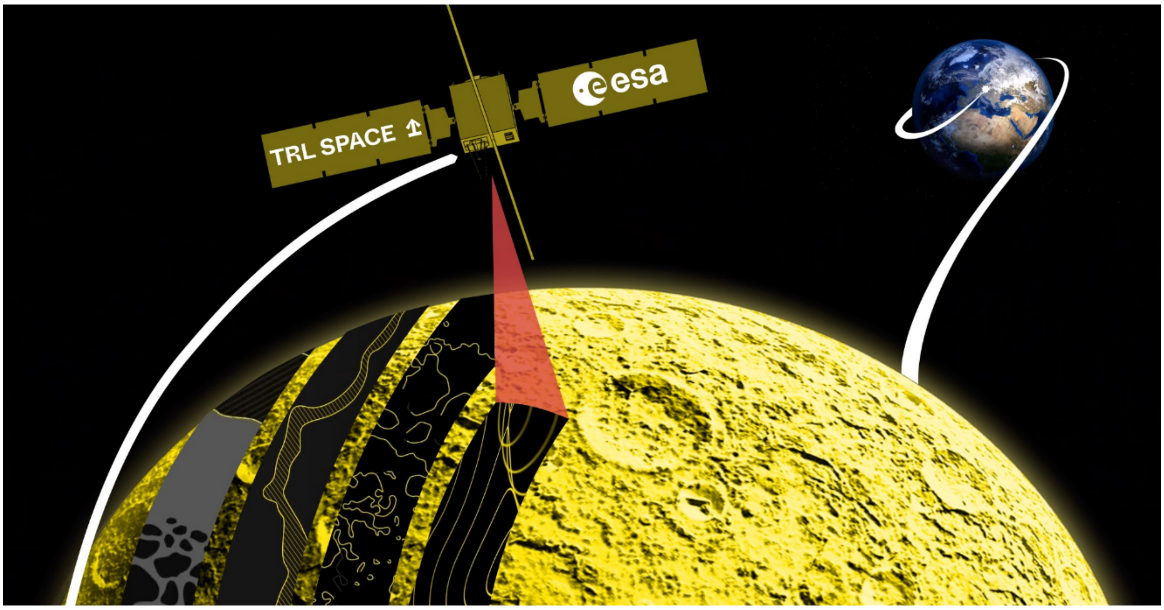

LUnar Geology Orbiter (LUGO)

Executive Summary

Study

ESA Open Space Innovation Platform (OSIP) Idea Id I-2022-02577 (Open Channel)

Affiliation(s): TRL Space Systems s.r.o. (Prime Contractor)

Activity Summary: The LUnar Geology Orbiter (LUGO) is a scientific and exploratory mission to study the thermal evolution of the Moon by characterizing Irregular Mare Patches, as well as lunar lava tubes. This will be accomplished by four payloads, a ground penetrating radar, a hyperspectral camera, LiDAR and narrow angle camera, which will produce images at a greater resolution than currently available. The scientific study will provide confirmation or refutation of current knowledge about the thermal evolution of the Moon. Lunar lava tubes can become potential habitats to provide shelter from the harsh conditions on the Moon, to include dramatic temperature changes, cosmic radiation and micrometeorites.

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1.1 APPLICABLE DOCUMENTS

AD	Reference	Document Title	Issue	Date
AD1	I-2022-05141	Idea I-2022-05141: 2nd Round: Lunar Geology Orbiter (LUGO)	1.0	13/01/2022

1.2 REFERENCE DOCUMENTS

RD1	Wilson, L., and Head, J. W. (2017). Eruption of magmatic foams on the Moon: Formation in the waning stages of dike emplacement events as an explanation of “irregular mare patches”. Journal of Volcanology and Geothermal Research, 335, 113-127.
RD2	Qiao, L., Head, J., Wilson, L., & Ling, Z. (2021). Ina Lunar Irregular Mare Patch Mission Concepts: Distinguishing between Ancient and Modern Volcanism Models. The Planetary Science Journal, 2, 66. DOI 10.3847/PSJ/abeaa0.
RD3	Braden, S. E., Stopar, J. D., Robinson, M. S., Lawrence, S. J., Van Der Bogert, C. H., & Hiesinger, H. (2014). Evidence for basaltic volcanism on the Moon within the past 100 million years. Nature Geoscience, 7(11), 787-791.
RD4	Esmaeili, S., Kruse, S., Jazayeri, S., Whelley, P., Bell, E., Richardson, J., Garry, W., & Young, K., (2020). Resolution of Lava Tubes with Ground Penetrating Radar: The TubeX Project. Journal of Geophysical Research 125, e2019JE006138.
RD5	Miyamoto H., Haruyama J., Rokugawa S., Onishi K., & Palmero A. (2002). Ground Penetrating Radar to detect lava tubes: preliminary results of a GPR application to Fuji volcano. Lunar and Planetary Science XXXIII, #1482.
RD6	Schultz, P. Floor-fractured lunar craters. The Moon 15, 241–273 (1976). https://doi.org/10.1007/BF00562240.
RD7	Jozwiak, L., Head, J., Zuber, M., Smith, D., & Neumann, G. (2012). Lunar floor- fractured craters: Classification, distribution, origin and implications for magmatism and shallow crustal structure. Journal of Geophysical Research: Planets, 117(E11).
RD8	Hulme, G., and G. Fielder, Effusion rates and rheology of lunar lavas, Philos. Trans. R. Soc. London, Ser. A., 285, 227-234, 1977.

