ESA MOONLIGHT CONSTELLATION - MANAGEMENT AND DEVELOPMENT PLAN PROPOSAL

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1 Introduction

The present report describes the development and management plans for the launch and deployment of a cis-lunar satellite constellation, scheduled to be launched in 2032, with an operational life of at least 5 years. The objective of the mission is to demonstrate the data rate, volume capabilities, and the Position, Navigation, and Timing service on the Moon Surface, with an expected Moon-Earth data transmission of at least 10% of the full offload. The mission shall involve the design, development, testing, and operation of a constellation of four small sat with communication interfaces and protocols compliant with NASA's LunaNet Interoperability Specification (Version 5) [6]. The final objective is to achieve the TRL 9 for the entire constellation. The mission is conducted in the frame of ESA's Moonlight Program [4]. The document is delivered in compliance with ESA's ECSS standards and includes a preliminary plan for all the standard development phases, from Phase 0 to Phase E, with a more detailed plan for Phase D. The following sections describe the planned work to be carried out in each phase as defined by the ECSS guidelines.

2 High-Level Requirements

This section introduces a preliminary high-level requirements analysis aimed at formalizing the needs of the top-level customer. Such requirements will then be refined during the needs identification, in Phase 0, and translated into technical specifications later, during the feasibility analysis, in Phase A. Table 2 constitutes an initial proposal, following the requirements [2] and tests [1] taxonomies according to the ECSS standard. Appendix A reports a summary of the aforementioned types, respectively, in Table 3 and Table 4.

Code	Category	Name	Description	Test
HLR-1	Configuration	Constellation Numerosity	The constellation shall include at least 3 satellites.	Review-of-design
HLR-2	Environmental	ELFOs Orbits	The constellation shall be deployed in Elliptical Lunar Frozen Orbits (ELFOs).	Review-of-design
HLR-3	Environmental	ELFOs Orbits	Each satellite of the constellation shall be able to operate in the environment of ELFO Lunar Orbit.	Test
HLR-4	Functional	PNT Service Capability	The constellation shall be able to provide h-24 PNT services across the entire lunar south pole.	Test
HLR-5	Functional	Moon-Earth Data Transfer	The constellation shall be able to transfer at least 10% of its data volume to an Earth relay station.	Test
HLR-6	Interface	LunaNet Standard Compliance	The mission shall be developed in compliance with LunaNet Interoperability Specifications (Version 5).	Review-of-design
HLR-7	Mission	Mission Lifetime	The constellation shall be functioning for at least 5 years from the launch date.	Review-of-design
HLR-8	Mission	Launch Date	The mission shall be launched in 2032.	Review-of-design
HLR-9	Physical	Mass	Each satellite of the constellation shall have a total mass that is at most 50Kg.	Inspection
HLR-10	Physical	Power Budget	Each satellite of the constellation shall have a power budget that is at least 500W.	Test
HLR-11	Product Assurance	Model Philosophy	The Model Philosophy shall include: Breadboarding, STM, EM, and PFM.	Inspection

Table 1: Preliminary High-Level Requirement Matrix

Note that the choice of the orbit is proposed in compliance with ESA Moonlight plan [5]. Programmatic aspects will also be explored more in-depth during feasibility, such as budget definition and commercial scouting for possible suppliers to provide the technology for the project. In particular, it is proposed to focus the market search on already space-proof TRL9 Commercial Off-The-Shelf (COTS) components. Such a guideline is fostered as the project is focused on bringing to the Moon capabilities that have already been tested in Earth's orbit. Reusing already established technologies should accelerate the schedule and reduce the risk of failure during operations. Finally, the preliminary risk assessment will be conducted. It is worth taking into consideration the risk of commercial and legal restrictions possibly derived by future evolutions of today's unstable geopolitical scenario.

3 Product Tree

The present section proposes a preliminary Product Tree. A product tree illustrates a hierarchical view of the final product to be launched and its sub-products down to the most atomic leaf components.

