Science Objectives and Investigations for the Lunar GNSS Receiver Experiment (LuGRE)

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ABSTRACT

In July 2020, NASA selected the Lunar GNSS Receiver Experiment (LuGRE) as the 10th payload of CLPS Task Order 19D. Firefly's Blue Ghost lander will deliver LuGRE and the other CLPS 19D payloads to the Moon's Mare Crisium. Developed jointly by NASA and the Italian Space Agency (ASI), LuGRE is intended to be the first demonstration of GNSS-based navigation beyond an altitude of 30 RE and the first to use GNSS on the lunar surface, expanding the proven reach of usable GNSS signals. Subsequent missions will be able to leverage LuGRE data and lessons learned to operationalize GNSS in the lunar regime, adding an existing, proven, real-time navigation source for spacecraft exploring the Moon.

The primary goal of the LuGRE project is to extend GNSS-based navigation and timing to the Moon. LuGRE will fulfill this goal by gathering and processing GNSS data across several mission phases. The LuGRE Science Definition Team (SDT) was formed for the purpose of proposing science and technology investigations to be executed by the LuGRE project. A primary outcome of the work of the LuGRE SDT is a set of specific, high-value, achievable investigations to be performed as part of the science program. This paper provides a detailed description of the LuGRE science investigations and will present preliminary analyses that show how these investigations will be used to support the realization of lunar GNSS use in the future.

1 INTRODUCTION

A resurgence in lunar activity is taking place, and the pace of Moon-bound launches is only expected to increase. A dozen missions have already launched to the Moon in the last decade. There are now more than 80 government space agencies and an increasing number of private space companies, many of which are planning missions to the Moon. From a navigation perspective, the goals of these future missions are ambitious (e.g., the 2018 Global Exploration Roadmap identified 100-meter position accuracy as a performance target for precision landing [1]). Robotic missions will not be able to rely on a human-in-the-loop approach and the sheer volume of planned missions will make ground-based tracking impractical.

Although robust lunar positioning, navigation, and timing (PNT) will rely on a variety of techniques in the long-term, Global Navigation Satellite Systems (GNSS) offer features that make them uniquely valuable for lunar exploration, especially in the near-term while planned Moon-based communications and navigation infrastructure is still in development [2][3][4][5]. GNSS may provide a scalable and reliable solution to lunar PNT for a sustainable return to the Moon, but the proven reach of GNSS must be extended to the Moon before widespread adoption can occur.

Several experiments flown in the late 1990s and early 2000s incrementally provided a more comprehensive understanding of the capabilities and limitations of high-altitude GPS navigation [6][7][8][9][10]. Data from these experiments supported the U.S. government's formal definition of the Space Service Volume (SSV) in 2006 [11]. The SSV overlaps and extends beyond the GNSS constellations themselves, so utilization of GNSS signals at high-altitude often requires signal reception from GNSS satellites on the opposite side of the Earth. As a result, signal availability is impaired by poor geometry, signal occultation by the Earth itself, and exceptionally weak signal strength [12].

Weak signal receivers [13] and high gain antenna technology has advanced to address signal strength issues in the SSV, and GNSS has been used operationally by Earth-orbiting spacecraft at altitudes halfway to the Moon, a distance of approximately 30 Earth radii (RE) [14][15]. Leveraging the data and insights from these spacecraft, GNSS-based navigation in the lunar vicinity has been extensively studied and shown to be not only feasible, but a valuable source of high fidelity PNT for lunar vehicles such as Gateway, especially as part of a multi-technique navigation system [16]. The first step to operationalizing this technique for widespread cislunar use is to perform an in-flight demonstration and collect data that can be used to develop the next generation of lunar-capable GNSS equipment.

In July 2020, NASA selected the Lunar GNSS Receiver Experiment (LuGRE) as the 10th payload of CLPS Task Order 19D [17]. In February 2021, NASA awarded Task Order 19D to Firefly Aerospace. Firefly's Blue Ghost Mission 1 (BGM1) will deliver LuGRE and the other CLPS 19D payloads to 18.6° N, 61.8° E in the Moon's Mare Crisium. LuGRE is intended to be the first demonstration of GNSS-based navigation beyond an altitude of 30 RE and the first to use GNSS on the lunar surface. Fulfillment of the LuGRE science objectives will expand the proven reach of usable GNSS signals. Subsequent missions will be able to leverage LuGRE data and lessons learned to operationalize GNSS in the lunar regime, adding an existing, proven, real-time navigation source for spacecraft exploring the Moon.

2 LUGRE SCIENCE GOALS

The primary goal of the LuGRE project is to extend GNSS-based navigation and timing to the Moon. As a technology demonstration payload on the BGM1 lunar lander, LuGRE will fulfill this goal by gathering and processing different types of GNSS data across several mission phases. These activities are codified in three overarching science objectives:

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 three objectives drive seven project-level requirements, three of which are allocated to the science program. The project-level requirements have both baseline and threshold levels, defined as follows:

- ***Baseline Requirements*****:** An agreed-to set of requirements that will have changes controlled through a formal approval and monitoring process.
- ***Threshold Requirements*****:** A minimum acceptable set of technical and project requirements; this set represents the descope position of the project.

The three project-level requirements allocated to science are as follows:

L101: GNSS measurements	***Baseline*:** The LuGRE project shall receive and downlink GNSS measurements from the GPS L1 C/A and L5 signals, and from the Galileo E1 and E5a signals, at the Moon. ***Threshold*:** The LuGRE project shall receive and downlink at least one type of GNSS measurement from any of the GPS L1 C/A, GPS L5, Galileo E1, or Galileo E5a signals, at the Moon. ***Rationale*:** Fulfills Objective 1. Baseline requirement is to receive all measurement types and signals. Threshold requirement is to receive at least one measurement type and signal. GNSS measurements are defined as GNSS observables (pseudorange, carrier phase), navigation products (point solutions, Kalman filter solutions), and raw frequency samples.
L102: Lunar navigation demonstration	***Baseline*:** The LuGRE project shall demonstrate real-time GNSS-based navigation in transit beyond 30 Earth radii (RE) from Earth and on the lunar surface. ***Threshold*:** The LuGRE project shall demonstrate GNSS-based navigation in transit beyond 30 RE from Earth or on the lunar surface using payload-collected data. ***Rationale*:** Fulfills Objective 2. Baseline requirement is for real-time navigation for both transit and lunar surface operations. Threshold requirement can be met with post-processed navigation or real-time navigation, for either transit or on the lunar surface. Transit phase of interest is above the maximum altitude of NASA's Magnetospheric Multiscale Mission, approximately 30 Earth radii (Earth radius = 6378 km). Transit phase is the period between launch and initiation of powered descent to the lunar surface and includes both Earth-to-Moon cruise and lunar orbital phase.
L108: Data formats	***Requirement*:** The LuGRE project shall provide measurement data in standard formats and with necessary metadata to support utilization for external lunar navigation studies and lunar-capable receiver development. ***Rationale*:** Fulfills Objective 3. Ensures that released data is useable for intended purposes.

To fulfill these science objectives, the LuGRE Science Definition Team (SDT) was formed in May 2021 for the purpose of proposing a set of science and technology investigations to be executed by the LuGRE project. A primary outcome of the work of the LuGRE SDT is a set of specific, high-value, achievable investigations to be performed as part of the science program. The team worked through a multi-step process involving brainstorming, refinement, prioritization, documentation, and review, arriving at investigations that are considered representative of best interest of the GNSS community at large.