2 ACRONYMS, ABBREVIATIONS AND DEFINITIONS

AoP	Argument of perigee
CEE	Central and Eastern Europe
COTS	Commercial off-the-shelf
DPC	Data Processing Centre
DPU	Data Processing Unit
DTE	Direct-to-Earth
ECSS	European Cooperation for Space Standardization
EM	Engineering Model
EOL	End-of-life
EPS	Electrical Power System
ESA	European Space Agency
ESOC	European Space Operations Centre
ESTRACK	ESA Tracking Stations
Etc	Et cetera
FFC	Floor-fractured craters
FM	Flight Model
FOC	Full Operational Capability
FoV	Field of View
GB	Gigabyte
Gbit	Gigabit (also Gb)
GEO	Geosynchronous equatorial orbit
GPR	Ground penetrating radar
GTO	Geosynchronous Transfer Orbit
Hera	ESA Mission
HSC	Hyperspectral camera
HSI	Hyperspectral Imager

IMP	Irregular Mare Patch
IOC	Initial Operational Capability
ISIS	Integrated Software for Imagers and Spectrometers
KSAT	Kongsberg Satellite Services
LBT	Low Ballistic Transfer
LCNS	Lunar Communication and Navigation Services
LEO	Low Earth Orbit
LiDAR	Light Detection and Ranging
LOI	Lunar Orbit Insertion
LRO	Lunar Reconnaissance Orbiter
LUGO	Lunar Geology Orbiter
MBSE	Model-based System Engineering
MOC	Mission Operation Centre
NAC	Narrow angle camera
NASA	National Aeronautics and Space Administration
OBC	On-board Computer
PA	Product Assurance
PCDU	Power Conditioning and Distribution Unit
PF	Platform
PL	Payload
QA	Quality Assurance
QM	Qualification Model
RAAN	Right ascension of the ascending node
S/C	Spacecraft
SD	Secure digital
SIS	Software Interface Specification
SMA	Semi-major axis
SME	Subject Matter Experts

SRR	System Requirements Review
TRL	Technology Readiness Level
TTC	Telemetry and Telecommand

3 Introduction

Lunar exploration has always been a subject of fascination and scientific curiosity for humankind. The Moon, Earth’s natural satellite, has captivated our attention for centuries, and space agencies around the world have embarked on numerous missions to explore its mysteries. The lunar surface presents a tapestry of geological features, ranging from vast volcanic plains known as maria, ancient crater formations, to rugged mountain ranges. Such diverse landscapes not only provide clues to the past of the Moon, but also offer an intriguing glimpse into the broader history of our own planet and its neighbouring celestial bodies. In support of these general objectives in lunar exploration, Project LUGO proposes a mission with which to study surface and subsurface geological features on the Moon to understand thermal evolution and support exploration and permanent settlements. LUGO aims to identify potential lunar habitats and fully utilize the proposed lunar infrastructure developed as part of ESA’s Terrae Novae 2030+ program. By doing so, the mission aligns with Europe's space strategy roadmap, fostering exploration, and supporting the development of sustainable lunar settlements while contributing to the broader goals of space exploration at the same time.

4 Mission Statement and Objectives

In support of lunar exploration, the LUGO mission is being proposed to study surface and subsurface geological features on the Moon to understand its thermal evolution and support exploration and permanent settlements. The objectives of the LUGO mission are twofold; to study Irregular Mare Patches (further referred to as IMPs), enigmatic volcanic landforms located on the near side of the Moon, due to the implications of their formation for the overall thermal evolution of the Moon, and to detect lava tubes and characterise their general shapes to help to evaluate their possible usage as plausible habitat locations in the future by astronauts. Both targets, IMPs and lava tubes, represent knowledge gaps, which are critical for better understanding of lunar thermal evolution as well as the understanding of lunar volcanism, but have not been gained by other missions to date.

Mission Statement:

Study surface and subsurface geological features on the Moon to understand its thermal evolution and support further human exploration and permanent settlements.

Primary Objective:

Determine the formation age of Irregular Mare Patches (IMPs) for confirmation or refutation of current knowledge about the thermal evolution of the Moon.

IMPs are characterised by two morphologically distinct units: a) by convex-upward mounds with smooth surface, uniform texture and little to no boulders, and b) unusually bright, optically immature hummocky/blocky floor units. Two mutually contradictory hypotheses have been proposed to explain the mechanism of IMPs formation; namely the effusion of compact lavas less than 100 million years ago, and the ascent of lava foams several billion years ago. Depending on the formation scenario (Fig. 4-1), mounds are interpreted as the viscous extrusion of foamy magma that had collected below the lava lake floor in the terminal stage of the volcanic eruption ([RD1], [RD2]), or as a compact lava flow that has been emplaced “recently” over the older surface [RD3]. Similarly, optically immature floor deposits forming rough surfaces between the mounds are explained as the crust of former lava lakes composed of macrovesicular basalts

([RD1], [RD2]), or as a layer of ~3-billion-year-old regolith formed from formerly emplaced basaltic mare lavas [RD3].