As shown in Figure 1, the mission is decomposed into two fundamental high-level products: the Space Segment and the Ground Segment, with the second being handled and acquired as a service by third-party organizations.

More specifically, the Ground Segment is planned to be composed of a Cyber Center of Excellence (CCoE) and a Precise Orbit Determination (POD) facility. Technically speaking, the main product is the RF chain, particularly the antenna, required for the X-Band Moon-Earth communications, according to LunaNet standard [6]. An external agency or supplier commissioned by ESA, will be responsible for the Ground Segment products.

On the Space Segment side, the main product is a Protoflight Model of the constellation's satellites. The realization of 3 satellites is initially planned, although it is recommended to consider the addition of an optional fourth satellite as a backup, enabler for altitude estimation, or fully dedicated for Moon-Earth communications. Each satellite is provided with all the canonical spacecraft subsystems and a Navigation payload able to compute precise position and time coordinates. The Thermal Subsystem shall be provided with active thermo-regulatory components, to keep the temperature stable both during daylight and eclipse. The Attitude Control subsystem shall be provided with everything needed to perform highly precise attitude determination and stabilization maneuvers in the absence of the Earth's magnetic field. The Telecommunication Subsystem is planned to fulfill the communication requirements in the standard radio band following LunaNet's guidelines. For this purpose, the spacecraft shall be equipped with an S/C/X band antenna for Lunar Surface-Orbit (LS-LO), Lunar Orbit-Orbit (LO-LO), and Lunar Orbit-Earth (LO-Earth) data transfer. The proposed power generation subsystem operates via solar arrays, storing energy in lithium batteries. Finally, a preliminary view of the On-Board Data Handling (OBDH) and the Structure Subsystem is provided, with an On-Board Computer (OBC) backup for improved availability.

3.1 Design and Implementation

The need for Electric Heaters, Heat Pipes, and more precise sizing and orbit determination is delayed to be carried out in between the Feasibility (Phase A) and the Preliminary Design (Phase B). Each subsystem, as well as the related products, is planned to be entirely commissioned to one supplier. A preliminary designated consortium has been adopted waiting for the approval of the committee. Redundancies are planned for small and digital components to ensure proper functioning in the event of radiation-induced failures. Lastly, the project is aimed at achieving TRL 9, as mentioned in Section 1. Furthermore, the desired capability is something already achieved in Earth's orbit by GNSS and SatCom constellations. For such reasons, it is strongly recommended to rely on already space-proof components with a high maturity level.

The required Model Philosophy, coherently with the previously introduced High-Level Requirements and Product Tree, is a Hybrid Philosophy that includes:

- **Breadboarding (BB)**: a preliminary model to test single electrical components and their wiring during the early stages of the project. If the recommendation of relying on high TRL COTS is followed then little to no BB should be required during the early phases.
- **Protoflight Model (FM)**: the complete system as it will eventually be both qualified and deployed during the operations. At least one PFM will be initially assembled to be then replicated in series;

- **Structural-Thermal Model (STM)**: a simplified model of the support structure and thermal system aimed at analyzing the size and weight of the system, as well as the thermo-regulation capability;
- **Engineering Model (EM)**: a simplified assembly of the electrical components: power supply, OBCs, and RF components and interfaces.

3.2 System Qualification

The products to be integrated into the spacecraft are proposed to be high-level space-proof technologies, as already mentioned in Section 3.1. Following this approach, the proposed models will require less intensive qualifications, accelerate the tests, and reduce the risk of failure. The focus shall be placed on: (i) qualification of original software code, (ii) testing the radio-trans-reception capabilities, potentially in an anechoic chamber; (iii) inspecting the conformity and robustness of the STM to size, weight, and thermal requirements; (iv) ensuring proper power supply.

4 Work Breakdown Structure

This section introduces the high-level Work Breakdown Structure (WBS) for Phase D. A WBS is a structured organization of the work into hierarchical packages, each of which is assigned to one or more WP Leaders.

