The Lunar GNSS Receiver Experiment (LuGRE)

Joel J. K. Parker[1], Fabio Dovis[2], Benjamin Anderson[1], Luigi Ansalone[2], Benjamin Ashman[1], Frank H. Bauer[3], Giuseppe D'Amore[2], Claudia Facchinetti[2], Samuele Fantinato[4], Gabriele Impresario[2], Stephen A. McKim[1], Efer Miotti[4], James J. Miller[5], Mario Musmeci[2], Oscar Pozzobon[4], Lauren Schlenker[1], Alberto Tuozzi[2], Lisa Valencia[6]

[1]*NASA Goddard Space Flight Center (GSFC)*
[2]*Italian Space Agency (ASI)*
[3]*FBauer Aerospace Consulting Services*
[4]*Qascom S.r.l.*
[5]*NASA Headquarters*
[6]*Overlook Systems*

BIOGRAPHIES

Joel J. K. Parker is a Senior Navigation Engineer in the Navigation and Mission Design Branch at NASA GSFC. He is the LuGRE Principal Investigator (PI).

Fabio Dovis is an associate professor at the Department of Electronics and Telecommunications of Politecnico di Torino coordinating the Navigation Signal Analysis and Simulation (NavSAS) group. He is the LuGRE ASI co-PI.

Benjamin Anderson serves as the NASA Mission Manager for LuGRE and as the Delay/Disruption Tolerant Networking (DTN) Enterprise Lead at Goddard Space Flight Center.

Luigi Ansalone is a Technologist at the Engineering and Future Space Systems Unit at ASI. He is a member of the LuGRE ASI technical team.

Benjamin Ashman is a navigation engineer in the Navigation and Mission Design Branch at NASA GSFC and is the 2021–2022 ION/AAAS Congressional Science and Engineering Fellow. He is a member of the LuGRE PI team.

Frank H. Bauer is President of FBauer Aerospace Consulting Services, and founded and led many NASA spaceborne GNSS activities, including development of the GPS Space Service Volume. Frank is a consulting member of the LuGRE PI team.

Giuseppe D'Amore is Head of Technological Development Program Office at ASI. He is a member of the LuGRE ASI technical team.

Claudia Facchinetti leads the Engineering, Cost Analysis & CEF Office within the Engineering and Future Space Systems Unit at ASI. She is the ASI Project Manager of the LuGRE Payload.

Samuele Fantinato is the Head of the Advanced Navigation Unit at Qascom. He is the Project Manager of the LuGRE payload.

Gabriele Impresario is a Space Systems Engineer at ASI. He is the ASI Product Assurance Manager and Technical Point of Contact of the Italian scientific agreement for LuGRE.

Stephen A. McKim is a Senior Propulsion Engineer in the Propulsion Branch at NASA GSFC. He is the LuGRE Instrument Systems Engineer (ISE).

Efer Miotti is the Head of the Engineering Unit at Qascom. He is the Chief System Engineering Manager of the LuGRE payload.

James J. Miller is Deputy Director of Policy and Strategic Communications within the Space Communications and Navigation (SCaN) Program at NASA Headquarters. He is the NASA Decision Authority for LuGRE.

Mario Musmeci is a senior staff member of the Telecommunication and Navigation Unit within ASI. He is the ASI System Manager/Product Development Lead for the LuGRE payload.

Oscar Pozzobon is the founder and Technical Director of Qascom. He leads and oversees the LuGRE payload development team

Lauren Schlenker is a Flight Dynamics Engineer in the Navigation and Mission Design Branch at NASA GSFC. Lauren is the Deputy PI for LuGRE.

Alberto Tuozzi is the head of European Relation Unit and head of Telecommunication and Navigation Unit within ASI. He is the ASI Decision Authority for LuGRE.

Lisa Valencia is a subject matter expert at Overlook Systems to the Space Communications and Navigation (SCaN) Program Office at NASA Headquarters. She is a systems engineering consultant for the NASA LuGRE team.

ABSTRACT

The Lunar GNSS Receiver Experiment (LuGRE) is a joint NASA-Italian Space Agency (ASI) payload on the Firefly Blue Ghost Mission 1 (BGM1) with the goal to demonstrate GNSS-based positioning, navigation, and timing at the Moon. LuGRE was chosen by the NASA Commercial Lunar Payload Services (CLPS) program as one of ten payloads on its "19D" task order for delivery to the lunar surface in 2023.

The LuGRE payload consists of a weak-signal GNSS receiver, a high-gain L-band patch antenna, a low-noise amplifier, and an RF filter. The receiver will track GPS L1 C/A and L5, and Galileo E1 and E5a signals and will return pseudorange, carrier phase, and Doppler measurements to the ground. It will also calculate least-squares point solutions and Kalman-filter based navigation solutions onboard. In addition, the receiver features the capability to record raw I/Q baseband samples for downlink and ground processing.

LuGRE will build on the legacy of prior missions in the Space Service Volume (SSV) including the initial experiments by AMSAT-OSCAR 40 and others, the GOES-R series of geostationary weather satellites, and the NASA Magnetospheric Multiscale (MMS) mission currently operating on GPS-based navigation at nearly 50% of lunar distance. Further, LuGRE will be one of the very first demonstrations of GNSS signal reception and navigation in the lunar environment and on the lunar surface, paving the way for operational use by future lunar missions such as Orion, Gateway, robotic and human landers, and surface rovers. Ultimately, all LuGRE science data will be released to a public data archive for the benefit of the GNSS and space communities.

This paper provides a detailed overview of the LuGRE payload, including its design, concept of operations, and its predicted ability to meet its core science objectives. The baseline science investigations and priorities are outlined. Simulated performance results are shown based on the latest calibrated models including signal strength, signal availability, onboard navigation performance and convergence properties, and ground-based post-processed navigation performance.

INTRODUCTION

The Lunar GNSS Receiver Experiment (LuGRE) is a joint NASA-Italian Space Agency (ASI) payload on the Firefly Blue Ghost Mission 1 (BGM1) with the goal to demonstrate GNSS-based positioning, navigation, and timing (PNT) at the Moon. When launched in 2023, LuGRE will collect GPS and Galileo measurements in transit between Earth and the Moon, in lunar orbit, and on the lunar surface, and will conduct onboard and ground-based navigation experiments using the collected data. Building on decades of study on the feasibility of lunar-distance GNSS-based navigation, LuGRE will perform key and pioneering demonstrations of this capability in-situ and will disseminate the data and results to the maximum extent possible as a stepping-stone to future broad operational use.

Use of GPS, and now multi-GNSS, for spacecraft navigation is routine in low Earth orbit (LEO) and is established in higher orbits as well [1]. The benefits are well-established: GNSS provides real-time, onboard, precise position, velocity and time to a spacecraft and its payloads with only the addition of a receiver and an L-band antenna, and leverages the existing and expanding capabilities of the terrestrial GNSS infrastructure [2]. These benefits are applicable to, and needed in, regimes far beyond LEO, leading to the definition and adoption in the last two decades of GNSS-based navigation in the Space Service Volume [3]. The first experiments using GPS above the constellation in the late 1990s and early 2000s opened the door to an extensive and multi-national technology development effort to utilize and operationalize GNSS-based navigation to geosynchronous orbit (GEO) and beyond [2]. In the United States, the Magnetospheric Multiscale (MMS) mission performed the first operational use of GPS at 12 Earth radii (RE), then later extended that further to 25 RE and 29 RE [4]. Just a year later, the NASA/NOAA Geostationary Operational Environmental Satellites (GOES) R-series launched and started operations using GPS for its onboard navigation under very demanding requirements [5]. Throughout this period, numerous studies [6–10] used this data to look further, asking at what distance reliable GNSS-based navigation could ultimately be utilized.

In 2018, the International Space Exploration Coordination Group (ISECG) published the 3rd edition of its Global Exploration Roadmap [11, 13], collecting the space exploration plans of over a dozen major space agencies in one combined roadmap. Reflecting the global pivot toward Lunar exploration, this edition identified dozens of upcoming missions to the Moon in the next decade, and identified navigation as a major technology development driver, with a target of 100 m position accuracy for landing. Likewise, NASA's 2020 Artemis Plan specifically identified GPS-based navigation for lunar use to meet its needs [13].

LuGRE will fly during a highly active and critical period for lunar navigation development. NASA and others envision GNSS as a key enabler for cislunar and lunar navigation, especially in the near term. Further, NASA and the European Space Agency (ESA) have published plans for lunar communications and navigation infrastructure [14, 15] that will provide one-way radionavigation signals in lunar orbit, addressing the visibility, geometry, and signal-strength limitations of using purely Earth-based GNSS. A phased approach is necessary to fully develop both capabilities and transition between them. First, flight demonstrations must show reliable use of GNSS for lunar navigation. Next, operational lunar GNSS receivers can be flown to establish the capability at Technology Readiness Level (TRL) 9 ("flight proven") [16], then commercialized or further developed to fulfill the broad range of mission needs, from flagship-level receivers to integrated chipsets incorporating both GNSS and lunar-vicinity navigation signals. This technology can then be infused into lunar activities as standard equipment allowing a fully integrated real-time navigation capability extending from near-Earth to the lunar surface. LuGRE is envisioned to satisfy the first step of this approach, opening the door to full utilization of GNSS for lunar navigation.