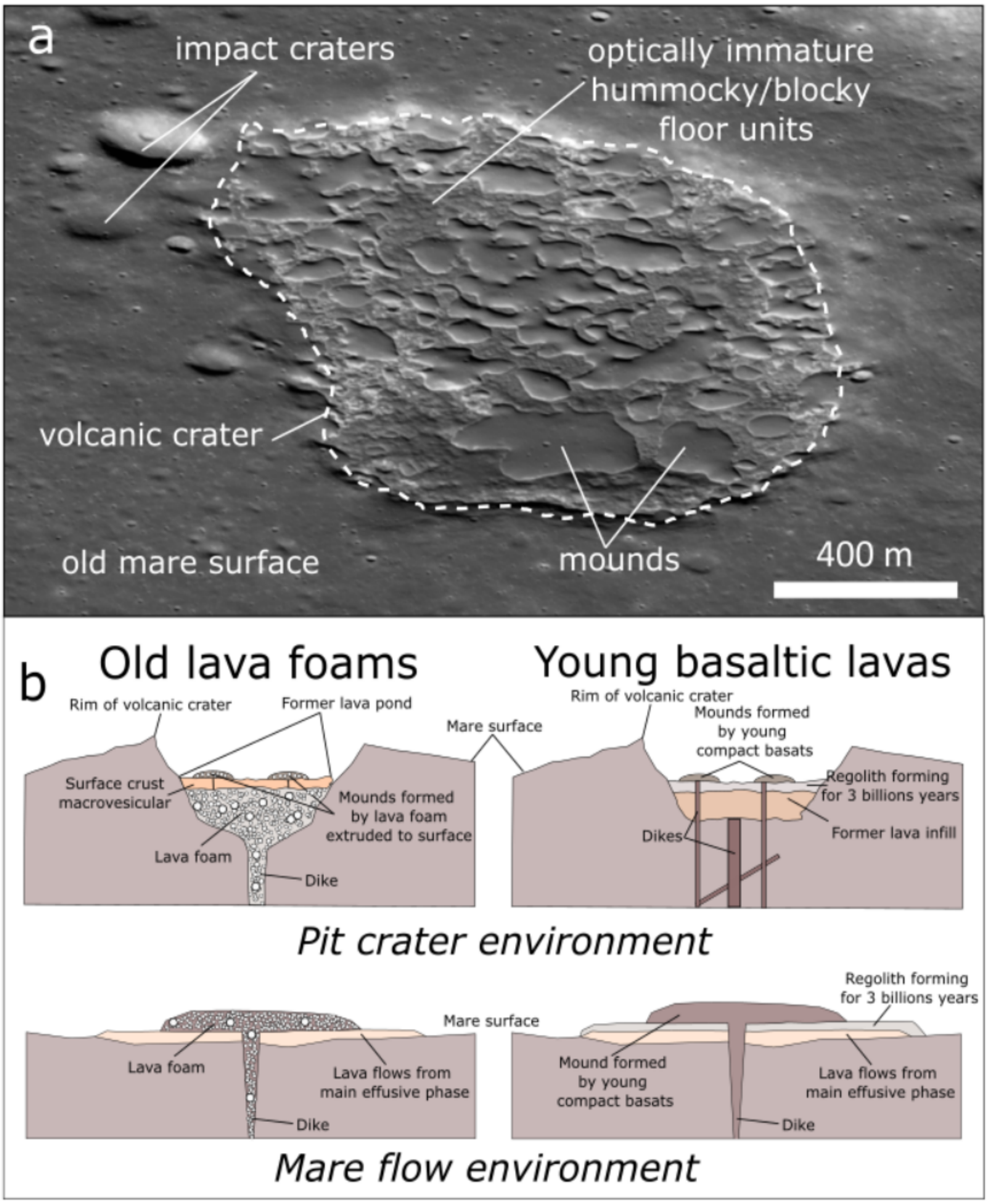


Figure 4-1:Perspective view of Ina-D, the most famous example of IMPs as seen in LRO imagery (a). Two competitive formation hypotheses about IMPs formation have been previously postulated and the aim of this mission is to test them (b). Modified from [RD2]. NASA/GSFC/ASU.

Four main physical parameters for studying IMP(s) have been selected by the scientific team to determine which of the two competitive hypotheses is more likely. These parameters are: a) the porosity and density of IMP(s) enables distinguishing whether IMPs are formed by porous lava foam(s) or compact basalt(s), b) the thickness of the regolith layer superposed on top of IMP(s) and surrounding mare enables revealing whether

IMPs have been formed recently or in ancient times as the thickness of regolith increases over time, c) the optical maturity of the regolith due to space weathering of IMPs and surrounding mare enables revealing whether the regolith is mature or fresh and hence old or young, and d) the topographic characteristics of IMPs and impact craters covering IMPs and surrounding mare units enable searching for indirect signs of the IMPs ages, as the distribution of boulders on the IMPs and the precise sizes of small impact craters excavating only the top most layer of the surface provide insights about their age as well. To study these four parameters, the scientific team assessed the necessary requirements for four instruments, namely ground penetrating radar (GPR), narrow angle camera (NAC), LiDAR, and hyperspectral camera (HSC), which are under consideration to be operated onboard the LUGO spacecraft.

Secondary Objective:

Detect and characterize lava tubes for their potential as future lunar habitat.

The secondary goal of the mission (Table 4-1, below) is to search for the presence of lava tubes hidden below the lunar surface and characterise their basic morphometric properties to support further lunar exploration and settlement by providing promising targets for further in situ investigation. To achieve this goal, the LUGO instruments, specifically GPR in cooperation with LiDAR, will image the subsurface in regions of interest selected based on previous studies indicating the presence of lava tunnels in certain lunar regions. The identification of candidate lava tunnels will then allow us to make a basic characterization of their size and length.