Phase D is the Qualification and Production step in a space mission development process that follows the ECSS standard. It encompasses the final qualification of the components, including model- and system-level verifications, and interoperability.

Figure 2 reports an illustration of the preliminary WBS proposed for this project. Each WP is illustrated as a block, reporting: (1) the main subsystem on which the WP is focused; (2) the high-level activity; (3) the WP leaders; (4) the unique identification code. The code follows the format: PPP-H-SS-AAUU, where:

- PPP is the project acronym;
- H is the phase;
- SS is the system number (i.e. spacecraft, payload, ground segment, launch segment, etc.);
- AA is the high-level activity number (i.e. Manufacturing & Qualification);
- UU is the specific activity number (i.e.);

The main high-level WPs include general activities related to the finalization of Assembly, Integration, and Verification (AIV), harnessing, and project management of both the spacecraft and the navigation payload, initiated in Phase C according to the plan. The AIV and harnessing activities are further broken down to be divided into all three models according to the philosophy elected in 3.1. Management activities include general monitoring of the project, procurement of residual components not yet obtained in Phase C, product assurance, and the release of the final acceptance data package. The same activities are also considered at system levels. It is planned to have WP for the Ground Segment and the Launch Segment. However, they are planned to be subcontracted to a third-party agency and are to be further defined during the first phases of the project. Furthermore, the WBS includes WP aimed to test the interoperability between Ground Segment and Space Segment, and between two spacecrafts of the constellation in the Space Segment. It is worth noting the need for the release of the Series Production Master Files, for both achieving the manufacturing of multiple satellites and the eventual future replacement of dismissed assets. Finally, a WP for disposal planning is scheduled.

5 Development Process Plan

5.1 Development Phases

This section structures the proposed project into the ECSS standard phases from Phase 0 to Phase D. Table 2 provides a structured view of the organization of the process into phases.

The table summarizes and tailors the information on the proposed project-specific characteristics. A detailed overview of all the phases and the related review and deliverables can be found in the ECSS standard documents [3].

The initial phases (Phase 0, and A) are mostly focused on a detailed definition of the needs and the objective, the scouting of already space-qualified technologies, and the feasibility of their integration, compliance with the LunaNet standard, and capability of operating in the lunar environment. Phase B is focused on the release of the main engineering/management diagrams (function tree, specification tree, product tree) and the model philosophy. Phases C and D are focused on the realization and test of the main models (BB, PFM, EM, STM), the AIV, and all the qualification activities aimed to certify the model for series production and operations.

5.2 Time Schedule

The GANTT chart in Figure 3 illustrates the preliminary plan for the development of all the phases of the project. The initial phases are expected to be short in comparison with the much more complex later phases involving the development and qualification activities. It is worth noting that Phase D is expected to last shortly with respect to Phase B and C, due to less intensive testing requirements for COTS components.

5.3 Cost Profile Estimation

The plot in Figure 4 illustrates the estimated cost profile for the project. Unlike what is traditionally estimated for space projects, such a plot shows a left shift in the peak that is usually located between phases C and D. This is due to the aforementioned reduced complexity of the qualification activities. In this case, slightly more attention is required on the feasibility and the design phases, phases B and C, with phase D focused on assembly and integration activities. A cost of €3M is assumed for the production of each satellite, including the payload and replication costs, with a risk margin of 10% (€300K) on the PFM due to possible bad technological choices to be corrected during development. The expected cost at launch for three satellites should be approximately €9.3M, excluding GT costs and the purchase of launch services from third parties.