MISSION OVERVIEW

LuGRE was chosen by the NASA Commercial Lunar Payload Services (CLPS) program as one of ten NASA-funded payloads on its Task Order 19D, which was awarded to Firefly Aerospace, Inc. in 2021. This marked the sixth awarded CLPS flight, and the first to Firefly. The Firefly BGM1 will deliver these payloads and others to the Mare Crisium region of the Moon by September 2023 and will operate on the surface for a minimum of 12 Earth days [17, 19].

LuGRE is one of three technology development payloads on the flight, and is the only payload provided by NASA's Exploration Systems Development Mission Directorate (ESDMD). The LuGRE project is a partnership between NASA and ASI, with NASA providing the flight, the principal investigator (PI), and overall systems engineering and project management responsibilities, and ASI providing the co-PI, the payload hardware and software, and any payload-level testing and integration. Both partners will jointly operate the payload, receive and analyze the data, and disseminate products and results. The NASA responsibilities are sponsored by the NASA Space Communications and Navigation (SCaN) program and led by the Exploration and Space Communications program at NASA Goddard Space Flight Center (GSFC). The CLPS program provides the flight.

LuGRE has three top-level objectives which together meet its overall goal of demonstrating GNSS-based PNT at the Moon:

> **OBJECTIVE 1**: Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
> **OBJECTIVE 2**: Demonstrate navigation and time estimation using GNSS data collected at the Moon.
> **OBJECTIVE 3**: Utilize collected data to support development of GNSS receivers specific to lunar use.

These objectives are realized as seven level 1 project requirements covering mission science, programmatic classification, integration into the BGM1 lander, operational lifetime, and availability of data and products. These level 1 requirements are then decomposed into requirements at levels 2–4 and mapped to the mission Concept of Operations and the Firefly BGM1 Payload ICD. Programmatically, LuGRE is classified as a "do no harm" mission, and so mission success is defined solely by the requirement that the payload do no harm to the host spacecraft. Payload-level success, however, requires meeting all level 1 science requirements.

The flight payload consists of a weak-signal GNSS receiver, a high-gain L-band antenna, and a low-noise amplifier integrated onto the Firefly Blue Ghost lander. The payload will receive and track GPS L1 C/A and L5, and Galileo E1 and E5a signals and produce pseudorange, carrier phase, and Doppler measurements. The receiver will perform real-time navigation and produce least-squares point solutions and onboard filter solutions. Other telemetry will include number of signals visible and tracked, dilution of precision, and carrier-to-noise-density ratio (C/N_0). In addition, the receiver has the capability to record short spans of raw L1 and L5 I/Q baseband samples, which can then be downlinked and later replayed as input to a ground-based receiver. LuGRE will operate both in-flight during the spacecraft Earth-Moon transfer and on the lunar surface.

CONCEPT OF OPERATIONS

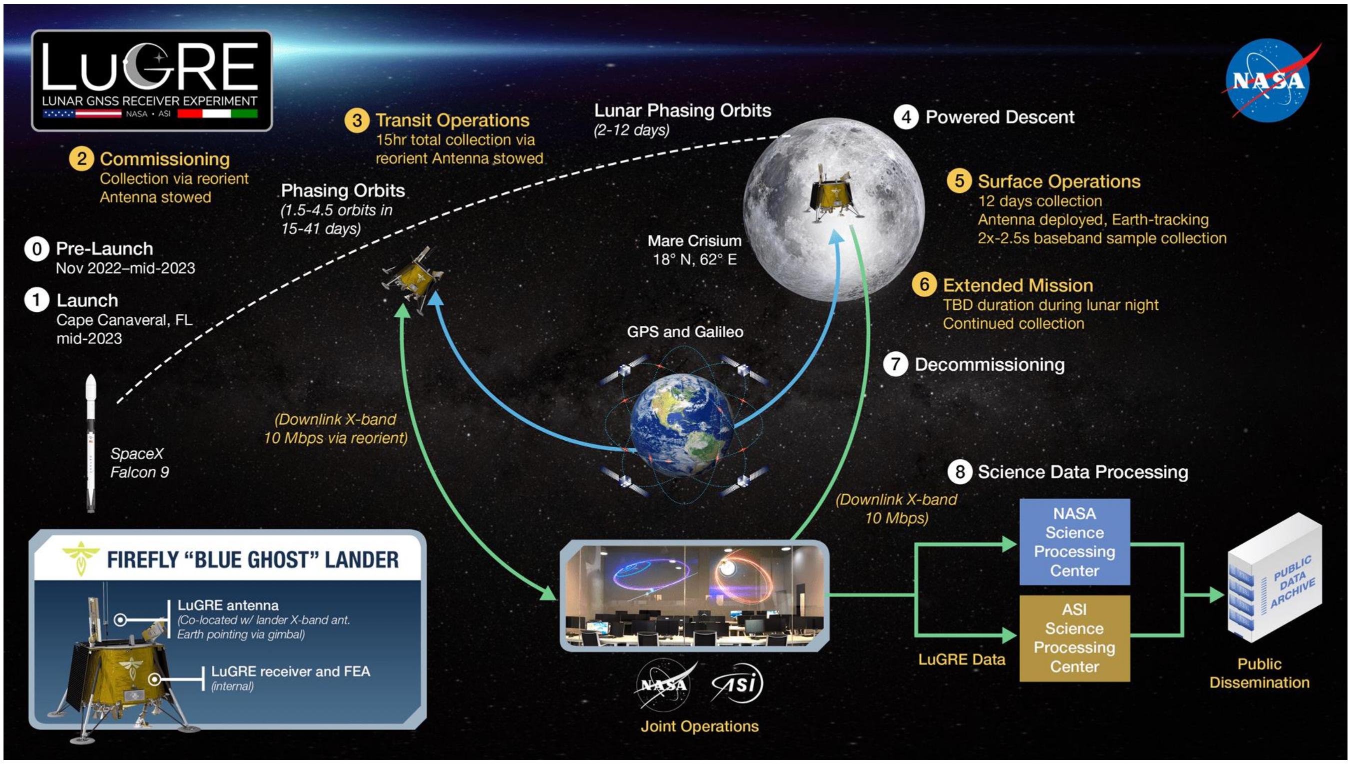


Figure 1. LuGRE Concept of Operations Overview

The LuGRE mission concept of operations is illustrated in Figure 1. It consists of nine distinct phases as outlined in the following sections.

0 Pre-Launch and 1 Launch

The pre-launch phase consists of all activities from delivery of the LuGRE payload to Firefly for integration, through Firefly's integration and test campaign, mission rehearsals, reviews, and delivery to and processing at the launch site, up to initiation of the launch countdown. The launch phase consists of the launch countdown and ascent of the launch vehicle, until spacecraft separation. The BGM1 lander will launch on a SpaceX Falcon 9 vehicle from Cape Canaveral, Florida, United States. The launch period is currently anticipated to open in mid-2023 for landing on the lunar surface by September 2023. The launch vehicle will place the spacecraft directly into a series of phasing loops that will be used to align the trajectory with the Moon for lunar orbit insertion, allow for spacecraft and payload checkout activities, and support transit-phase payload operations.

2 Payload Commissioning and 3 Transit Operations

The BGM1 Earth-Moon transfer trajectory consists of an Earth-centered portion and a Moon-centered portion, which together make up the mission transit phase. The Earth-centered trajectory consists of up to four and one-half phasing loops with apogee near 55 RE and perigee near 1000–4000 km altitude. Each phasing loop has a period of approximately 11 days, leading to a total time between launch vehicle separation and lunar orbit insertion (LOI) of up to 41 days. This time will be used for spacecraft-level commissioning of the Firefly lander and payload-level commissioning for each of its hosted payloads, and also for various operational activities as defined by each payload. Figure 2 shows the Earth-centered phasing loop portion of the trajectory.

After the Earth-centered phasing loops, the lander performs the first of three LOI maneuvers, LOI1, placing the vehicle in a high lunar orbit. LOI2 establishes a 250km x 100km orbit for six revolutions. LOI3, circularizes the lunar orbit at 100 km, which is held for approximately 2 days prior to initiation of the lander powered descent phase. The lunar-centered transit period is also used for lander- and payload-level operations activities. Figure 3 shows the Moon-centered portion of the trajectory. LuGRE has baselined an extensive transit-phase operations concept in both Earth-centered and Moon-centered portions, as described below.