These investigations are intended as recommendations for mission development as part of the executed LuGRE science program and may be augmented further by the LuGRE Science Team, either for implementation by the LuGRE project or by external participating investigators. The investigations serve as guideposts for the mission, ensuring that as the mission requirements develop and the concept of operations evolves, the driving objectives of the mission are upheld and will be fulfilled by the specific execution plan finalized by the LuGRE project.

This paper provides a detailed description of the LuGRE science investigations and where relevant, presents preliminary analyses that show how these investigations will be used to support the realization of lunar GNSS use in the future. The investigations established by the LuGRE SDT broadly fall into 4 categories of increasing processing complexity. The levels are as follows:

- **Signal Level:** baseline collection of raw GNSS signal samples; post-processing of collected raw signals [18]; low-level characterization of the properties of signals used in higher processing levels; calibration of models used to simulate GNSS signal power and link budget through the mission and at the lunar surface.
- **Measurement Level:** data collected in the form of GNSS observables such as pseudorange, Doppler shift, carrier phase, as well as local clock data.

- **Navigation Level:** usage and application of collected GNSS observables for navigation purposes; characterization of navigation performance throughout the mission and on the lunar surface [19]; extrapolation of achievable navigation performance for future missions given the observed properties of the collected observables.
- **Opportunistic Science:** science investigations that may occur as time and resources permit; these are not necessarily "traditional" navigation investigations; but utilize collected signals to investigate and draw conclusions about the environment in which they are collected.

These investigations are summarized in the graphic shown in **FIGURE 1**, categorized by processing level and increasing complexity, and ranked by priority (P1, P2, P3). Further detail is provided in Section 4.

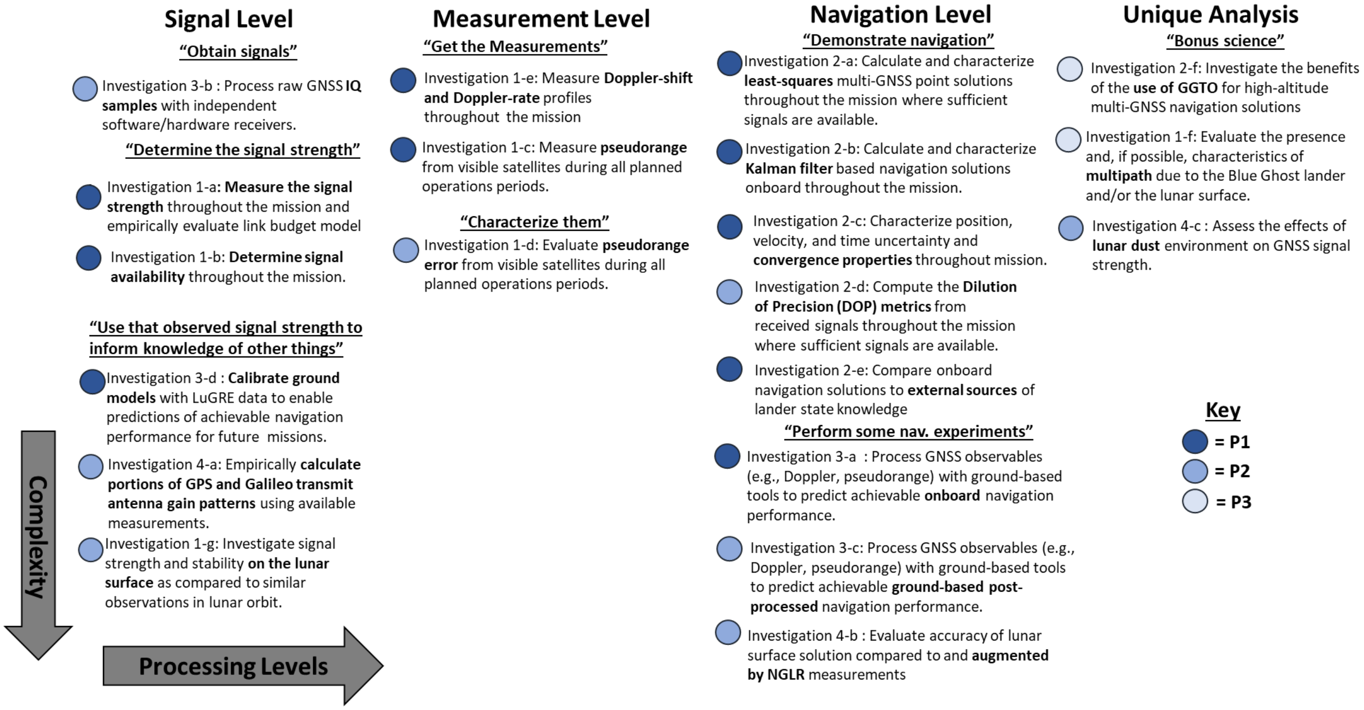


FIGURE 1: Science Investigations: Categorization and Prioritization

3 LUGRE MISSION OVERVIEW

3.1 Hardware

The LuGRE payload is developed jointly by NASA and the Italian Space Agency (ASI). The payload consists of a GNSS receiver, high-gain L-band antenna, front-end assembly (FEA), and radio frequency (RF) cable harnesses. The receiver is specially designed and built for lunar applications by Qascom srl, based on their low altitude QN400-SPACE multi-frequency receiver product line. The receiver utilizes two cold-redundant Xilinx Zynq-7000 FPGAs, the use of which is monitored and controlled by a radiation hardened supervisory board. The receiver is capable of weak-signal acquisition and tracking of Global Positioning System (GPS) L1/L5 and Galileo E1/E5 signals with a carrier to noise spectral density (C/N0) as low as 23 dB-Hz. The receiver can switch between a nominal real time processing mode, providing GNSS observables and associated navigation solutions, and a sample acquisition mode, capturing raw complex signal samples for offline post-processing, referred to as *In-phase Quadrature Samples* (IQS). The total mass of the receiver, pictured in **FIGURE 2**, is less than 1.3 kg with an operating power less than 14W.

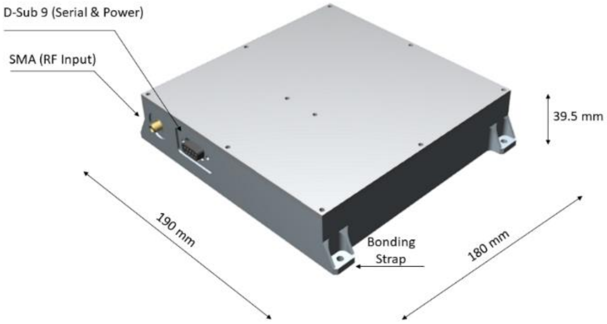


FIGURE 2: *LuGRE GNSS Receiver*

The internal receiver clock is a space-grade voltage-controlled temperature compensated crystal oscillator (VCTCXO). Measured Allan deviation properties of an identical clock of the same model are shown in **FIGURE 3**, compared for reference to similar clocks such as a rubidium atomic frequency standard (RAFS) and the ultra-stable oscillator (USO) used by the MMS mission.