Table 4-1: List of observables for lava tubes detection and characterization of their basic morphometric properties.

Physical parameter	Observables		Instrument	Reference(s)
Location of lava tubes and revelation of their sizes	GPR signal difference between rock and empty voids at the ceiling and floor	Depth, location relative to surface volcanic constructs, internal volume, debris on the floor, width and height change along it	GPR	[RD4], [RD5]
Lava tubes interior	Floor smoothness, fallen boulders	Radar signal noise and floor surface clutter	GPR	
Physical dimension, skylight openings	Distances between cave walls and relation to the lunar surface	Depth and survey of roof wall continuity, lithology above tubes	GPR, NAC	

The physical conditions (location, depth and size) would then allow us to evaluate the possibility of using some tubes in the future for subsurface habitat utilisation. However, by identification of the lava tubes, and their routes in the subsurface, it would be possible to study the volcanic effusive processes under lower specific gravity and absence of atmospheric pressure on the Moon compared to Earth. Revelation of the length, shape and volume plus tracks of lava tubes will help to estimate the effusion rate, viscosity and related temperature of lava which was released in the past over the lunar surface. These data together with surface observation and composition of the lava (above the tube, e.g., their roof material) will help to improve their current estimated physical parameters using Earth based experience to infer conditions of the lava flow during the eruption.

Other Objective:

LUGO instruments could also be used to observe other volcanic features on the lunar surface. For example, the GPR would be an ideal tool to gain deeper insight in the formation mechanisms of floor-fractured craters (FFC). FFCs are lunar impact craters that have been recognized to have deformed and fractured crater floors caused by the intrusion of magma in the shallowest 1-3 km of the lunar crust [RD6]. By studying FFCs, insight into the plumbing system(s) associated with lunar volcanism could be acquired. The plumbing system of those FFCs, composed of likely dense basalt [RD1], may present radar permittivity characteristics that could serve as an interesting comparative feature for imaging intrusive plumbing system architectures similar to those of IMPs, if the latter would consist of young and dense magma proposed a classification based on FFC surface morphology [RD7], which could potentially be used to select suitable targets for further study if LUGO proves to have spare observing capacity after the primary and secondary mission targets have been met.

Mission Success Criteria

The mission success criteria were established as stated below, Table 4-2 pertains.

Table 4-2: Mission Success Criteria

	Minimum Success	Full Success	Stretch Goals
Purpose	Acquire data from one subsurface measurement for both scientific/exploration objectives at minimum 2 IMPs and 2 lava tube locations with single pass.	Acquire data from surface and subsurface measurements both scientific/exploration objectives at minimum >2 IMPs and >2 lava tube locations with at least two passes.	Acquire data for all eleven selected surface and subsurface measurements for both scientific/exploration objectives at minimum >5 IMPs and >5 lava tube locations with multiple passes.
Objectives	Turn on & deploy GPR; map >2 IMPs and two lava tube locations; transmit the data to Earth.	Turn on & deploy GPR and NAC/HSC/LiDAR; map >2 IMPs and >2 lava tube locations; transmit the data to Earth.	Turn on & deploy all instruments; map >5 IMP and >5 lava tube locations; transmit the data to Earth.

5 Mission Concept and Analysis

The orbit selection for this mission involved multiple evaluation factors to ensure the operability of the satellite. One key factor is orbit stability, a requirement for any mission intending to be in space for a prolonged duration. LUGO anticipates a year-long mission orbiting above the lunar surface.

Eccentric Orbit – Selection

Preliminary orbital parameters were selected such that they would comply with the preliminary identified mission objectives and were chosen for its stability. The orbital parameters are shown in Table 5-1 below.

Table 5-1: Selected operational orbital parameters

Orbital Parameter	Value
SMA [km]	1801.915
Eccentricity [-]	0.021929
Inclination [deg]	86
RAAN [deg]	0*
AoP [deg]	180*
True Anomaly [deg]	0*
Epoch	09-12-2022 13:00:00 UTC*

* RAAN, AoP and True anomaly will need to be accessed during the forthcoming iteration.

Launch Strategies

The different launch strategies will have an impact on the total Δv expenditure and consequently on the mass of fuel that will need to be considered during the spacecraft design. The final launch strategy will be assessed in the next phase.

The following transfer strategy have been evaluated (see Figure 5-1):

Hohmann Transfer (Direct)

A Hohmann transfer to the Moon involves a two main impulse manoeuvre where the spacecraft is first injected into a low Earth orbit (LEO) or geosynchronous transfer orbit (GTO), and later to an high elliptical orbit that terminates in the apogee at the desired lunar distance.

Elliptic Transfer

This method involves three main impulsive burns: one to send the spacecraft into an initial high-altitude elliptical Earth orbit, the second at the perigee of this orbit to raise the orbit's apogee further away from the Moon's orbit.

Phasing Spiral

This approach uses continuous low-thrust propulsion to gradually expand the spacecraft's orbit through a series of spirals until it intersects the Moon's orbit.

Low Energy Transfer (Lunar Ballistic Capture or LBT)

The spacecraft enters a ballistic trajectory that brings it close to the Moon, relying on careful trajectory design and lunar gravity to eventually be captured in lunar orbit.