During the transit phase, the LuGRE antenna will be in the stowed configuration on the lander. It will be oriented flat and nearly flush with the top face (x-axis) of the lander, with the gained side facing outward. Thus, the LuGRE payload will only be able to receive GNSS signals if the fixed, stowed antenna is pointed toward the Earth. As the spacecraft nominal attitude points its x-axis toward the Sun, this will be accomplished via a reorientation of the spacecraft to point this axis in the Earth direction instead. The lander uses cold-gas (helium) thrusters for attitude control, requiring expenditure of helium for each reorientation slew and for inertial hold during the Earth-pointing periods. Given the lander's helium budget, which must account for spacecraft slews for other purposes including the powered descent phase, LuGRE has been allocated 15 hours of total pointed time during the full transit phase, to include both commissioning and operational activities, and with a maximum continuous pointing duration of 1 hour. The LuGRE team has as a baseline allocated this available operations time as shown in Figure 2 and Figure 3.

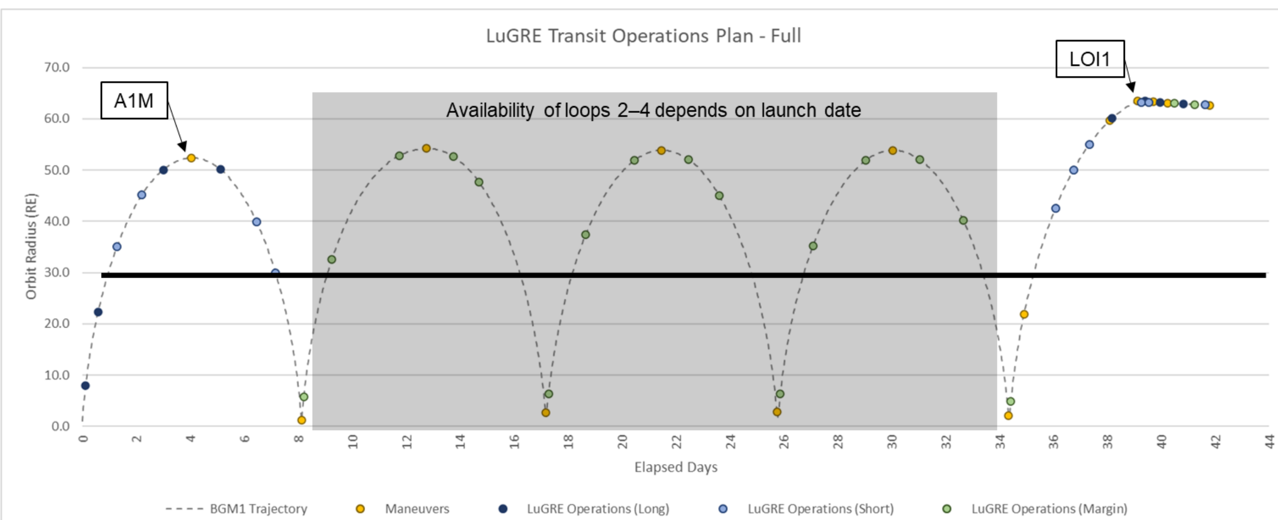


Figure 2. LuGRE Transit Operations Plan, Earth-centered period

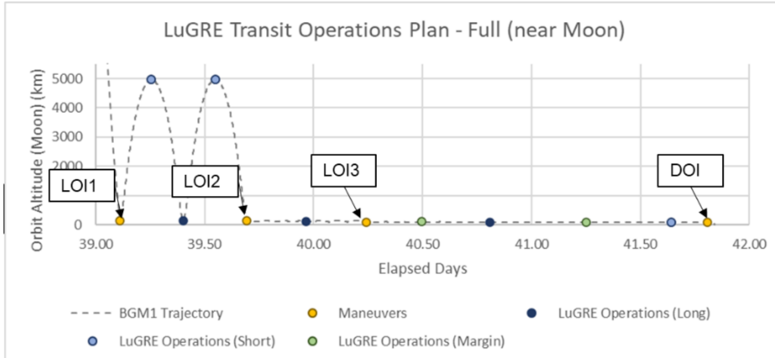


Figure 3. LuGRE Transit Operations Plan, Moon-centered period

This figure captures the desired baseline operations periods (blue dots) and a series of requested additional "margin operations" (green dots) that can be planned and scheduled immediately if the Firefly team determines that additional operations time is available, such as via release of helium budget margin. The overall transit operations plan features the following guiding principles:

- Two 1 hr commissioning periods, both occurring below 30 RE radius of Earth to overlap with MMS data.
- Two 1 hr operational periods surrounding the key high-altitude maneuvers during the phasing loops. The first coincides with the final maneuver planning tracking pass prior to the maneuver, and the second coincides with the maneuver calibration tracking pass after.
- Shorter (42 min) periods placed to maximize unique sampling of the region between 30 RE and 55 RE radius from Earth. These are scattered between the first loop (outbound and inbound) and the last outbound leg prior to LOI1, as the second through fourth phasing loops may be dropped depending on the launch date. At least one pair of opportunities is planned at the same distance to allow self-consistency verification of measurements.
- Baseline periods in the phasing loops planned initially for the first loop and the last outbound leg, as loops 2–4 may not be available depending on launch date. If these loops are confirmed, the baseline periods may be spread among them.
- In the lunar orbit phase, opportunities are placed in order to investigate planning and recovery from LOI2 and LOI3, and to coincide with planning for the final descent maneuver.

4 Descent, 5 Surface Operations, 6 Extended Mission, and 7 Decommissioning

The BGM1 spacecraft will perform a powered descent to the Mare Crisium region of the Moon by September 2023. The descent phase will last less than 1 hr and will occur with all CLPS payloads, including LuGRE, powered off.

Once on the surface, LuGRE will be powered on within 3 hr of landing and will operate continuously for the full duration of the 12-day lunar surface operational period. The only exception will be during the ±24 hr around lunar noon, when it will duty-cycle to reduce average power due to thermal considerations by the lander. During surface operations, and when powered during the lunar noon period, the payload will continuously track and downlink GNSS observables and navigation products. Additionally, LuGRE will perform two sample collection activities in which it collects raw samples of the L1/E1 and L5/E5a baseband and downlinks this data to the ground for further processing in ground-based receivers. It is anticipated that up to 2.5s of samples can be collected during each opportunity, depending on the sample rate and band. These samples will then be transmitted slowly to the ground alongside ongoing observation data over the following 24 hr.

Following the baseline 12-day surface operational mission, the BGM1 lander will support an extended mission during lunar night to the extent power is available from the spacecraft batteries. It is anticipated that LuGRE will continue nominal surface operations during this period until power is lost and the payload is decommissioned in-place.

8 Science Data Processing

During the operational phases, payload data will be transmitted to the ground by the BGM1 spacecraft and be distributed to the payload team for real-time and post-mission processing and analysis, and then ultimately for public dissemination. This phase is discussed further in the Ground Segment & Operations section.

PAYLOAD

The LuGRE payload has been conceived as a state-of-the-art high-altitude GNSS receiver capable of collecting and characterizing GNSS signals in the cislunar environment and on the lunar surface, paired with a high-gain Earth-pointing L-band antenna. The payload has the following characteristics to meet these design goals:

- Acquisition and tracking of both GPS L1 C/A and L5, and Galileo E1 and E5a open signals;
- Employs a Software Defined Radio (SDR) Receiver for high flexibility and re-configurability
- High performance tracking, processing and navigation algorithms that produce both instantaneous, real-time and filter navigation solutions with position, velocity and time at lunar distances;
- Can acquire and track GNSS signals as weak as 23 dB-Hz

The LuGRE Payload is a robust, low-mass and power efficient design that enables it to withstand the cislunar and lunar surface environments and be accommodated on the BGM1 lander. The Payload is comprised of four main components:

- A high gain antenna (HGA) optimized for GNSS L1/E1 and L5/E5a bands with filtering stage
- A front-end assembly incorporating a low noise amplifier (LNA)
- Two GNSS receivers in dual cold redundant configuration, managed by a supervisory board
- Coaxial RF cable harnesses connecting all components

The heart of the Payload is the Qascom QN400 GNSS Receiver, which has suborbital flight heritage on multiple sounding rocket missions and in LEO on the Bobcat-1 CubeSat mission [18]. This heritage, combined with the extensive use of commercial and/or pre-qualified components, reduces development and overall mission risk. The Payload itself draws a maximum operational power of 14W and has a total mass of less than 5 kg. Figure 4 shows the high level payload architecture:

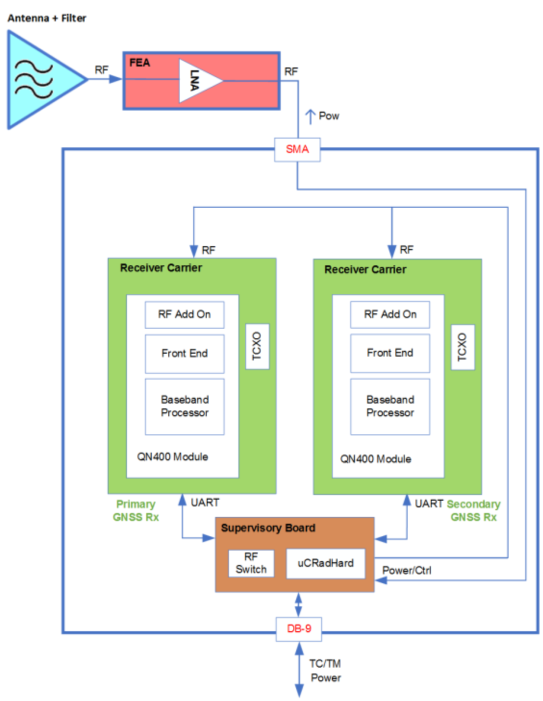
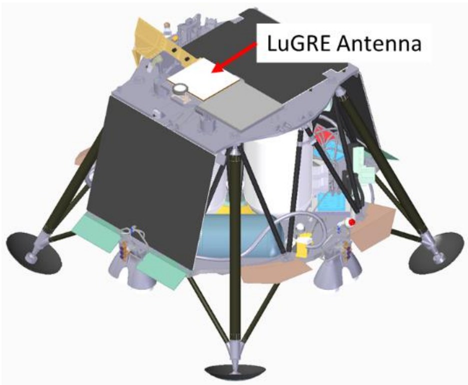


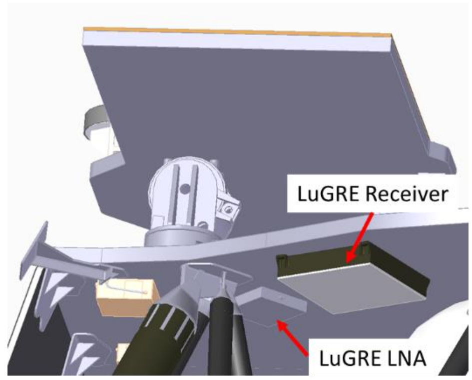
Figure 4. LuGRE Payload high level Architecture

Each component of the LuGRE payload is accommodated on the BGM1 lander in different locations as illustrated in Figure 5.

The LuGRE high gain antenna is co-located with the BGM1 lander X-band antenna on an arm connected to the lander's Earth-pointing mechanism mounted to the top deck. The 2-axis gimbal is operated during the lunar surface operations to point towards Earth center within +/- 1 degree, enabling acquisition of low power GNSS signals. The LNA and receiver are mounted in the internal cavity of the lander, on the bottom side of the top deck. This provides a less harsh and more stable thermal environment for both components.



A) lander Top Deck, External View



B) lander Top Deck, Internal View

Figure 5. External (A) and Internal (B) views of the BGM1 lander and LuGRE Payload Locations

Receiver

The LuGRE receiver is the core of the payload and has been designed to ensure maximum performance in GNSS signal acquisition, processing, and data management in the lunar environment, while also keeping the size, mass, and power needs as low as possible.

The receiver is a custom development based on the Qascom QN400-Space GNSS receiver. The QN400 is modular in both hardware construction and software implementation. The receiver is made of two core modules: a baseband processor and a radio frequency (RF) front-end. These modules work in tandem to capture RF signals and process them digitally. The receiver utilizes software defined radio (SDR) technologies which provide a high degree of flexibility in allocation of correlation resources and configurable architectures that are customizable to the signals being processed. This architecture allows it to be adapted for use in the cislunar and lunar environment.

The Receiver itself employs a cold redundant architecture, as shown in Figure 4. A supervisory board enables selection of the primary and backup receiver, passing through power and data interfaces and the RF chain while maintaining a single electrical and power interface with the lander. Swapping between primary and redundant boards can be accomplished autonomously and via ground command. The supervisory board also provides health monitoring of both boards to mitigate single event effects and is constructed using radiation hardened parts to improve its own radiation tolerance.

The receiver interfaces with the lander power and data interface via a single DB-9 connector. RF signals from the HGA and LNA are received via an SMA connection.

Table 1 summarizes the basic performance specifications of the LuGRE Receiver, and Figure 6 depicts the receiver physical layout.

Table 1. LuGRE receiver technical parameters.

Parameter	Value
Mass	1.24 kg
Power	14 W (max. operating)
Envelope	19.0 x 18.0 x 3.95 cm
Operating Temperature Range	-35°C to 50°C
Signal Reception	GPS L1 C/A and L5 Galileo Open Service E1 and E5a
Weak Signal Acquisition and Tracking Threshold	< 23 dB-Hz

Capabilities	Lunar-capable extended Kalman filter Capture of raw IQ samples Navigation ephemeris and aiding data upload via telecommand
Data Product Output	Least-squares point solutions Extended Kalman filter solutions with covariance Pseudorange observations Doppler Carrier phase observations Tracking status & C/N0 Raw IQ samples

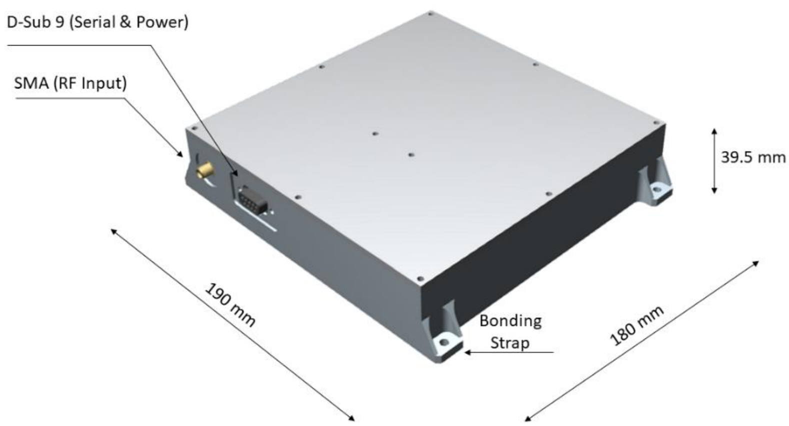
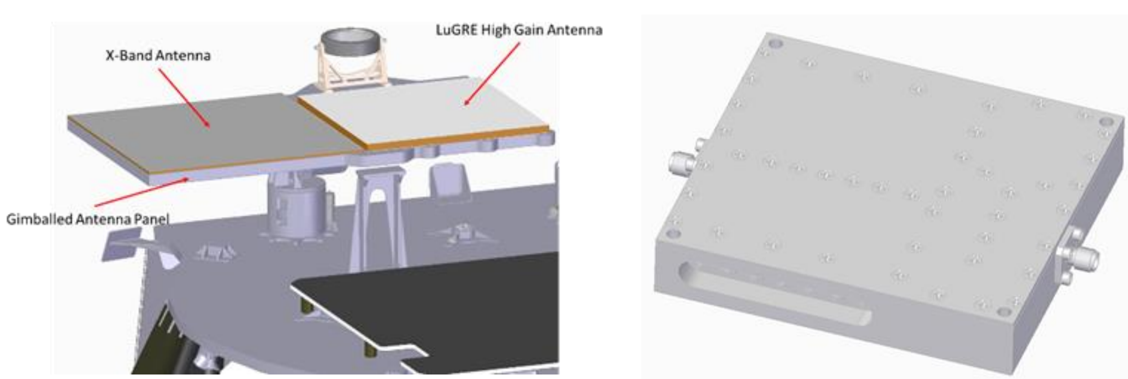


Figure 6. GNSS Receiver—physical layout

HGA and LNA

The LuGRE High Gain Antenna (HGA), Low Noise Amplifier (LNA) and interconnecting harnessing comprise the RF Chain of the LuGRE Payload. This subsystem has been designed and optimized to enable reception of GNSS signals at lunar distances. The RF chain includes power limiters to protect downstream amplifiers and filtering stages for rejection of out-of-band interference that may saturate the amplifier. These features ensure operability even when placed near other antenna systems operating in different bands.

The HGA operates with the L1/E1 and L5/E5a GNSS bands, providing appropriate gain to allow acquisition of GPS and Galileo constellations from the lunar distances. The antenna is mounted on a 2-axis gimbaled support arm with a specific Earth Pointing Panel structure on the lander top deck. The gimbal has been designed to point the HGA to the required accuracy of +/- 1 degree. See Figure 7.



(a) (b)

Figure 7. LuGRE HGA (a) and LNA (b)

The antenna features phased-array technology composed of individual, small footprint modules. The layout of these modules is optimized to enable maximum reception of L1/L5 and E1/E5a signals at lunar distances. The antenna has a nominal RHCP polarization, capable of receiving the nominal polarization used by GNSS constellations. Table 2 summarizes the basic technical parameters of the LuGRE HGA.