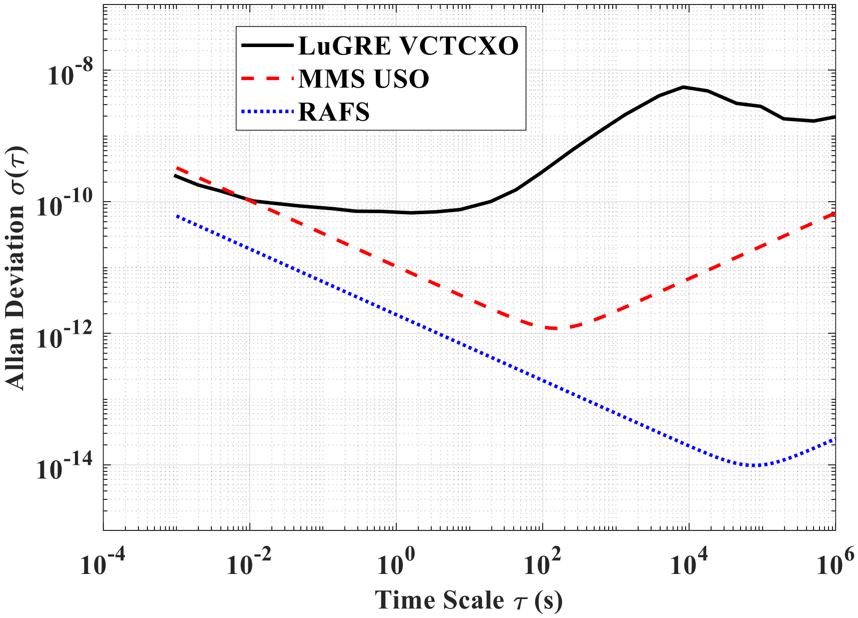
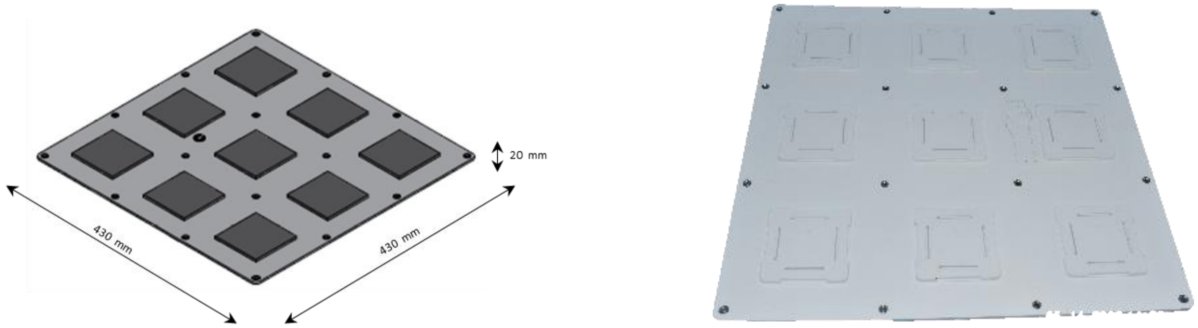


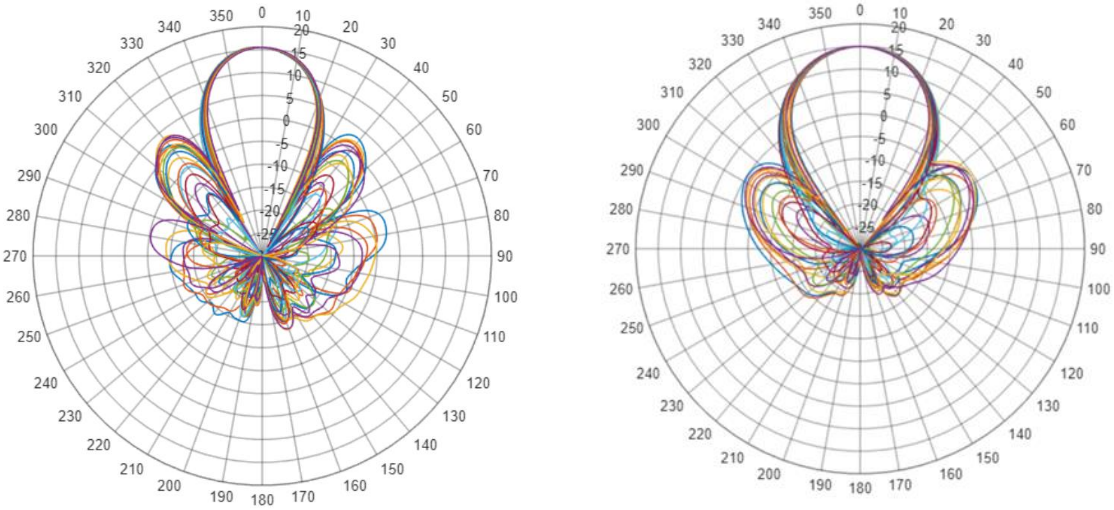
FIGURE 3: *LuGRE VCTCXO Allan Deviation*

The LuGRE antenna is a high-gain passive L-band antenna with 9 array elements designed for both L1/E1 and L5/E5a frequencies procured commercially from Haigh-Farr. The peak gain is 15.5 dBic at L1 and 14.9 dBic at L5 with half power beamwidth (HPBW) of about 25 deg (i.e., ± 12.5 deg) at L1 and about 28 deg at L5. The antenna includes an integrated stripline preselection filter with an insertion loss below 0.5 dB over the L1/E1 and L5/E5a bands. The antenna is mounted on the Blue Ghost Lander Earth-pointing mechanism and located adjacent to the Lander X-band antenna. The LuGRE antenna will be pointed to the Earth center within +/-1 degree during all data collection activities. The antenna is shown in **FIGURE 4**. The tested antenna pattern of the HGA is shown in **FIGURE 5**, with resolution of 1 deg in theta and 10 deg in phi.



(a) HGA layout *(b) HGA Top View*

FIGURE 4: *LuGRE High Gain Antenna*



(a) HGA Gain Pattern L1, Measured *(b) HGA Gain Pattern L5, Measured*

FIGURE 5: *LuGRE High Gain Antenna L1/E1 and L5/E5 Gain Patterns (dB)*

3.2 Mission Concept of Operations

The LuGRE mission concept of operations is illustrated in **FIGURE 6**, with an inset that depicts where the LuGRE hardware is physically located on the lander. The HGA is mounted alongside Firefly’s communication antenna on a gimballed panel, and the receiver and front-end electronics are mounted within the body of the lander on the bottom of the uppermost deck.