Dedicated Launch

A launch for a lunar mission means the spacecraft is launched directly on a trajectory to the Moon without entering a prolonged Earth orbit. This strategy uses a powerful launcher.

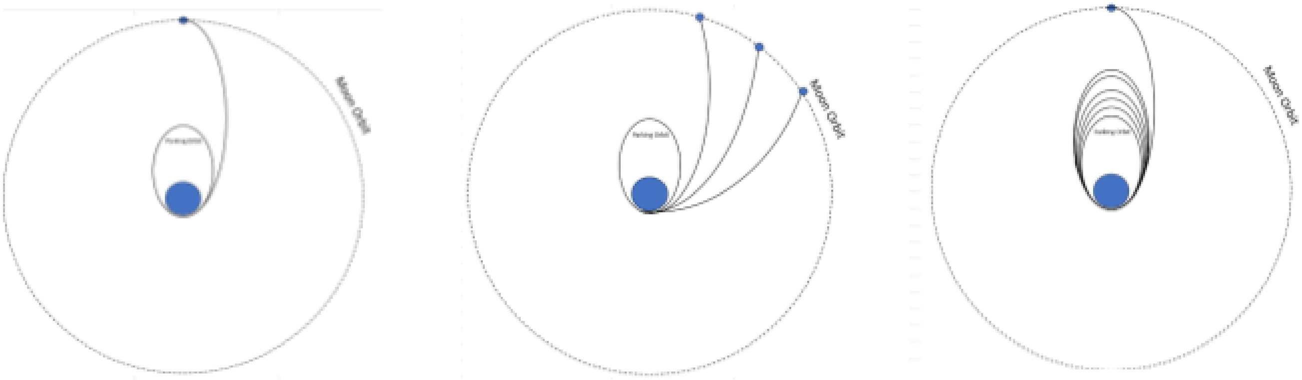


Figure 5-1: Hohmann, elliptical and phasing spiral transfer

6 Payload Concepts and Requirements

As previously stated, four payloads have been considered for the LUGO mission, as follows: GPR, LiDAR, HSC and a NAC. Below in Table 6-1, there is a summary of the payloads and their connection with the science objectives.

Table 6-1: Instrument used for each science objective

Science Objective	LiDAR	GPR	HCS	NAC
IMP porosity	x	x		
IMP bulk density	x	x		
Regolith thickness	x			x
Regolith maturity			x	
Boulders	x			x
Crater morphologies	x			x
Crater density				x
IMP’s morphology				x
Lava Tubes		x (4)		x

Furthermore, important parameters for each payload were defined and are shown in Table 6-2 below.

Table 6-2: Summary of payload parameters

Instrument	Details	Mass [kg]	Size [mm]	Power [W]	Data
LiDAR	**Resolution:** H: 30 cm H, V: 10 cm **FoV:** 30 cm - 150 m **Swath@20km:** up to 10 x 30 cm stripes separated by 15 m **Swath@100km:** NA	11	650 x 500 x 800 mm^3	**Acquisition mode:** 200 W x 10 mins **Processing mode**: 40 W **Idle mode:** 10 W	**Data rate:** 100 MB/orbit assumed 10 beams **Internal/external storage:** NA
GPR	**Resolution:** H : < 1 km x 1.7 km at 25 km, V: <=10 m, Penetration depth: 100 m (baseline) Possibility to extend to 200 m. **FoV:** 63° **Swath@20km:** 35 km, **Swath@100km:** 177.6 km	<25	365 x 185 x 140 mm^3 x 4 Antenna ≤16000	**Nominal power:** <60 W **Power peak:** N/A **Stand-by mode:** <20 W	**Data rate:** < 79 MB/orbit **Internal /external storage:** S/C or DPU mass memory
HSC	**Resolution:** - 10 m/px @20 km, - 50 m/px @100 km **FoV**: 25°x25° VIS, 17°x13° NIR **Swath@20km:** 10 km, **Swath@100km:** 50 km	2	100 x 100 x 200 mm^3	**Nominal power:** 10 W **Power peak:** 10 W **Power supply:** 5 V DC	**Data rate:** 45 MB/orbit assumed 1 targets per orbit **Internal /external storage:** 2x 8 GB integral SD cards + up to 64 GB external eMMC
NAC	**Resolution:** ⊥ GSD 22 cm/px at 20 km, 110 cm/px at 100 km **FoV:** 2 x 1.29 deg **Swath@20km:** 2 x 450 x 450 m **Swath@100km:** 2 x 2250 x 2250 m	4x2	250 x 200 x 150 mm^3	**Nominal power:** 2 W x number of cameras active at time **Power peak:** 10 W (less than 1 ms)	**Data rate:** ~500 Mbit/s per active camera **Internal /external storage:** S/C or DPU mass memory

The LUGO mission is designed to mount a variety of instruments with different technology readiness levels. GPR, HSC and NAC can boast a relevant heritage and well-known technology and processes to develop the final product. Conversely, the LiDAR is an immature technology which has not been proven in space as it is currently envisioned, and it represents the highest risk in the LUGO development plan. The related cost and risk are side aspects to achieve the scientific goal and deliver measurements which are beyond the current available Moon data sets. Figure 6-1 pertains (below).