Table 2. HGA technical parameters

Parameter	Value
Mass	2.2 kg
Power	passive
Envelope	43.0 x 43.0 x 2.00 cm
Operating Temperature Range	-145°C to 125°C
Antenna Type	Passive Planar Antenna Array
Polarization	RHCP
Gain	≥ 14 dBi
Working Band 1	1575.42 +/- 12.276 MHz (L1/E1)
Working Band 2	1176.45 +/- 10.230 MHz (L5/E5a)
Connector	1x SMA

The LNA adds gain to the signal to properly feed the receiver. The LNA design is comprised of a dual-band filter with bands at L1 and L5 and a microstrip-based, multi-stage amplifier design. The LNA is integrated on the bottom side of the top deck, inside of the lander cavity. The distance from the HGA to the LNA has been minimized to limit cable path loss prior to amplification to the greatest extent feasible. Table 3 summarizes the basic performance specifications of the LuGRE LNA.

Table 3. LNA technical parameters

Parameter	Value
Mass	0.85 kg
Power	0.7W
Envelope	9.3 x 10.2 x 1.8 cm
Operating Temperature Range	-35°C to 50°C
1st Band:	1575.42 +/- 12.276 MHz (L1/E1)
2nd Band:	1176.45 +/- 10.230 MHz (L5/E5a)
Noise Figure	≤ 3 dB
Connector	2x SMA

The interconnecting harness between the antenna, LNA and receiver is based on a flight proven harnessing with low losses, optimal VSWR and a wide, qualified temperature range. The LNA is connected to the antenna and receiver box through coaxial RF cables with SMA connectors. The harness is qualified for use in space through a series of tests demonstrating the ability to operate successfully in all mission-relevant environments and throughout its lifetime.

INTEGRATION & TESTING

Integration and testing of the LuGRE Payload occurs in multiple facilities in two different countries and represents collaborative effort across many different organizations. The Payload is developed under a full qualification program, utilizing an Engineering Qualification Model (EQM) and a Flight Model (FM), with each Model tested to qualification and acceptance levels, respectively. The top-level flow is shown in Figure 8.

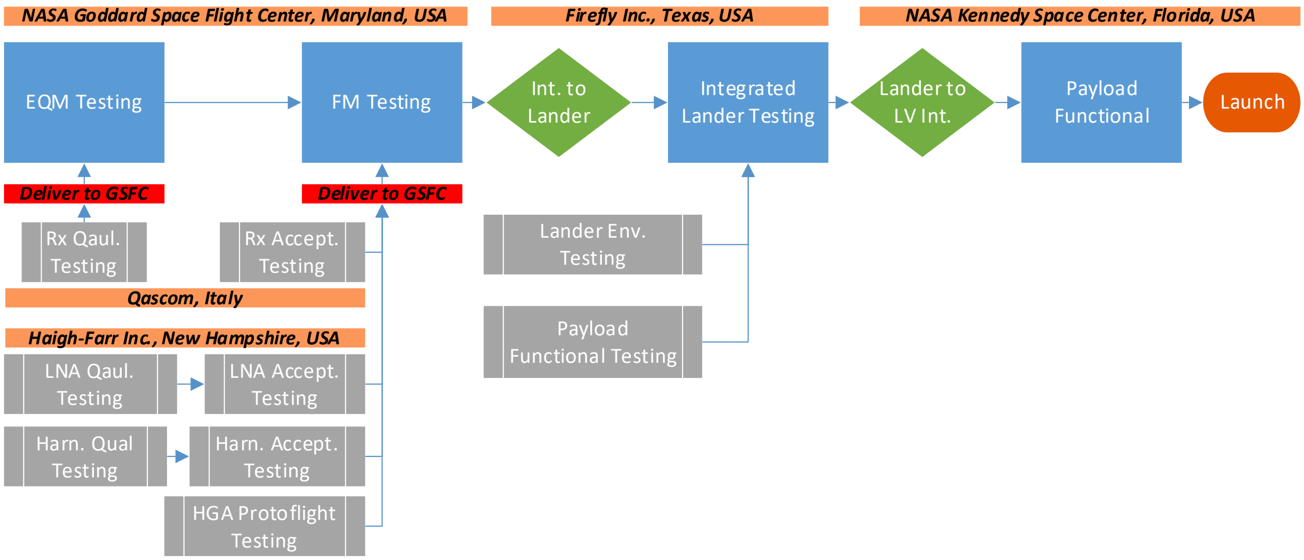


Figure 8. Overall LuGRE Integration and Test Flow

Non-flight qualification units are manufactured for the receiver, LNA, and harnessing. The qualification test program consists of subjecting each EQM payload component to a series of thermal vacuum, sine and random vibration, shock, and electromagnetic compatibility (EMC) testing. The same battery of tests—excluding shock testing—are repeated on the FM components, but at reduced acceptance testing levels. A protoflight High Gain Antenna (HGA) is manufactured instead of a qualification unit and will undergo a protoflight testing program consisting of thermal cycling, random vibration, and performance measurements.

Receiver functional testing is performed by Qascom in Bassano del Grappa, Italy. EMC testing is performed by Teslab and mechanical and thermal testing are performed by SERMS Lab, both located in Italy. Haigh-Farr is responsible for all testing on the HGA, LNA and harnessing in the United States.

Once component-level testing is completed, the EQM and FM units are shipped to NASA GSFC in Maryland, United States for payload-level testing. The fully assembled payload is subjected to a series of tests designed to verify key performance, functionality, and electrical interface requirements. These tests include testing of the RF chain, characterization of magnetic interference, full End-to-End testing of the Payload, and verification of key flight software (FSW) interfaces using a spacecraft emulator.

The LuGRE payload is then shipped to Firefly Aerospace in Texas, United States, where it will be integrated to the BGM1 lander structure. The payload will undergo all lander-level environmental testing, including EMC, vibration, and thermal testing with periodic payload functional tests taking place between major lander environmental tests. Flight operational scenarios will also be executed. The fully tested and integrated lander is then shipped to the launch site in Florida, United States, where the LuGRE Payload will undergo a final, pre-launch functional test prior to lander integration with the launch vehicle.

GROUND SEGMENT & OPERATIONS

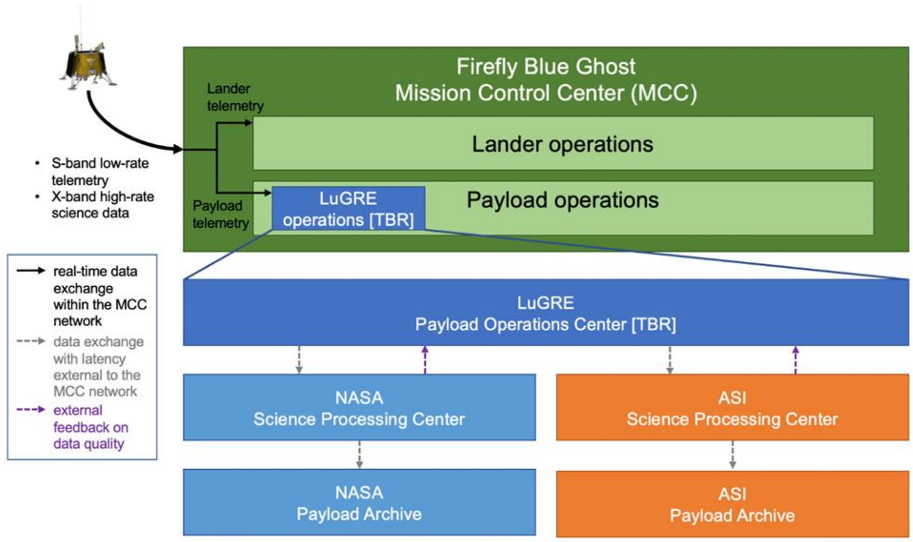


Figure 9. LuGRE Ground Concept of Operations

The LuGRE ground segment concept, shown in Figure 9, traces the flow of LuGRE payload data from the spacecraft through the ground operations infrastructure and out to the LuGRE science processing team. Onboard, the LuGRE payload will interface with the BGM1 lander telemetry and commanding system, which manages all data flows. Payload telemetry, including core navigation observables and solutions, will be downlinked over the high-rate X-band communications channel to the Firefly Mission Control Center (MCC) in Cedar Park, Texas, United States. The LuGRE team will have a core team, termed the Payload Operations Center (POC), co-located at the MCC with the ability to view real-time payload data and construct commands for uplink.

Payload telemetry data received by the POC at the MCC will be transmitted in near-real-time (≤15 min latency) to two parallel Science Processing Centers (SPCs) at NASA and ASI. The SPCs will perform the core science data verification, analysis, processing, and product generation functions for the mission, and will operate both independently and collaboratively in their activities, as described in the Mission Science section. Each SPC will manage a Payload Archive which will form the official repository for the mission data by each partner.

Ultimately, LuGRE payload data will be made available publicly to the greatest extent possible for the benefit of the GNSS space user community. The precise public repository for this data will be identified closer to launch.

MISSION SCIENCE

LuGRE is fundamentally a technology demonstration payload. Therefore, the typical Mission Science role is used to perform the core technology demonstration activities for the mission, such as characterizing the GNSS signal properties at lunar distance and performing onboard navigation demonstrations. However, the Mission Science activities may also include more conventional fundamental science activities as well, as defined by the Science Team.