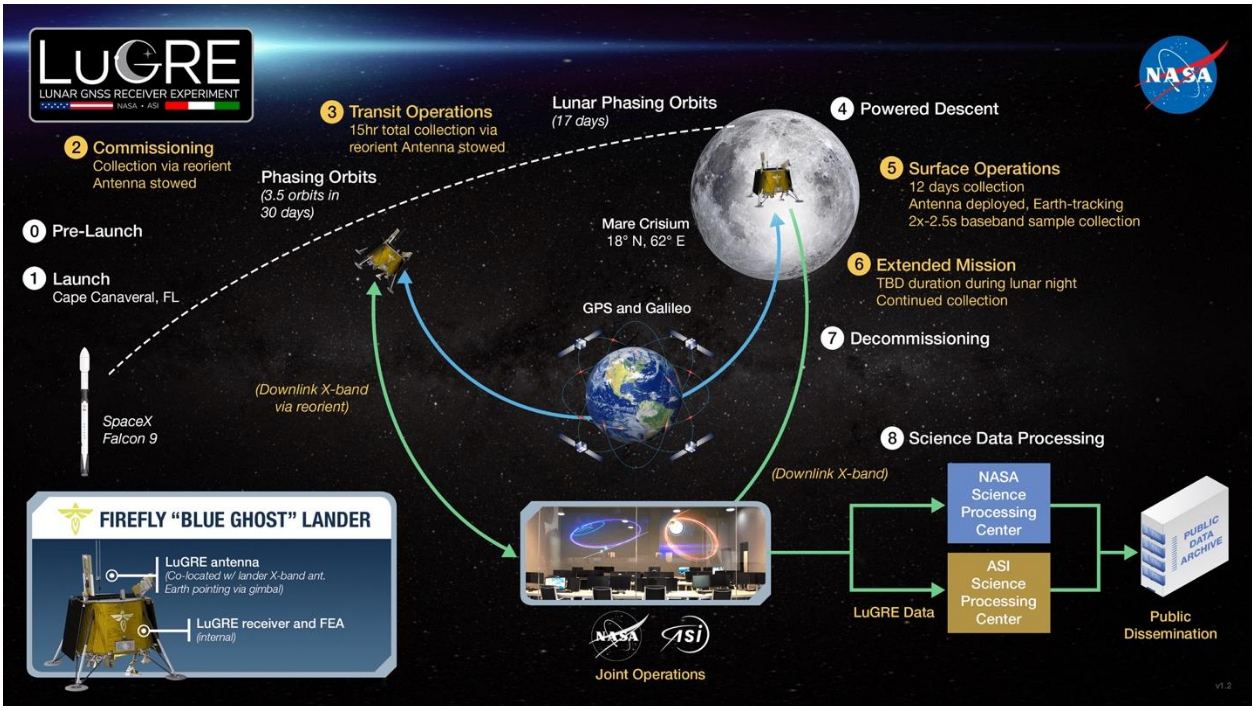


FIGURE 6: *LuGRE within the Blue Ghost Mission 1 Concept of Operations*

The mission consists of nine distinct phases:

- **0 - Pre-Launch**: 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.
- **1 - Launch**: 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 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. See Section 3.3 for more details.
- **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 three and one-half phasing loops with apogee above 320,000km (50 RE) and perigee below 10,000 km altitude (1.5 RE). Each phasing loop has a period of approximately 8.5 days, leading to a total time between launch vehicle separation and lunar orbit insertion (LOI) of about 30 days. The lander performs three LOI maneuvers to place the vehicle into a 5,000km x 100km high lunar orbit for three revolutions before transitioning to a 100km-radius circular orbit around the Moon. The lunar orbit period from LOI1 to initiation of the descent to the surface is approximately 16 days. LuGRE will perform periodic observations during transit, to be described in detail in the next section.
- **4 - Descent**: The BGM1 spacecraft will perform a powered descent to the Mare Crisium region of the Moon. The descent phase will last less than 1 hour and will occur with LuGRE powered off.
- **5 - Surface Operations**: During the surface period, the lander will point the LuGRE antenna to continuously track Earth within 1 degree.
- **6 - Extended Mission**: The lander will perform an extended mission of unknown duration after onset of lunar night, dependent on the extent of power available in its batteries. Payload operations during this period will be prioritized by the CLPS Project Scientist. LuGRE anticipates continuing nominal operations during this period, if allowed.
- **7 - Decommissioning**: LuGRE will be decommissioned on loss of power from the lander.
- **8 - Science Data Processing**: During the operational phases, payload data will be transmitted to the ground by the BGM1 spacecraft and distributed to the payload team for real-time and post-mission processing and analysis. This phase is envisioned to last 6 months after the end of LuGRE operations. Payload data will then be made publicly available to the greatest extent possible.

3.3 Science Operations

During the transit phase, the antenna panel will be in the stowed configuration on the lander, flat and nearly flush with the top deck (x-axis) of the lander, with the boresight facing outward. LuGRE pointing during transit can therefore only be achieved via reorientation of the spacecraft to point this axis in the Earth direction, a maneuver that can be performed for no more than 15 hours of total duration during this period due to cold-gas availability for attitude control. LuGRE can allocate this time in 1-hour operational segments, totaling 15 operations between launch and lunar landing during which a maximum of 7.3 MB of data may be downlinked. In addition to these 15 baseline opportunities, additional time may be released by Firefly post-launch after engineering maneuvers take place and the cold-gas budget is increasingly well understood. Because the Firefly antenna and LuGRE antenna are co-located on the same panel, supplementary unplanned opportunities could also arise if Firefly must re-orient the lander for data downlinks.

Given the limited total time for collecting science data during transit, several criteria are used to prioritize scheduling of the 15 baseline 1-hour science periods. These criteria are chosen to fulfill mission science objectives most thoroughly, while also allowing for flexibility if spacecraft anomalies arise that must be prioritized over payload science. The guiding criteria determined by the SDT are generally as follows:

- Allocate two initial commissioning periods as soon as possible after separation from the launch vehicle, and below 30RE, to ensure payload health and safety.
- Place science periods uniformly between 30 RE and 60 RE in altitude to form a complete picture of GNSS signal properties and expected navigation performance at altitudes which have never been tested.
- Form altitude pairs pre- and post- apogee (e.g. place an opportunity at 45 RE outbound and complete the pair at 45 RE inbound.) This will allow for investigating potential differences in receiver performance under differing Doppler magnitudes.
- Prioritize periods in lunar orbit, where it is expected that a large proportion of future cislunar users might rely on GNSS signals for PNT.
- Allocate some science observation periods as close as possible to the times shortly before and after Firefly's planned trajectory correction maneuvers. This approach enables the use of the data collected during these periods to explore how GNSS-based orbit determination can be utilized for both planning and reconstructing these maneuvers, potentially in conjunction with ground-based tracking data collected simultaneously during these periods.

FIGURE 7 illustrates a schedule of 15 baseline transit activities overlaid on a representative transit trajectory, plotted in terms of the distance from Earth's center and beginning from the separation of the lander from the Falcon 9 upper stage. These activities were selected using the criteria defined above. Yellow dots represent the locations of planned lander maneuvers, and brown dots represent the baseline LuGRE activities. Activities are nominally front-loaded to the first phasing loop. However, except for the initial two commissioning activities, if spacecraft or payload anomalies arise early on that need to be addressed, these activities can be deferred to similar altitudes or scenarios (e.g., pre- and post-maneuver) in later phasing loops without compromising science goals. After ~30 days the spacecraft is placed into lunar orbit; these activities are depicted in the figure inset as a function of altitude above the lunar surface, with the orbit dimensions labeled in blue on the x-axis.