Figure 1: View of the preliminary high-level Product Tree

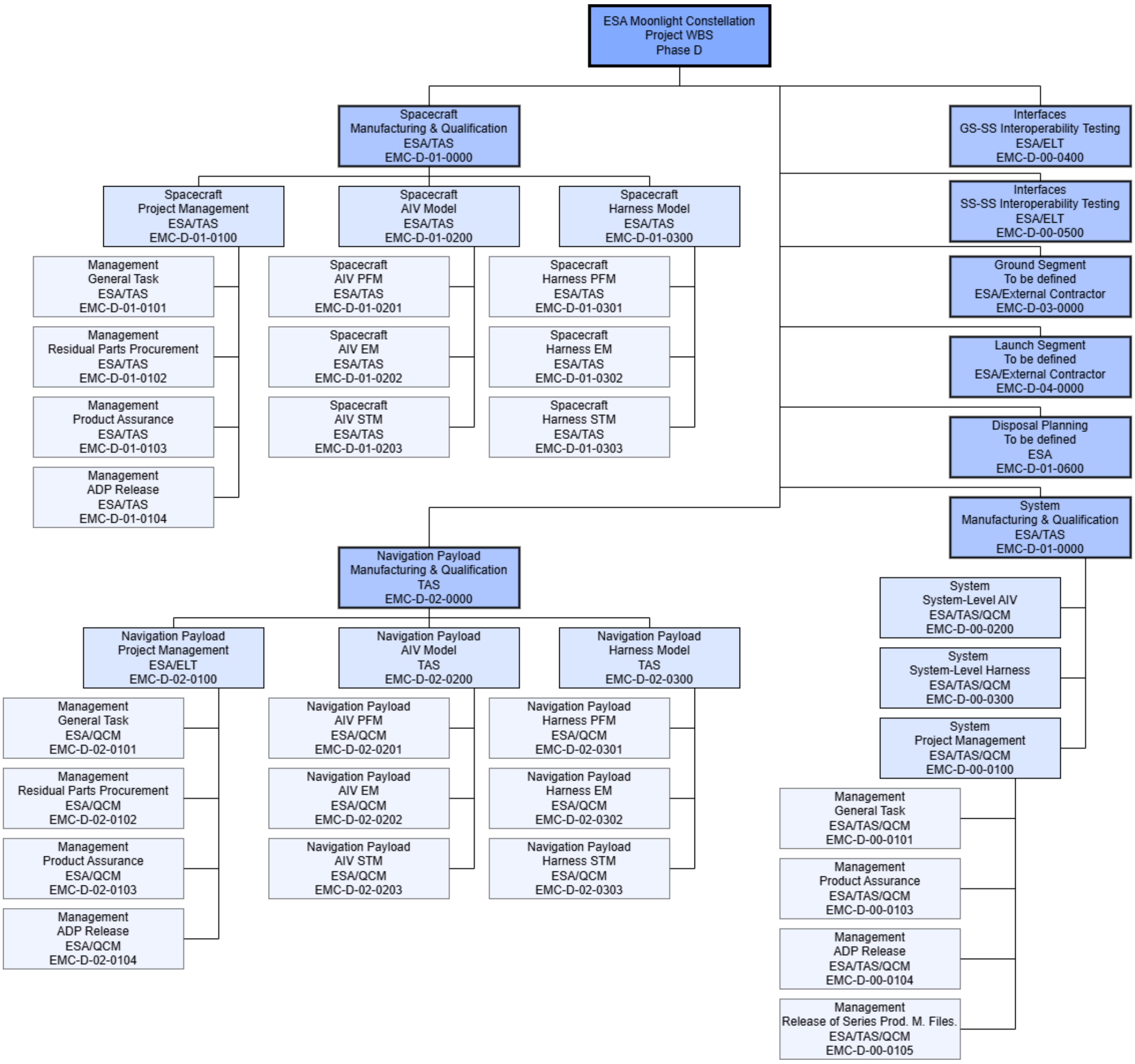

Figure 2: View of the preliminary high-level Work Breakdown Structure

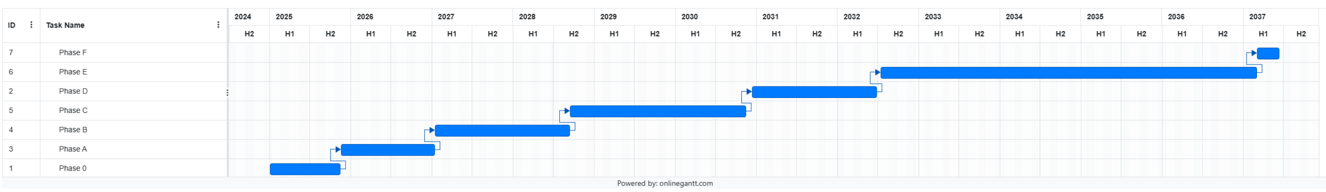

Figure 3: View of the preliminary high-level Work Breakdown Structure

Phase			Final Review	
Code	Name	Activities	Review	Objective
0	Mission Analysis/Needs Identification	Definition of the needs and preliminary PNT/network technical requirements, and data transfer expected performance; market analysis and scouting for candidate suppliers.	Mission Definition Review (MDR)	Release Mission Statement; Release Preliminary Technical Requirements; Define Programmatic Aspects.
A	Feasibility	Identification of the required functionalities and analysis of the feasibility with respect to the time and cost constraints. Scouting for already space-proven technologies. Preliminary feasibility for transferring technologies qualified in space orbit to lunar orbits. Analysis of the applicability of the required standards, including Moonlight program guidelines and LunaNet compatibility standard.	Preliminary Requirement Review (PRR)	Release Preliminary management, engineering, and product assurance plan; Release Technical Requirements specification; Confirm technical/programmatic feasibility; Preliminary selection of the final Model Philosophy; Preliminary selection of the Verification Approaches.
B	Preliminary Definition	Completion of trade-off studies and elaboration of the baseline master schedule and cost of the project. Finalization of the major artifacts (function tree, product tree, etc.) and definition of the verification plan (including the model philosophy).	System Requirements Review (SRR)	Release the updated technical requirements specifications; Asses the preliminary design definition; Asses the preliminary verification program.
			Preliminary Design Review (PDR)	Verify the preliminary design against the requirements; Release the final management, engineering, and product assurance plans; Release product tree, work breakdown structure, and specification tree; Release the verification plan (including model philosophy).