The LuGRE Science Team is comprised of the two primary science teams at NASA and ASI, plus any external research partners. The NASA and ASI teams are led by the LuGRE PI and co-PI, respectively, and have primary responsibility for meeting the LuGRE science requirements listed in the Mission Overview section. Each team will lead a Science Processing Center that will receive near-real-time data from the Firefly MCC and perform validation, processing, and analysis to meet the mission science requirements and any specific investigations of interest. It is planned that research partners will be solicited as well. Partners would receive privileged data access and would process the data independently in accordance with their own investigations of interest. Such investigations could include measuring ionospheric properties at the Earth and the Moon, performing lunar regolith reflectometry, or measuring plasma total electron count in cis-lunar space. Ultimately, after an initial data processing and validation period, all LuGRE science data will be made available to the public to the greatest extent possible via an open repository. The exact mechanism for public dissemination is pending.

To guide its activities, the Science Team has identified a set of discrete investigations that together respond to the three overall mission objectives described in the Mission Overview section. Each investigation prioritized as P1 (driving), P2 (baseline), or P3 (best-effort), based on its criticality to meet the overall LuGRE science requirements and its relative importance and difficulty. Common high-priority investigations will be performed jointly by both NASA and ASI, while each party may lead others that are of particular local interest. The full list of investigations is shown in Table 4.

Table 4. Driving LuGRE science investigations

Objective 1
Measure the signal strength throughout the mission and empirically evaluate link budget model.
Determine signal availability throughout the mission.
Measure Doppler-shift and Doppler-rate profiles throughout the mission.
Measure pseudorange from visible satellites during all planned operations periods.
Objective 2
Calculate and characterize least-squares multi-GNSS point solutions throughout the mission where sufficient signals are available.
Calculate and characterize Kalman filter based navigation solutions onboard throughout the mission.
Compare onboard navigation solutions to external sources (e.g., ground-based measurement processing, planned trajectory, Blue Ghost navigation solution).
Characterize position, velocity, and time uncertainty and convergence properties throughout mission.
Objective 3
Process GNSS observables (e.g., Doppler, pseudorange) with ground-based tools to predict achievable onboard navigation performance.
Calibrate ground models with LuGRE data and utilize to predict achievable navigation performance for future missions.

This list of investigations will be further refined prior to launch and will be augmented with investigations defined by any partner science teams. At the completion of the mission, it is intended that all high-priority investigations will be addressed, which will in turn satisfy the LuGRE level 1 science requirements, and thus the overall mission objectives. The variety of investigations is enabled by the receiver's ability to provide both the GNSS raw observables and raw RF baseband samples that can be post-processed by hardware or software receivers on the ground. While limited in duration, these samples can be used to "replay" the lunar signal environment to enable further characterization [20]. This approach has been already used for critical environments with specific features that would be poorly modeled by signal simulators [21].

EXPECTED PERFORMANCE

The expected performance of the LuGRE payload has been studied with respect to onboard navigation, ground-based navigation using GNSS observables, and utilization of the raw I/Q baseband samples. NASA has simulated performance in the L1/E1 band using the Goddard Enhanced Onboard Navigation System (GEONS) Ground MATLAB Simulation (GGMS). GGMS is a MATLAB front-end to GEONS, a GSFC-developed navigation filter with extensive flight heritage. An ephemeris of the planned BGM1 was used as the truth trajectory to generate GPS and Galileo pseudorange and doppler measurements, which were processed in the GEONS extended Kalman filter (EKF).

The GGMS simulation uses the following link budget equation to model the C/N0 obtained by the receiver:

$$C/N_0 = P_T + G_T(\phi,\theta) - 20\log\left(\frac{4\pi d}{\lambda_{L1}}\right) + G_R(\phi,\theta) - L_{pol} - 10\log\left(kT_{sys}\right) - R_{loss}$$

where d is the line-of-sight distance of the receiver to the transmitting GNSS satellite, λ_{L1} is the L1/E1 carrier frequency, k is the Boltzmann constant, and the remaining parameters are summarized in Table 5. An acquisition threshold of C/N0 > 23 dB-Hz is assumed per expected receiver properties with an additional 3dB of margin.

Table 5: Link budget parameters

Parameter	Value	Parameter	Value
Receiver Implementation Losses R_{loss}	0.9 dB	P_T (GPS Block IIR)	17.3 dBW

System Temperature T_{sys}	295 K	P_T (GPS Block IIR-M)	18.8 dBW
Polarization Losses L_{pol}	3 dB	P_T (GPS Block IIF)	16.2 dBW
		P_T (GPS Block III)	18.8 dBW
		$P_T + G_T(peak)$ (Galileo)	11 dBW

Block-specific transmit powers P_T are obtained using calibration analysis [9] of high-altitude flight data from MMS [4] and antenna pattern data from the GPS Antenna Characterization Experiment (ACE) [22]. Block III values are assumed to be the same as Block IIR-M. For Galileo, an 11dB EIRP pattern out to 20° is assumed, as used in prior analysis by ESA [23]. Transmit antenna gain patterns are specified as a function $G_T(\phi, \theta)$ of off-boresight angle ϕ and azimuth angle θ given by a combination of the GPS ACE dataset and publicly available GPS IIR/IIR-M patterns [24]. The receiver antenna gain $G_R(\phi, \theta)$ is modeled as a 16 dB peak 11° half-peak beam width antenna given current knowledge of the expected antenna.

Figure 10 depicts the planned 4.5-loop transit trajectory from the Earth to lunar orbit as supplied by Firefly. Figure 11 shows the corresponding GNSS visibility, including both GPS and Galileo, for this trajectory assuming an Earth-pointing antenna, both in transit and for the 12-day operational period on the surface.

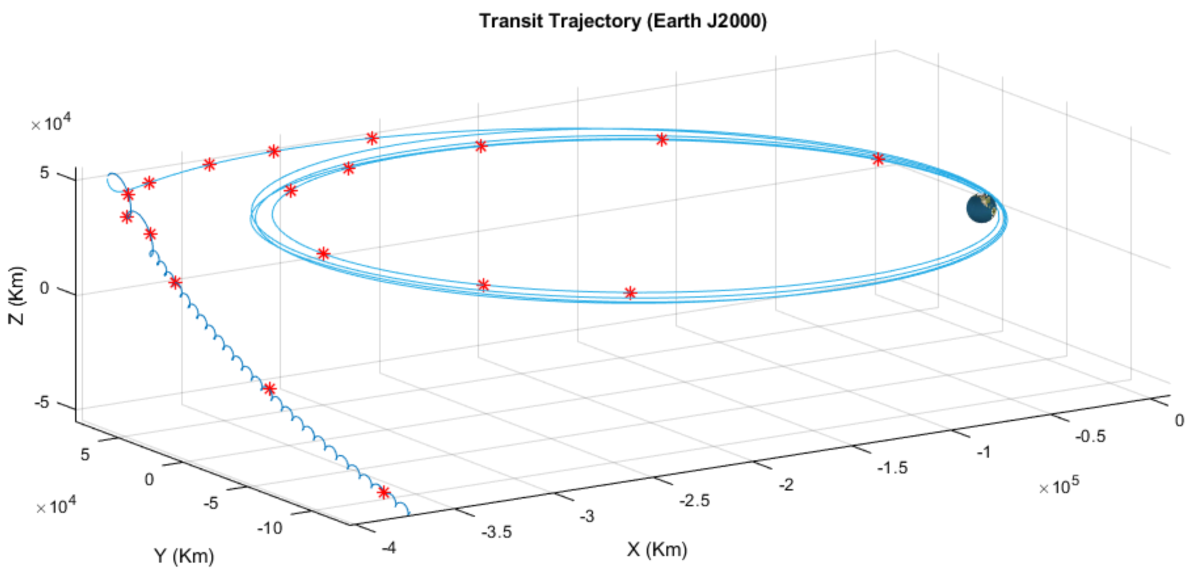


Figure 10: Earth-centered transit trajectory in the J2000 frame. Measurement periods are indicated by red stars.