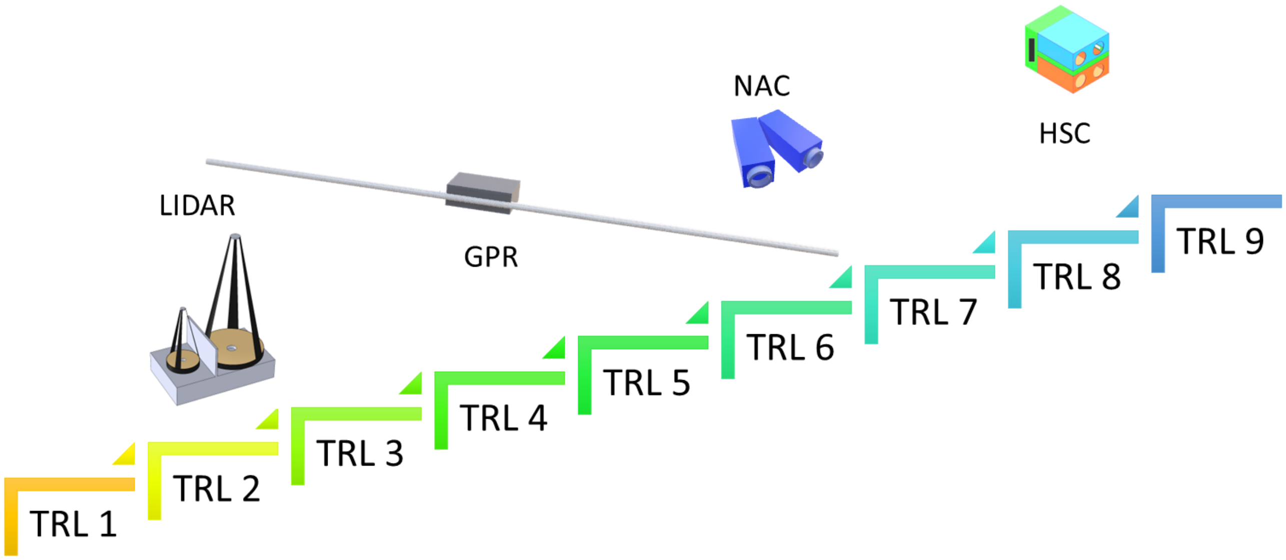


Figure 6-1: TRL level instrument representation

7 Ground Segment and Operations Preliminary Requirements

LUGO is considered a standardl ESA mission from the mission operation concept point of view. As such, a compatibility of the space segment with an existing ground segment infrastructure is currently available. In addition, a communication network, such as Moonlight LCNS, which is currently in development, will be available at the time of the LUGO launch. This usage can be translated into a cost containment on the operations side.

Operations

The following phases shown in Table 7-1 below are considered in the LUGO mission life.

Table 7-1: LUGO Mission Phases vs System Modes

Phase	Duration	Description	System Modes
Pre-Launch		Space and ground segment testing readiness. Preparation of the operations and launch activities to get the launch authorization.	Launch mode (OFF)
Launch to GTO	~ 11 hours	Launch activities from the countdown sequence to the GTO	OFF
Transfer from GTO to LOI	Between 3 to 90 days (highly dependent on the final GTO and LOI strategy)	Manoeuvre to reach the initial Lunar Parking Orbit	OFF
Platform Commissioning	2 weeks	Spacecraft activation and commissioning of the platform subsystems. Configure and checkout the spacecraft before starting the payload activation.	Initialization mode, Nominal mode
Payload Commissioning	4 weeks	In this phase all instruments are activated, calibrated and commissioned. Note the LIDAR needs to be calibrated on the final orbit.	Nominal mode, Communication, Science mode or any PL submode if needed
Science Operations	1 year	In the first year the primary targets are sensed. The collection of science data is alternated with routine operations such as station keeping, reorientation for communication, low power consumption mode during eclipse and eventually safe mode maintenance.	Nominal, Communication, Science mode
Extended Science Operations	TBD	In case that additional science is possible, the spacecraft will be maintained in orbit and secondary targets will be sensed.	Nominal, Communication, Science mode
Decommissioning	1 week	All activities to plan and configure the spacecraft for end-of-life. Controlled impact on the Moon surface.	Disposal mode

Communications

As LUGO aims to be connected with the Terra Novae 2030+ vision, it will integrate previously mentioned goals. Class A Reference User Terminals are considered for the LUGO mission, as they align with the category of Nanosats and Microsats, with the specified parameters provided below. Values intend to define a minimum performance threshold at the user proximity link interface.

As an early adopter of the Moonlight LCNS program, which is expected to achieve full operational capability (FOC) in 2030, with initial operational capability (IOC). The aim is to use the most cost-effective, lightweight and adaptable system. The LUGO mission can leverage Moonlight LCNS, primarily in terms of communication and operations. In the Figure 7-1, a preliminary overview of the LUGO communications architecture is provided.