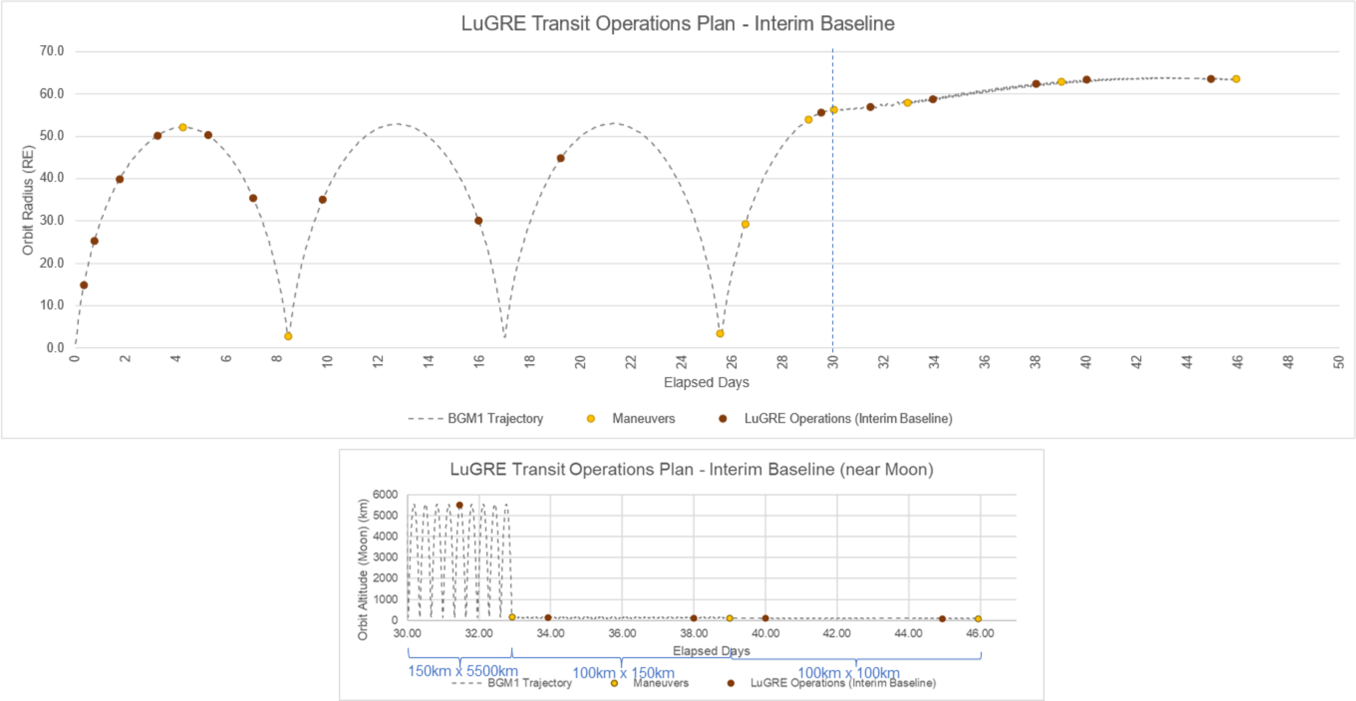


FIGURE 7: LuGRE Transit Operations Plan

As shown in **FIGURE 8**, LuGRE will be powered on within 3 hours of landing and will operate nearly continuously for the full nominal 12-day duration of lunar surface operations. The only exception will be during the ±24 hours around lunar noon, when LuGRE will perform worst-case 50% duty cycling in 1-hour on/off segments to reduce heat dissipation to satisfy lander thermal constraints. Additionally, LuGRE will perform two sample collection activities in which it collects raw samples of the L1/E1 and L5/E5a baseband. It is anticipated that up to 2.5s of samples can be collected during each opportunity, depending on the quantization depth, sample rate, and band. These samples will then be transmitted slowly to the ground alongside ongoing observation data over the following 24 hours. LuGRE is allocated 7.3 MB of data downlink each hour during normal operations, and an additional 64 MB over the 24 hours following a sample collection opportunity.

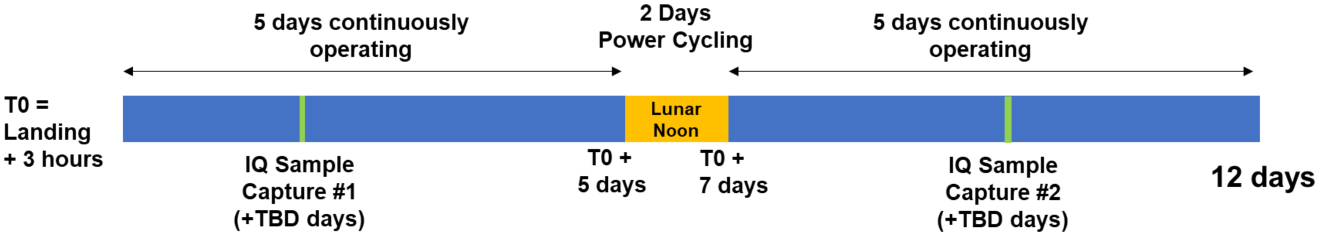


FIGURE 8: LuGRE Surface Operations Plan

3.4 Telemetry

The LuGRE receiver generates a variety of telemetry, including receiver health and status, raw measurements, and navigation products. Periodic health and status telemetry messages contain data such as messages about the current operating mode, hardware temperatures, and version number. Acquisition specific telemetry messages contain status of the receiver acquisition loops, including computed correlator values and noise floors, and initial estimates of Doppler, Code Phase, and C/N0 upon successful acquisition.

There are two forms of raw measurement telemetry depending on the operating mode commanded. In *sample capture mode*, the receiver records, stores, and outputs complex baseband in-phase and quadrature (IQ) RF samples with user-configurable sampling and quantization. In *real-time processing mode*, the receiver computes and outputs GNSS observables for each signal tracked., including Pseudorange, Doppler, Doppler rate, carrier phase, and C/N0.

In real-time processing mode, the LuGRE receiver computes two additional types of telemetry containing navigation products; a message containing least-squares point solutions and a message containing Extended Kalman Filter (EKF) solutions. The point solution message contains the results of the instantaneous least-squares point solution calculated at each timestep, calculated in the Earth-centered inertial (ECI) frame. This message is only available once four satellites are tracked, with any mix of GPS or Galileo. The GGTO broadcast parameter is used to relate the time between constellations. However, the output of the receiver onboard EKF is captured as soon as at least one satellite is tracked. This message contains the state (position, velocity, time bias, and carrier phase ambiguity) and the 1-sigma covariance diagonals. The measurement model within the EKF is based on the group and phase ionospheric correction (GRAPHIC) combination of pseudorange and carrier phase.

All receiver telemetry is timestamped with the receiver reference time, the source of which depends on the state of receiver tracking. At startup, the receiver time is initialized to the GPS epoch (i.e., January 6, 1980, at 00:00 UTC). The receiver time is synchronized with a time command sent from the lander onboard computer just after receiver startup and the receiver time is then propagated by the receiver VCTCXO. Once the first GPS or Galileo satellite is acquired, the receiver time is synchronized to GPS time. This time is then propagated by the receiver VCTCXO and is reported in telemetry in GPST, using the Galileo-GPS Time Offset (GGTO) navigation message parameter to convert if necessary. If tracking is lost, the receiver continues to propagate time via the VCTCXO until tracking is regained.

4 SCIENCE INVESTIGATIONS

This section details each science investigation defined by the SDT in order of increasing complexity, with investigations that have common goals grouped together. Beyond the information summarized in this paper, each investigation is formally defined with a set of telemetry to be collected by the receiver and the conditions under which these data should be collected to fulfill the stated goals. For brevity, these properties are not stated within this paper but are contained with the internal Science Definition Team Report (SDTR) used by the team. The SDTR guides the science team when decisions concerning concept of operations are considered to ensure science return for the mission is maximized.

4.1 Signal Level Investigations

Signal level investigations are those which involve studying the properties of the GNSS signals collected and returned during the mission. Collecting and characterizing signals is the first step towards understanding the properties of GNSS signals available at the Moon and how a user may expect to use them for more complex tasks like navigation. In the context of LuGRE, a signal can mean a traditionally processed GNSS signal produced by the receiver acquisition and tracking modules, or the "raw" or baseband IQS collected by the receiver.

4.1.1 Raw Sample Capture

Investigation ID	Investigation Statement
3-b	Process raw GNSS IQ samples with independent software/hardware receivers.