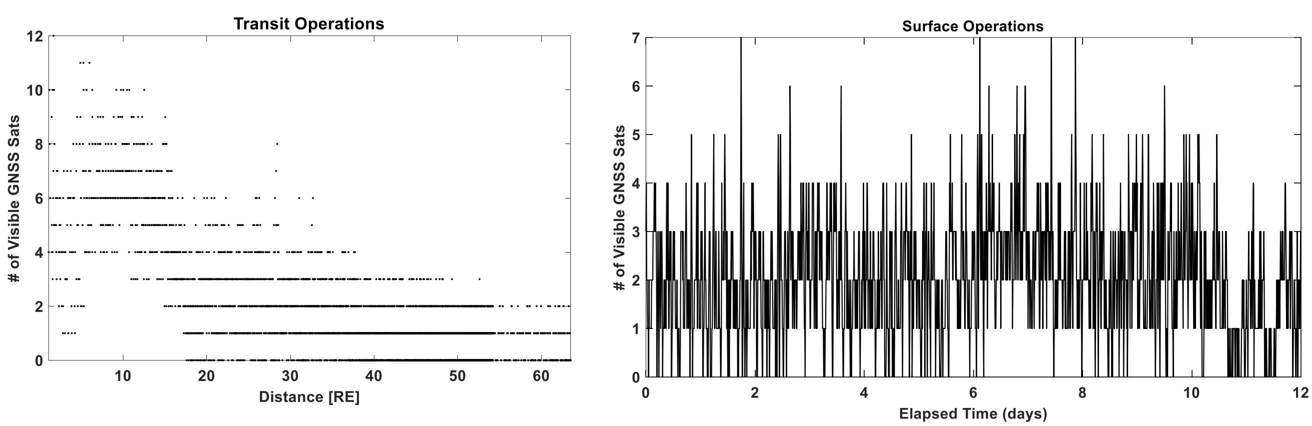


Figure 11: Summary of expected total GNSS visibility throughout transit (left) and during surface operations (right).

Figure 12 shows an example of the characteristics of C/N_0 for the signals observed during the lunar surface simulation over a duration of 24 hours. Simulations like this illustrate the properties that LuGRE is aiming to characterize while at the moon, including visibility of multiple satellites as well as satellites entering and exiting the field of view of the antenna.

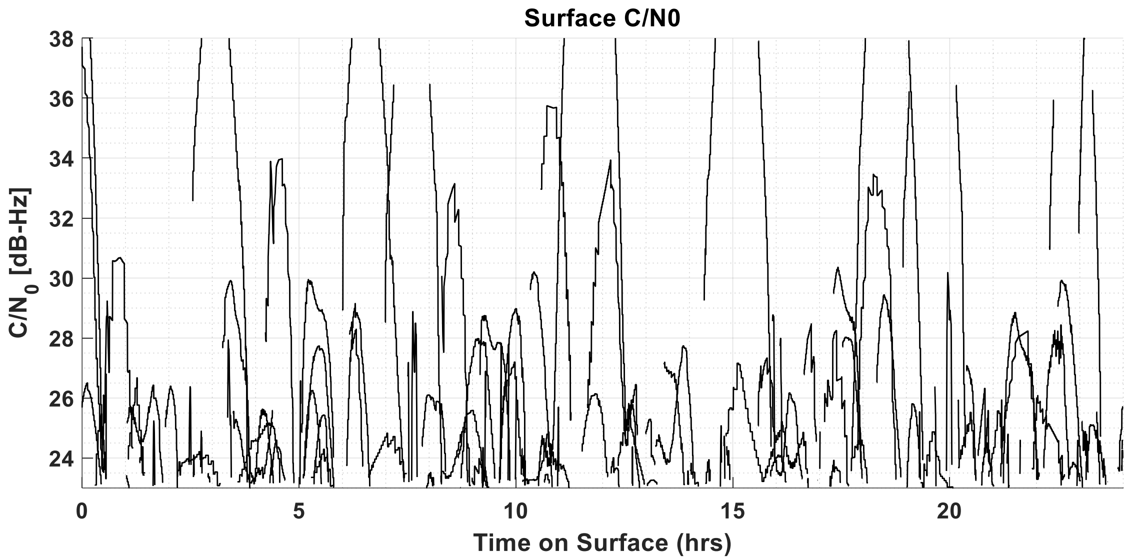


Figure 12. Example C/N0 arcs expected during lunar surface operations

Figure 13 shows snapshots of the expected filter performance achieved for each of the observation cases planned during the transit phase and in lunar orbit. For each case, an initial state covariance and error of 10 km in position and 10 cm/s in velocity 3σ is assumed. The results are shown as a function of altitude in RE, where each dot represents a single 42 to 60 minute long measurement period. The left subplots depict the RSS 3σ position and velocity covariance magnitude at the end of each filtering period. The middle subplot depicts the average number of GNSS satellites visible for each case, with error bars depicting visibility range. The right subplot shows the average C/N_0 observed during the observation period, with the minimum and maximum observed C/N_0 depicted by error bars. Markers overlaid with stars indicate measurement periods that occur in lunar orbit.

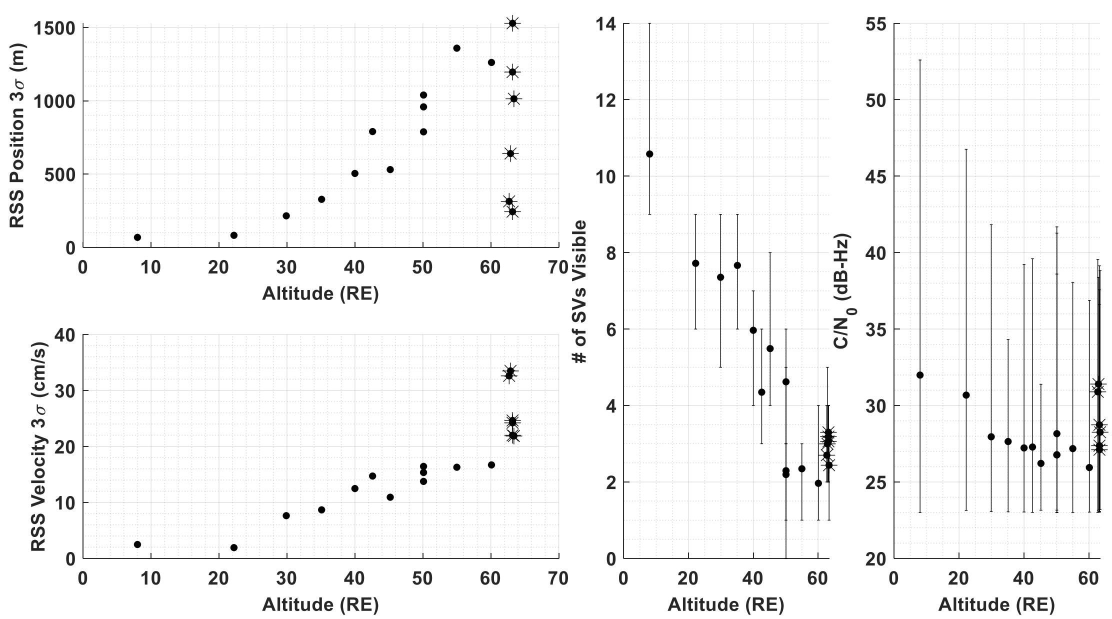


Figure 13: Summary of filter results for various altitudes in the transit trajectory (•) and in lunar orbit (*).

These results illustrate the types of trends that can be observed in transit, allowing for comparison with the high-altitude results of MMS and demonstrating the extension of data farther into cislunar space. Of particular interest are the visibility and signal strength achieved as a function of altitude, which can be used to aid in future receiver design to ensure sufficient signals are available to perform navigation. Additionally, the 6 measurement periods that occur in lunar orbit, all above 60RE, demonstrate how filter performance at these challenging distances can vary greatly depending on visibility and signal strength.

Additional analyses were performed by ASI with the support of the research team at Politecnico di Torino, focusing on processing of the raw signal samples. A GNSS simulator was tailored to simulate the received GNSS signal at different points on the expected trajectory, as well as on the surface. The scope was to assess the feasibility of GNSS signal acquisition from the signal samples collected over a limited time window, specifically the minimum integration time to acquire the signal given a target decision false alarm probability, at different points along the trajectory.

The processing was based on the NavSAS software receiver that implements specific solutions to cope with the dynamics of the space environment and emulates external aiding for Doppler and Doppler rate value estimation. It is well known [25] that for high-sensitivity acquisition the probability of detection is inversely proportional to the size of the search space. Table 6 reports the obtained minimum coherent integration time needed to successfully acquire the signal, for different C/N0 and limiting the search space to Doppler bins, thus representing different accuracy of the aiding information.

Table 6. Raw I/Q sample minimum integration time to acquire signal

C/N0 (dB-Hz)	(ms) (Full SS)	(ms) (Nd = 5)	(ms) (Nd = 3)
36.4	6	4	4
32.2	8	6	6
27.2	55	45	45
24.0	120	90	90
21.9	105	100	100
20.2	175	160	160
18.6	415	370	230

CONCLUSIONS

The Lunar GNSS Receiver Experiment (LuGRE) payload will demonstrate GNSS-based positioning, navigation, and timing (PNT) in transit to the Moon and on the lunar surface. LuGRE is a partnership between NASA and the Italian Space Agency (ASI) and will fly under the NASA Commercial Lunar Payload Services (CLPS) program on the Firefly Blue Ghost Mission 1 flight in late 2023. LuGRE consists of a Qascom-developed lunar GNSS receiver based on the QN400-Space heritage that will receive GPS L1 C/A and L5, and Galileo E1 and E5a open signals down to 23 dB-Hz C/N0; a high-gain L-band antenna; and a low-noise amplifier. The payload will acquire and track GNSS signals during at least 15 hr of operations during the Earth-Moon transit phase and in lunar orbit, then nearly continuously for 12 Earth days on the lunar surface. All data will be downlinked to joint NASA and ASI payload centers for verification and science processing.