C	Detailed Definition	Detailed definition of the assembly for the COTS components into the defined models, prequalification of the models, detailed definition of the interfaces in compliance with the defined standards, initiation of model developments;	Critical Design Review (CDR)	Asses the qualification and validation status, and readiness for Phase D; Confirm compatibility with external interfaces; Release the final design; Release the assembly, integration, and test planning; Release flight hardware/software manufacturing, assembly, and testing; Release user manual.
D	Qualification and Production	Completion of AIV activities of both the payload and the spacecraft for all models and at system levels; completion of the interoperability testing for LO-Earth, LO-LO, LO-LS communications in test environments; Confirmation of the reproducibility and release of the master files for series production.	Qualification Review (QR)	Confirm the verification of the design; Confirm the completeness of the verification record; Confirm the acceptability of all waivers and deviations; Reproducibility analysis; Produce master files for series productions; Accept the series production file by the customer.
			Acceptance Review (AR)	Confirm flight-readiness; Confirm the verification record at all the levels in the customer-supplier chain; Confirm that all the deliverable products are available; Perform comparison between the as-build and the as-design configurations of the products; Verify the acceptability of all waivers and deviations; Verify the Acceptance Data Package; Authorize of the product's delivery; Release the certificate of acceptance.
			Operational Readiness Review (ORR)	Confirm the operational procedures and their compatibility with the flight system; Confirm of the readiness of the operations teams; Accept and release the ground segment for operations.