In addition to real-time operations with LuGRE onboard receiver—computing GNSS measurements and estimating Position, Velocity, and Time (PVT) solutions—digitized GNSS signals will be collected and sent to the ground segment for parallel investigation and further post-processing.The collection of digital IQS data throughout the mission enables characterization of the lunar and cislunar GNSS signal environment necessary to fulfill Objective 1 of the overarching science goals. Furthermore, access to raw, unprocessed data is crucial for the ongoing development of GNSS signal processing architectures tailored to the unique lunar environment (Objective 3).

IQS are baseband digital signal samples collected at the output of the LuGRE frontend and Analog-to-Digital Converter (ADC), as illustrated in **FIGURE 9**. In-phase and Quadrature components are recorded separately. Originating from the Software Defined Radio (SDR) domain [20], this concept enables early-stage post-processing of signals in the receiver's processing chain, making it ideal for environments with unique characteristics that are difficult to model with signal simulators [21]. This approach opens extensive opportunities for ground-based signal processing and scientific investigation after data collection [22].

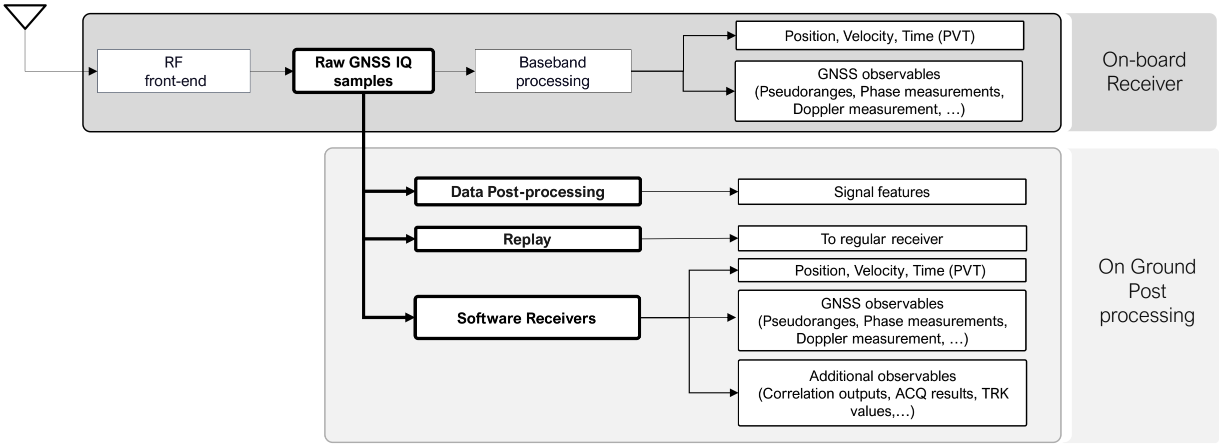


FIGURE 9: *IQS collection and analysis paradigm, from onboard sample capture to ground post-processing.*

As shown in **FIGURE 9**, IQS data can be processed at various levels. Dedicated algorithms can be used for (i) data probing and analysis to extract and observe signal features, and (ii) GNSS software receiver processing to compute GNSS observables such as pseudoranges, phase and Doppler measurements, correlation outputs, and acquisition and tracking results. The ability to construct these observables depends largely on the IQS snapshot duration [23][24]. For sufficiently long snapshots, even PVT estimation could be performed independently or with external navigation message information, although this is unlikely for the LuGRE mission due to data volume constraints. Storage capacity, data transfer windows, and downlink capabilities limit the duration of IQS snapshots. The corresponding data volume is also influenced by the sample rate and quantization depth. Preliminary trade-off analyses [23][24] have shown that snapshots of at least 300-400 ms are necessary to maximize scientific returns while adhering to mission constraints, providing reasonable chances of acquiring and tracking GPS and Galileo signals along the MTO.

IQS can also be used to (iii) replay the digital signal to other GNSS receivers, enabling the replication of the signal environment across different processing architectures. This flexibility in IQS applications (i-iii) supports a risk minimization approach for the mission, expanding the limited real-time processing solutions adopted onboard to a wide array of potential processing architectures tailored to specific datasets under investigation. Additionally, the reconfigurability of software implementations allows them to act as digital twins of the onboard receiver and as post-processing tools to test various receiver parameter settings.

In this context, IQS analysis plays a significant role in LuGRE investigations and experiments. Beyond contributing to signal-level investigations (Section 4.1) IQS provides a first-hand, unprocessed source of information, making it a primary data source for opportunistic science. This is particularly valuable for assessing unforeseen effects on signals, which existing processing architectures designed for signal tracking and PVT estimation cannot typically address. Additionally, IQS analysis can serve as a validation tool for the post-correlation data computed by the LuGRE onboard receiver, enabling comprehensive post-processing on the ground. However, the large data volume and limited downlink rate pose significant constraints, restricting the duration of the collected IQS batches. Despite these limitations, certain observables, such as Carrier-to-Noise Ratio (C/N0) and Doppler shift, can still be estimated by means of cross-ambiguity function (CAF) computation and compared to the refined onboard measurements. The prominent features (i-iii) of this analysis allows therefore to fulfill the objectives of *Investigation 3-b*, that has been designed to leverage IQS to assess the quality of GNSS signals (i), cross-validate the results of the on-board processing (ii), replicate the other investigations and expanding the acquired GNSS constellations (iii).

Although preliminary analyses have been conducted to assess the performance of acquisition and tracking stages over IQS batches generated using a Monte Carlo approach [23][24], realistic hardware-in-the-loop analyses have recently been performed with a GNSS RF simulator and the LuGRE receiver. This analysis utilized IQS post-processing for *a posteriori* signal acquisition, validating the C/N0 levels and Doppler shift estimated by the LuGRE onboard receiver's tracking module.

Along selected segments of a potential LuGRE trajectory, the GNSS RF environment was simulated and injected into the LuGRE receiver. The receiver performed an initial sample capture phase, then switched to real time processing mode to compute GNSS observables. By post-processing the captured IQS for a trajectory segment at a distance of 17 RE and without resorting to high sensitivity techniques, we were able to confirm the presence of GPS PRN 21. In **FIGURE 10** it is possible to observe the CAF for PRN 21 together with estimated C/N0 levels of other PRNs. By comparing these results with the C/N0 observations computed by the tracking stage of the LuGRE receiver shown in **FIGURE 11**, it is possible to verify that PRN 21 corresponds to the strongest signal, with an estimated C/N0 of 42 dB-Hz. It is worth noting that this value has been measured a few minutes after the sample capture; the slightly higher C/N0 estimation in **FIGURE 10** is possibly consistent with the decreasing trend observed in **FIGURE 11**, thereby validating the IQS analysis.