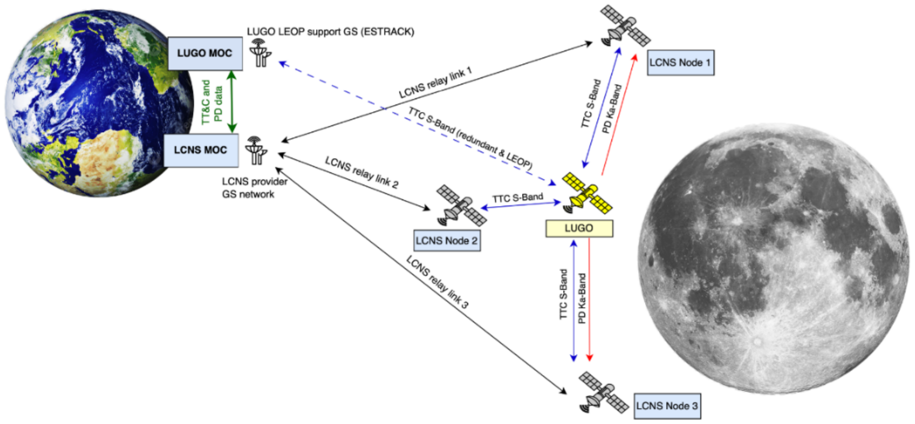


Figure 7-1: LUGO Communication Architecture

The ground segment of the LUGO mission serves as the Earth-based infrastructure essential for the control, monitoring, and data management of the mission's space assets. The LUGO MOC (responsible for planning, command, and control of the mission) will fall under the purview of ESA. The ground station will be responsible for the downlink of the data, as well as for receiving data from the Moonlight LCNS relay satellites and sending commands back to it. The operation of the ground station falls under the responsibilities of ESA as stated in the proposal. The ground segment is shown in a simplified schematic below (Figure 7-2 pertains).

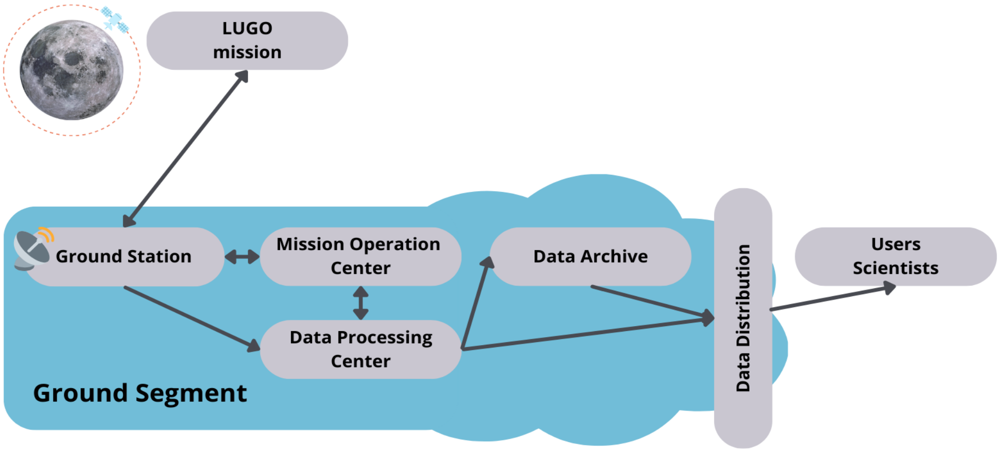


Figure 7-2: Ground Segment diagram

The Data Processing Center (DPC) is tasked with the initial processing and analysis of the raw data received, converting it into a standard product with data from individual sensors accompanied with auxiliary metadata (payload and satellite parameters, quality metadata, etc.). DPC is accompanied with operational storage as the main access point for data distribution. The Data Archive stores raw and processed data (ready products) for long-term retention and future reference. Finally, the Data Distribution component ensures that the data is disseminated to the relevant stakeholders, which may include scientists, researchers, and other end-users. Together, these components work in a coordinated manner to ensure the successful execution and data yield of the space mission.

Data Processing

The data processing on board the payloads will be handled as follows:

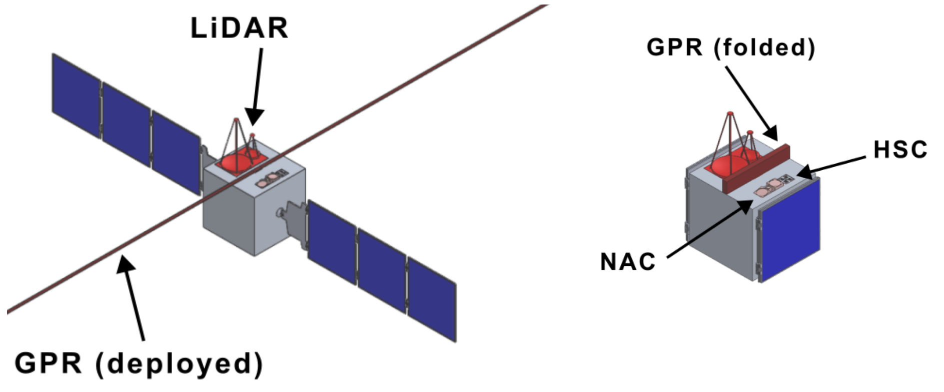
Output generated by the instruments onboard LUGO shall be processed, calibrated and archived. Calibrated data shall be converted to physical units independent of experiment. Data processing pipelines (preferably using Integrated Software for Imagers and Spectrometers (ISIS) shall be designed according to each instrument's specific data outputs and documented by the developers.

Technical specifications of the instruments and data products, including details on data processing and archiving, shall be described in a Product Specification Document (similar to NASA's Software Interface Specification - SIS) for mission team members and the general planetary science community, for each instrument. This document should describe how products are processed, formatted, labeled, and uniquely identified. The science team is responsible to verify that the instrument teams conform to the specifications defined in the SIS.