Preliminary analysis of the LuGRE operations indicates a high degree of signal visibility throughout the mission, with an average of 4 signals GNSS in view even on the lunar surface. Analysis of the transit phase shows the ability of an extended Kalman filter to process pseudorange measurements and converge within the available time throughout the transit operations periods. Further, analysis confirms the ability to acquire signals in postprocessing using downlinked raw I/Q baseband samples. The LuGRE Science Team has identified ten science investigations that will drive the data processing and product generation, and over a dozen others that will be undertaken as best effort. All LuGRE data will be released publicly to the greatest extent possible, for the benefit of the GNSS space user community.

ACKNOWLEDGEMENTS

The LuGRE team would like to acknowledge and thank the following individuals for their support: the NASA Commercial Lunar Payload Services program, especially Mark Dillard, the CLPS Payload Integration Manager; Firefly Aerospace, especially Jesus Charles, Firefly Payload Integration Manager; and Gregory Mann, NASA Office of Interagency and International Relations.

At NASA, this work is sponsored by the Policy and Strategic Communications Office, NASA Space Communications and Navigation (SCaN). The flight is provided by the NASA Commercial Lunar Payload Services (CLPS) program. The team would like to thank Badri Younes, Deputy Associate Administrator for Space Communications and Navigation, for his sponsorship.

From ASI, for this challenging scientific and technological opportunity to test Galileo and GPS on the Moon, we wish to thank all ASI colleagues involved from the different units and departments, the Director for the International Affairs, Mrs. Gabriella Arrigo, and in particular Mr. Claudio Canu for his role on the ARTEMIS NASA/ASI agreement setup and implementation agreement.

From Qascom, the authors would like to acknowledge and thank the following teams and individuals for their commitment and passion in supporting the LuGRE challenges: the System Engineering team (Matilde Boschiero, Matteo Pulliero, Davide Marcantonio, Giacomo Cittadin, Francesco Longhi), the GNSS Receiver Software Team (Marco Bartolucci, Marco Bergamin, Antonello Contini, Simone Tedesco, Federica Rozzi, Luca Canzian, Fabio Bernardi) and the GNSS Receiver Hardware Team (Andrea Dalla Chiara, Andrea Pastega, Gianluca Gastaldello).

REFERENCES

1. Bauer, F. H., Hartman, K. R., and Lightsey, E. G., "Spaceborne GPS Current Status and Future Visions," *Proceedings of the 11th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 1998)*, Nashville, TN, September 1998, pp. 1493-1508.
2. Ashman, B. W., Bauer, F. H., Parker, J. J. K., and Donaldson, J. E., "GPS Operations in High Earth Orbit: Recent Experiences and Future Opportunities," AIAA 2018-2568. 2018 SpaceOps Conference. May 2018.
3. Bauer, F. H., Moreau, M. C., Dahle-Melsaether M. E., Petrofski W. P., Stanton B. J., Thomason S., Harris G. A, Sena R. P., and Temple III, L. P., "The GPS Space Service Volume", *Proceedings of the 19th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2006),* Fort Worth, TX, September 2006, pp. 2503-2514.
4. Winternitz, L. B., Bamford, W. A., and Price, S. R., "New High-Altitude GPS Navigation Results from the Magnetospheric Multiscale Spacecraft and Simulations at Lunar Distances," *Proceedings of the 30th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2017)*, Portland, Oregon, September 2017, pp. 1114-1126. https://doi.org/10.33012/2017.15367
5. Winkler, A., Ramsey, G., Frey, C., Chapel, J., Chu, D., Freesland, D., Krimchansky, A., and Concha, M., "GPS Receiver On-Orbit Performance for the GOES-R Spacecraft," *GNC 2017: 10th International ESA Conference on Guidance, Navigation & Control Systems*, Salzburg, Austria, May 2017.
6. Lee, T., Long, A., Berry, K., Carpenter, J., Moreau, M., and Holt, G., "Navigating the Return Trip from the Moon Using Earth-Based Ground Tracking and GPS," *Proceedings of AAS Guidance and Control Conference*, Breckenridge, CO, February 2009.
7. Ashman, B., Parker, J., Bauer, F., Esswein, M., "Exploring the Limits of High Altitude GPS for Lunar Missions," *Proceedings of AAS Guidance and Control Conference*, Breckenridge, CO, American Astronautical Society, February 2018.
8. Capuano, V., Botteron, C., Leclare, J., Tian, J., Wang, Y., and Farine, P., "Feasibility Study of GNSS as Navigation Systems to Reach the Moon," *Acta Astronautica*, July 2015.
9. Winternitz, L. B., Bamford W. A., Long A. C., Hassouneh M., "GPS Based Autonomous Navigation Study for the Lunar Gateway," *42nd Annual American Astronautical Society (AAS) Guidance, Navigation, and Control Conference*, Breckenridge, CO, February 2019.
10. Ashman, B. W., Schlenker, L. G., Parker, J. J. K., Bauer, F. H., Winternitz, L. B., Long, A. C., and Craft, K. J., "Applications and Benefits of GNSS for Lunar Exploration," SpaceOps 2021, May 2021.
11. International Space Exploration Coordination Group, *Global Exploration Roadmap*, January 2018 https://www.globalspaceexploration.org/wordpress/wp-content/isecg/GER_2018_small_mobile.pdf, (accessed 3 January 2022).
12. International Space Exploration Coordination Group, *Global Exploration Roadmap Supplement August 2020: Lunar Surface Exploration Scenario Update*, August 2020, https://www.globalspaceexploration.org/wp-content/uploads/2020/08/GER_2020_supplement.pdf, (accessed 3 January 2022).
13. NASA, *2020 Artemis Plan*, https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf, (accessed 3 January 2022).

14. Israel D., “A LunaNet Implementation Approach”, *Proceedings of the 16th International Conference on Space Operations*, SpaceOps 2021, May 2021.
15. Schönfeldt, M., Grenier, A., Delépaut, A., Swinden, R., Giordano, P., and Ventura-Traveset, J., “Across the Lunar Landscape Towards a Dedicated Lunar PNT System”, *InsideGNSS*, November/December 2020.
16. NASA, “Technology Readiness Level,” October 2012, https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level (accessed 3 January 2022).
17. NASA, “NASA Selects Firefly Aerospace for Artemis Commercial Moon Delivery in 2023,” February 2021, https://www.nasa.gov/press-release/nasa-selects-firefly-aerospace-for-artemis-commercial-moon-delivery-in-2023 (accessed 3 January 2022).
18. European Union Agency for the Space Programme, “Galileo is heading to the International Space Station on board the cubesat mission BOBCAT-1,” October 2020, https://www.euspa.europa.eu/newsroom/news/galileo-heading-international-space-station-board-cubesat-mission-bobcat-1 (accessed 3 January 2022).
19. Firefly Aerospace, “Firefly Aerospace is One Step Closer to Landing on the Moon,” October 2021, https://firefly.com/firefly-aerospace-is-one-step-closer-to-landing-on-the-moon/ (accessed 3 January 2022).
20. Linty, N., Dovis, F., and Alfonsi, L., “Software-defined radio technology for GNSS scintillation analysis: bring Antarctica to the lab,” *GPS Solutions*, vol. 22, no. 4, 2018. doi: 10.1007/s10291-018-0761-7
21. Cristodaro, C., Ruotsalainen, L., and Dovis, F., “Benefits and limitations of the record and replay approach for GNSS receiver performance assessment in harsh scenarios,” *Sensors (Switzerland)*, vol. 18, no. 7, 2018. doi: 10.3390/s18072189
22. Donaldson, J. E., Parker, J. J. K., Moreau, M. C., Highsmith, D. E., and Martzen, P. D., “Characterization of on-orbit GPS transmit antenna patterns for space users”, *NAVIGATION-US*. 2020; 67: 411– 438. https://doi.org/10.1002/navi.361
23. Enderle, Werner & Gini, Francesco & Schönemann, Erik & Mayer, Volker. (2019). PROBA-3 Precise Orbit Determination based on GNSS Observations. 1187-1198. 10.33012/2019.17083.
24. United States Coast Guard, “GPS Technical References,” https://navcen.uscg.gov/?pageName=gpsTechnicalReferences (accessed 3 January 2022).
25. Borio, D., Camoriano, L., and Lo Presti, L., “Impact of GPS acquisition strategy on decision probabilities,” *IEEE Transactions on Aerospace and Electronic Systems*, vol. 44, no. 3, pp. 996-1011, July 2008, doi: 10.1109/TAES.2008.4655359.