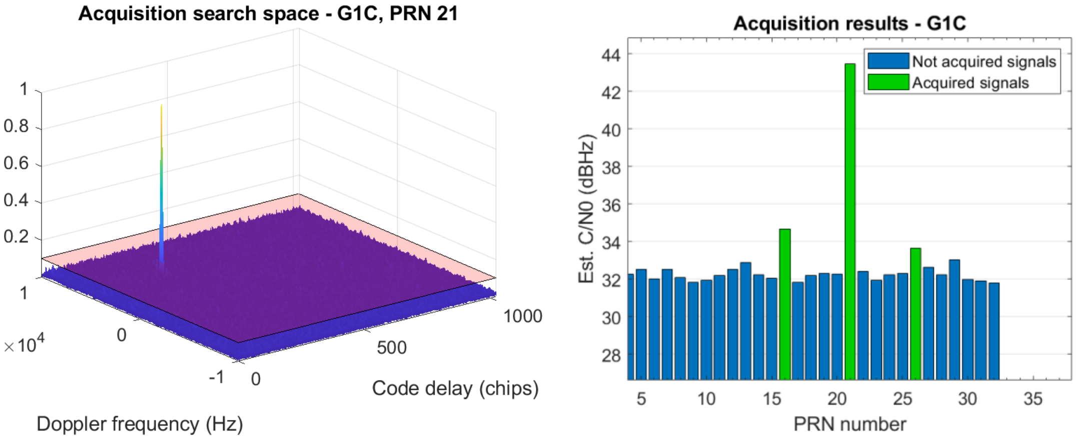


FIGURE 10: *CAF for PRN 21 (left). CN0 estimation based on CAF for GPS satellites signals on L1 C/A*

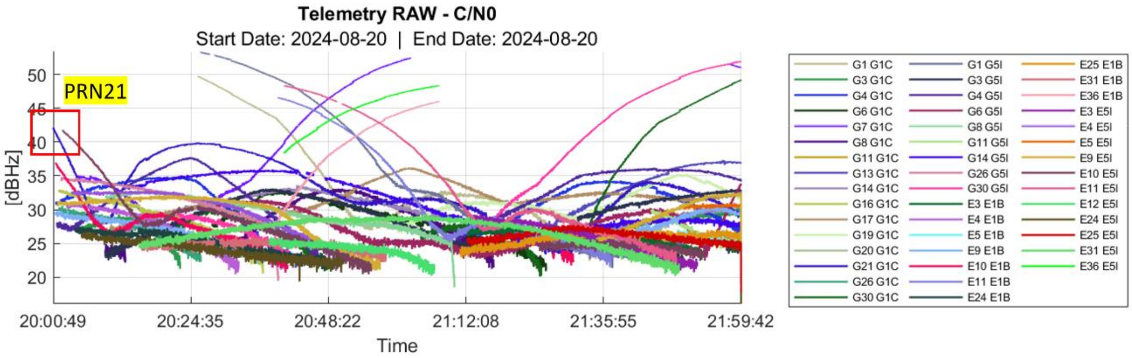


FIGURE 11: *GNSS observables collected by the LuGRE receiver during RF signal simulation at 17 RE.*

4.1.2 GNSS Signal Visibility

Investigation ID	**Investigation Statement**
1-a	Measure the signal strength throughout the mission and empirically evaluate link budget model.
1-b	Determine signal availability throughout the mission.
1-g	Investigate signal strength and stability on the lunar surface as compared to similar observations in lunar orbit.

Before navigating with GNSS, you must first receive and track signals. While MMS has collected and processed GNSS signals at altitudes as high as 29 RE [26][27], the signal environment beyond this altitude is unproven and only inferred through simulations that extend the models supported by MMS observations. This leaves a gap of approximately 30 RE up to lunar altitude in which the GNSS signal reception environment is unknown. This environment must be observed and studied before it is characterized well enough to support ambitious plans for future lunar navigation. As described in Section 3.3, the LuGRE concept of operations has been tailored to fill this gap by collecting signals from an altitude of 30 RE all the way to the lunar surface.

Collection of high-altitude signals in this gap will first allow for validation of the on-orbit link budget parameters specific to the LuGRE architecture. When the LuGRE link budget is well characterized, the properties of the observed signals may then be extrapolated to different architectures, predicting what the strength of similar signals could be if using a stronger or weaker antenna or different receiver sensitivity. A high fidelity understanding of available signal strength at high altitude is the first step in modeling the ability to receive signals in the first place.

The relationship between observed signal strength and bulk visibility is well understood to be a direct influence on achievable navigation performance. **FIGURE 12**, from previous studies [28], depicts how signals collected over the duration of the LuGRE mission will reveal trends in signal strength and bulk visibility as a function of altitude up to the lunar surface. These relationships then show how achievable navigation performance, characterized by 3 sigma RSS covariance of a simulated EKF, is directly proportional to the number and strength of the signals used to navigate, seen on the right of **FIGURE 12**. Validating trends such as these with flight data will provide credible evidence of the factors that most impact the ability to effectively use lunar GNSS for spacecraft navigation.

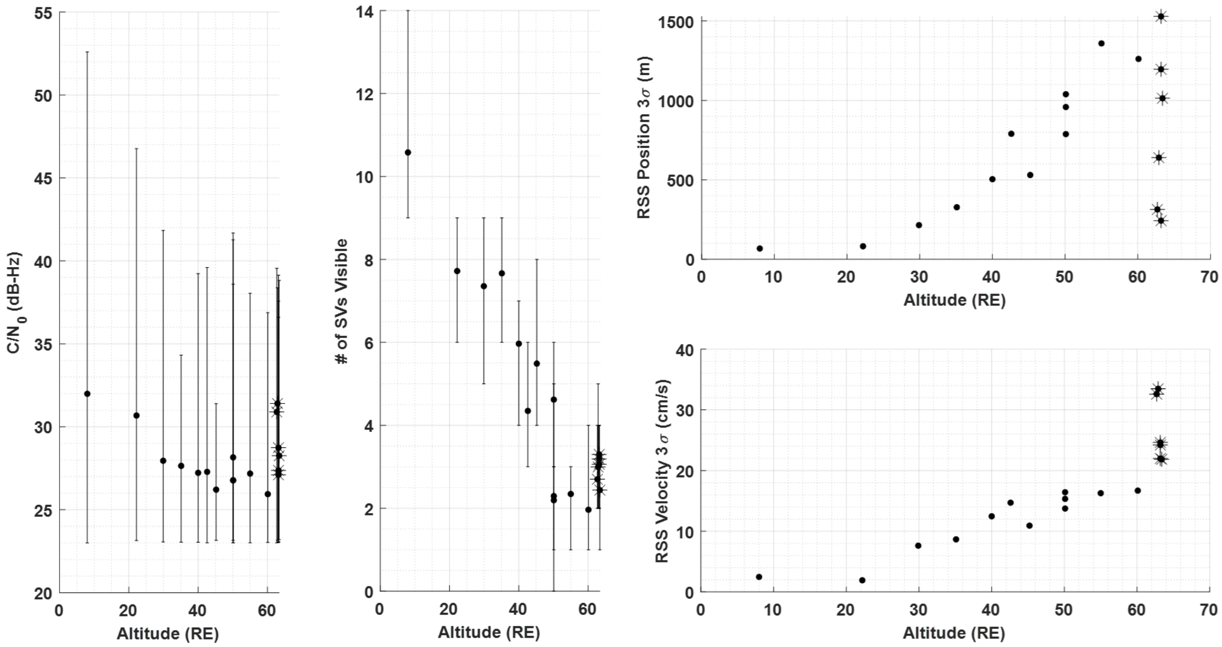


FIGURE 12: *Relationship Between Altitude, Signal Strength, Satellite Visibility, and Resulting Navigation Performance*

Finally, wherever possible, it is important to measure and quantify whether signals received on the lunar surface display degraded strength or different properties as compared to signals collected in lunar orbit. Degradation may be present due to electromagnetic properties of lunar regolith, thermal conditions on the surface, reflections, or even interference from other payloads operating during the surface phase of the mission. If such degradations or differences in signal properties are observed, they should be characterized to better understand the influence that the lunar surface environment has on electromagnetic signal reception and propagation.

4.1.3 Model Calibration

Investigation ID	Investigation Statement
3-d	Calibrate ground models with LuGRE data to enable predictions of achievable navigation performance for future missions.
4-a	Empirically calculate portions of GPS and Galileo transmit antenna gain patterns using available measurements.