8 Space Segment and Preliminary Requirements

An overview of the platform with the most meaningful parameters is provided in Table 8-1 below. The payload mass (51kg), power (328 W) and data requested (3151 Mb x orbit) it is estimated that the wet mass is approximately 375 kg. The satellite dimensions are estimated with a conservative margin considering the first spacecraft power and mass budget. However, in the next phases when further analysis results are available the possibility of using components with reduced mass and size that can possibly deliver sufficient performances will be explored.

Table 8-1: S/C subsystems baseline overview

Subsystem	**Description**	
Deployed (left) and Stowed (right) Configuration		
Mass	Dry Mass (w/margin)	280 kg
	Wet Mass	375 kg
Dimensions	Stowed (estimated size)	0.8 m x 1.5 m x 0.75 m
	Deployed (estimated size)	16 m (antenna) x 7.5 m (solar panels) x 1.5 m
Power	Eclipse Payload	49.4 W
	Peak Payload	328 W
	Eclipse S/C	495 W
	Peak S/C	1055 W
Science Data	3154 Mb x orbit	
AOCS & GNC	The spacecraft will be 3-axis-stabilized. Reaction wheels will act as actuators. Thrusters will be used to support momentum dumping and reorientation of the S/C. 6x coarse sun sensors 2x star trackers 2x gyroscopes 4x reaction wheels	

Propulsion	The basic configuration will consist of at least 1 main thruster for orbital manoeuvres and 4 thrusters to support attitude control. 1x 10 N main thruster 4x 1 N thrusters
Power	The EPS subsystem is composed of a PCDU, a rechargeable battery pack and a deployable and rotating (one axis) solar panel. 1x PCDU (internally redundant) 2x solar array (total area around 6 m2, each panel 2.8 x 1.2 ca.) 3x rechargeable batteries (420 Wh)
Data Handling	The baseline solution includes an on-board computer and a payload data processing unit able to store up to 128 GB for at least 47 days. 1x OBC: main spacecraft control and communication 1x DPU: payload control and data processing
Communication	The TTC is planned to mount at least one S-band antenna for the normal command, control and monitoring and a Ka-band antenna for the science data downlink. 2x S-band transceiver and antenna 2x Ka-band transceiver and antenna (redundancy is not strictly necessary, for all parts if highly reliable and with low failure probability) Additional wave guides and harness.
Thermal	An active control is needed to maintain the temperature in the operation thermal range. The subsystem will consist of radiators, insulation, heaters and sensors as in a traditional satellite. No cryogenics is needed for LUGO payload.
Structure and Mechanism	A simple cuboid structure assembled with a typical sandwich panel can be used for the LUGO mission. Possibly central tubes or panels for assembly needed. Mechanisms for the solar panel and GPR antenna deployment.

One approach to make the mission feasible is to reduce the mass to fit in one platform with TRL >7, which can accommodate a smaller payload. Following factors should be taken into account:

- the instrument with the highest power need is the LiDAR
- the most data is generated by the NAC
- the payload with the largest mass is the GPR
- the payload with the highest risk for development is the LiDAR
- the most relevant instruments to accomplish the mission are GPR and NAC
- HSC is based on the Hera camera, has a relatively low mass and it generates a comp amount of data, however it has some observation constraints (phase angle <10 deg)

Options can be studied to make the mission feasible within a smaller mass and cost:

- reduce the power needed by the payloads (introduced above)
- study the feasibility of a passive thermal control
- consider power saving options for the satellite attitude control (study a stable configuration and improve the mass distribution)
- study the possible elongation of the mission to use the satellite in hibernation mode when in eclipse to reduce the power budget, this can be trade off with the mission Δv.

Here, we have explored opportunities to support the evaluation of the LUGO feasibility. There is the possibility to reduce the mass by reducing the number of payloads. This will also depend on the state of their development and the timeline set forth in future planning, as well as results of the feasibility study conducted during Phase A.

8 Project LUGO summary

From the inception of Project LUGO, the return of humankind to the Moon has played in the forefront of the development of this project. Not only has Project LUGO intended to provide a better understanding of some of the unanswered science questions, the thermal evolution of the Moon, but to also provide a means for humanity to return to the Moon to stay, by characterizing lava tubes and their void spaces to plan for human habitation below the surface. This project included four very advanced payloads (GPR, LiDAR, HSC and NAC) to accomplish the objectives of this mission at a resolution better than any other to date.

Inasmuch that Phase 0 has provided a glimpse of what can be accomplished, it is recognized that there may be some necessary changes to increase the effectiveness of the mission. As noted earlier in the document, as new technologies are developed, unforeseen risks in terms of development and costs pose a substantial risk. Calibration of the expectations can occur during Phase A, as part of the feasibility study, to ensure the success of the mission. This may entail a reduced number of payloads or additional participants not previously identified to increase the likelihood of success. As it stands, TRL Space has gathered scientists and subject matter experts together, not only in Eastern Europe, but throughout Europe and with the additional personnel supplemented by ESA, many of the larger questions have been answered.

As Project LUGO moves forward into Phase A, the possibilities are defined for the mission. The next step is to decide if the project is feasible, as ESA envisions it and in keeping with ESA’s Terra Novae 2030+ to develop a lunar infrastructure. By doing so, the mission aligns with Europe's space strategy roadmap, fostering exploration, and supporting the development of sustainable lunar settlements while contributing to the broader goals of space exploration at the same time. The planning for Phases A/B has considered full compliance with ECSS standards and adjusted accordingly with the expectations, to make a 2030 launch possible.