Table 2: Development Process organization according to the ECSS Standard

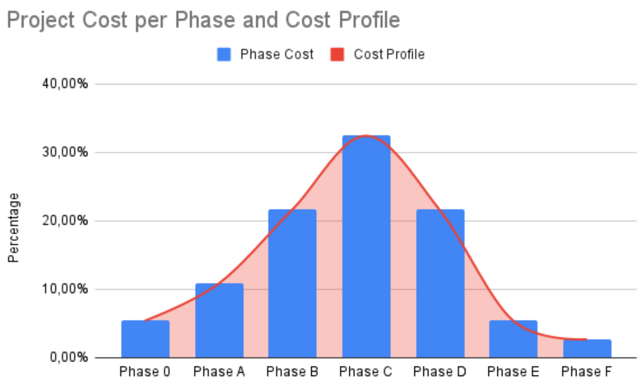

Figure 4: Project Cost per Phase and Cost Profile

A Appendix

ECSS-E-ST-10-06C	
Requirement Type	**Description**
Functional requirements	Requirements that define what the product shall perform, in order to conform to the needs / mission statement or requirements of the user.
Mission requirements	Requirements related to a task, a function, a constraint, or an action induced by the mission scenario.
Interface requirements	Requirements related to the interconnection or relationship characteristics between the product and other items.
Environmental requirements	Requirements related to a product or the system environment during its life cycle
Operational requirements	Requirements related to the system operability.
Human factor requirements	Requirements related to a product or a process adapted to human capabilities considering basic human characteristics.
(Integrated) logistics support requirements	Requirements related to the (integrated) logistics support considerations to ensure the effective and economical support of a system for its life cycle.
Physical requirements	Requirements that establish the boundary conditions to ensure physical compatibility and that are not defined by the interface requirements, design and construction requirements, or referenced drawings.
Product assurance (PA) induced requirements	Requirements related to the relevant activities covered by the product assurance.
Configuration requirements	Requirements related to the composition of the product or its organization.
Design requirements	Requirements related to the imposed design and construction standards such as design standards, selection list of components or materials, interchangeability, safety or margins.
Verification requirements	Requirements related to the imposed verification methods, such as compliance to verification standards, usage of test methods or facilities.

Table 3: Requirement Topology from ECSS-E-ST-10-06C

ECSS-E-ST-10-02C	
Test Type	**Description**
Test Type	Verification by test shall consist of measuring product performance and functions under representative simulated environments.
Analysis	Verification by analysis shall consist of performing theoretical or empirical evaluation using techniques agreed with the Customer.
Review-of-Desing	Verification by Review-of design (ROD) shall consist of using approved records or evidence that unambiguously show that the requirement is met.
Inspection	Verification by inspection shall consist of visual determination of physical characteristics.

Table 4: Verification methods topology from ECSS-E-ST-10-02C

References

[1] *ECSS-E-ST-10-02C: Verification*. ECSS Standard ECSS-E-ST-10-02C. European Cooperation for Space Standardization (ECSS), 2018. URL: https://ecss.nl/standard/ecss-e-st-10-02c-rev-1-verification-1-february-2018/.

[2] *ECSS-E-ST-10-06C: Technical Requirements Specification*. ECSS Standard ECSS-E-ST-10-06C. European Cooperation for Space Standardization (ECSS), 2009. URL: https://ecss.nl/standard/ecss-e-st-10-06c-technical-requirements-specification/.

[3] *ECSS-E-ST-106C: Project planning and implementation*. ECSS Standard ECSS-E-ST-106C. European Cooperation for Space Standardization (ECSS), 2009. URL: https://ecss.nl/standard/ecss-m-st-10c-rev-1-project-planning-and-implementation/.

[4] ESA. *ESA - Moonlight*. 2021. URL: https://www.esa.int/Applications/Connectivity_and_Secure_Communications/Moonlight.

[5] ESA. *ESA Lunar Navigation Plans: Lunar Pathfinder Moonlight*. URL: https://www.unoosa.org/documents/pdf/icg/2022/ICG16/WG-B/ICG16_WG-B_05.pdf.

[6] *LunaNet Interoperability Specification – Version 5*. NASA Standard 5. NASA, 2025. URL: https://www.nasa.gov/directorates/somd/space-communications-navigation-program/lunanet-interoperability-specification/.