rxLNA = SCComponent("telecoms RX LNA",Subsystem.PAYLOAD,0.1,0,0,0,-40,-0)
telecoms.add_active_phase(operations)
txLNA.add_active_phase(operations)
rxLNA.add_active_phase(operations)

opticalCCS = SCComponent("Optical Comms",Subsystem.PAYLOAD,1.6*2,0,0,0,-20,0)
opticalCCS.add_active_phase(operations)


# add components to spacecraft
myspacecraft.add_component(frame)
myspacecraft.add_component(mech_sp_deploy)
myspacecraft.add_component(mech_sp_rotate)

myspacecraft.add_component(halleffect)
myspacecraft.add_component(tank)
myspacecraft.add_component(lcppu)

myspacecraft.add_component(solarpanels)
myspacecraft.add_component(batteries)
myspacecraft.add_component(launcher_gen)

myspacecraft.add_component(OBC)
myspacecraft.add_component(ttnc)

```

```
myspacecraft.add_component(tmu)
myspacecraft.add_component(radiator)

myspacecraft.add_component(startrackers)
myspacecraft.add_component(cmgs)
myspacecraft.add_component(mips)
myspacecraft.add_component(gyros)

myspacecraft.add_component(gnss)
myspacecraft.add_component(atomic_clock)
myspacecraft.add_component(heli)
myspacecraft.add_component(gnssSigGen)

myspacecraft.add_component(telecoms)
myspacecraft.add_component(txLNA)
myspacecraft.add_component(rxLNA)

misc = SCComponent("Miscellaneous",Subsystem.STRUCTURE,myspacecraft.mass*(0.1),0,0,0,0,0) # 10%
    mass margin
myspacecraft.add_component(misc)

#flight phases properties
leo.duration = 10*SECPDAY # 10 days

# added inclinaison corr from sso to leo
inc_chg = np.abs(28.5 - 23.44 - 5.14)
print("inclinaison change {} deg".format(inc_chg))
leo.dv = 2*np.sqrt(MU_EARTH/(R_EARTH+ 500e3))*np.sin(np.deg2rad(inc_chg)/2)

tlo.compute_spiral_dV(MU_EARTH,R_EARTH + 500e3,RS_MOON)
tlo.compute_duration(myspacecraft.thrust,myspacecraft.mass)
tlo.set_max_duration(240*SECPDAY)

llo_inj.compute_spiral_dV(MU_MOON,DIST_EARTH_MOON - RS_MOON,4400e3)
llo_inj.compute_duration(myspacecraft.thrust,myspacecraft.mass)
llo_inj.set_max_duration(120*SECPDAY)

operations.duration = 5*365*SECPDAY # 5 years
operations.dv = 2 * operations.duration/(SECPDAY*365) # ~2 km/s per year

eol_burn.compute_spiral_dV(MU_MOON,R_MOON + 4400e3,R_MOON + 600e3)
eol_burn.compute_duration(myspacecraft.thrust,myspacecraft.mass)
eol_burn.set_max_duration(120*SECPDAY)

#contigency
eol_burn.dv += 0.5e3 # 500 m/s or 10% contigency

endoflife.set_mass_end(myspacecraft.dry_mass)
endoflife.comp_mass_start(halleffect.isp,True)

myspacecraft.add_flight_phase(launch)
myspacecraft.add_flight_phase(leo)
myspacecraft.add_flight_phase(tlo)
myspacecraft.add_flight_phase(llo_inj)
myspacecraft.add_flight_phase(operations)
myspacecraft.add_flight_phase(eol_burn)
myspacecraft.add_flight_phase(endoflife)

myspacecraft.comp_propmass()
myspacecraft.compute_elec_energy(myspacecraft.max_energy_storage,leo)
myspacecraft.inertia_estimate([0.4,0.2,0.2]) #(16U)
myspacecraft.set_torque([112e-3,112e-3,112e-3])# 112mNm of 1 cmg
myspacecraft.comp_axis_accel()

myspacecraft.print_info()
```