When planning a mission that will use high-altitude GNSS for navigation, it is critical to have well-understood and trusted models for anticipated performance. A key factor is the link budget of the system, as the expected availability of signals directly drives the navigation performance of the system. A typical link budget for a GNSS system is shown in Equation 1:

$$ {}^{C}/_{N_0} = P_T + G_T(\phi,\theta) - \underbrace{20\,log\left(\frac{4\pi d}{\lambda}\right)}_{(a)} + G_R(\phi,\theta) - L_{pol} - \underbrace{10\,log\left(kT_{sys}\right)}_{(b)} - R_{loss} \qquad (1) $$

where C/N_0 is the carrier to noise density ratio, P_T is the transmit power of the GNSS signal, G_T is the local transmit antenna gain applied to the signal, (a) is the path loss, G_R is the local receive antenna gain, L_{pol} is the polarization mismatch loss, (b) is the noise temperature loss, and R_{loss} represents miscellaneous receiver losses.

While it is possible for the user to thoroughly characterize and understand their own components in the link budget, such as receive antenna gain (G_R) and receiver losses (R_{loss}), other systemic components such as the transmit side of the link budget must be calibrated in-flight.

Until recently, only limited gain pattern and transmit power data for the GPS and Galileo satellites has been available, preventing users from accurately assessing weak-signal mission performance using those system. Recently however, several data sources have become available. For GPS, ground-tested transmit antenna gain patterns are available for all on-orbit satellites [29], and on-orbit measured data is available from NASA [30]. For Galileo, representative EIRP patterns are available for all on-orbit satellites [31]. However, data remains lacking in regard to GPS transmit power and Galileo per-satellite EIRP.

LuGRE C/N0 data, combined with known transmit constellation and lander data, will allow calibration of the transmit-side and systematic components of the link budget. This calibration will be compared to existing calibrated datasets from other high-altitude missions such as MMS, resulting in a better overall understanding of the weak-signal GNSS link budget in cislunar space.

4.2 Measurement Level Investigations

Investigation ID	Investigation Statement
1-c	Measure pseudorange from visible satellites during all planned operations periods.
1-d	Evaluate pseudorange error from visible satellites during all planned operations periods.
1-e	Measure Doppler shift and Doppler rate profiles throughout the mission.

One of the primary and most critical goals of the LuGRE mission is to demonstrate the feasibility of collecting GNSS measurements at cislunar altitudes. However, the data acquired by the LuGRE receiver will not only verify the ability to collect GNSS measurements at these altitudes but will also provide information about the properties of these measurements to be expected for future missions. This information will enhance existing models and bolster the credibility of simulations that rely on these models. Verifying and understanding these models as precisely as possible with flight data is crucial for near-term lunar missions which have rigorous navigation needs and must choose hardware accordingly to ensure mission requirements can be met [32].

In navigation applications using GNSS observables, understanding their statistical properties is important because these properties directly influence the accuracy of computed navigation solutions. Currently, there are no datasets containing GNSS measurements at altitudes beyond approximately 29 Earth radii (RE). Consequently, models for the statistical properties of pseudorange and Doppler measurements at cislunar altitudes remain unverified and may lack critical effects observable only using flight data. The measurements gathered by the LuGRE receiver will facilitate the augmentation of existing altitude-based models for pseudorange and Doppler measurement noise, extending these models up to and including the lunar surface. These updated models will then lend flight-proven credibility to simulations that predict the navigation performance of future missions in lunar environments.

To achieve these objectives, the LuGRE receiver will record pseudorange and Doppler values alongside onboard clock status, as described in Section 3.4. After the mission, collected data will undergo comparison against ground simulations of the operations scenarios. This process involves analyzing deviations between measured and theoretical values for visible satellites, accounting for user clock biases. These deviations, representing residual errors at specific time instances, will be studied to identify and verify trends related to signal strength and altitude.

An aggregate of these data across multiple LuGRE activities will be studied; pseudorange residuals computed against simulated expectations of these measurements can reveal the amount of noise that is present in the measurements due to receiver hardware and signal strength, particularly as altitude increases. Analyzing the statistics of these trends will confirm existing models for measurement error as a function of C/N0 given the stability properties of the receiver clock. Unmodeled behavior or outliers may reveal the need to perform investigations into additional phenomenon such as multipath or effects due to lunar dust, as discussed in Section 4.4.

4.3 Navigation Level Investigations

Performing navigation is one of the primary reasons a lunar user might want to collect and process GNSS signals in the first place. Understanding what a user may expect to obtain is important for promoting the use of high-altitude GNSS as a feasible and useful type of navigation at the Moon. These investigations aim to use signals and observables collected by the LuGRE receiver to both demonstrate and extrapolate how a typical user near and at the Moon may expect to navigate in their own missions. This includes implementing and studying simpler navigation techniques such as least-squares solutions (where available), more dynamic methods such as Kalman filter based navigation solutions, and more complex ground-based methods such as performing full orbit determination using a set of collected observables across a long period of time. Additionally, users may wish to perform their navigation onboard or on the ground for post-processing; both styles of navigation will be investigated in the context of the specifics of the LuGRE mission, as well as how these takeaways may apply more broadly to the typical user.

4.3.1 Instantaneous Navigation

Investigation ID	Investigation Statement
2-a	Calculate and characterize least-squares multi-GNSS point solutions throughout the mission where sufficient signals are available.
2-e	Compare onboard navigation solutions to external sources of lander state knowledge

The Least Squares (LS) filter is a relatively simple and prevalent filter used to obtain instantaneous PVT solutions, provided four or more GNSS satellites are in view. The Magnetospheric Multiscale (MMS) mission is the highest orbiting mission to demonstrate the use of GPS navigation operationally, and was frequently able to obtain point solutions from GPS signals at 25 RE and acquire signals up to nearly 30 RE [26][33]. Least squares PVT solutions can be used to initialize more complex filters such as the Kalman Filter with an initial state and covariance estimate without the need for ground-based updates. Extending this capability beyond 30 RE to the lunar surface could allow users to factor in more spacecraft autonomy, using GNSS for navigation and reducing dependency on ground-based infrastructure.

The LuGRE receiver can generate LS derived PVT solutions from observed GNSS signals, provided enough tracked signals are obtained at a particular instant in time. The onboard LS algorithms are capable of processing measurements from both GPS and Galileo constellations, as described in Section 3.1, thereby increasing the bulk visibility of GNSS satellites usable by the receiver, which is an improvement over prior high altitude GNSS navigation operations. The GNSS observables processed by the LuGRE receiver are single frequency code pseudorange and carrier phase measurements from GPS L1 C/A & L5 signals and Galileo E1 & E5a signals. This multi-GNSS measurement processing approach will also require and demonstrate the use of the GGTO; see Section 4.4.3. The additional satellites and multi-frequency signals from Galileo and GPS increase the frequency at which least squares PVT solutions can be computed.

The properties of the least squares PVT solutions obtained throughout the mission will be characterized to understand the measurement uncertainty and solution accuracy with regards to the acquired signals and signal environment when they were generated. The PVT solutions will be compared against external sources of the lander state to quantify the measurement accuracy relative to the best-known truth.

One significant influence on least squares solution uncertainty is the Dilution of Precision (DOP) of the signals used for the solution; generally, as DOP increases the uncertainty in the PVT solution increases. The effects of DOP on high altitude GNSS navigation has been explored in prior work; range and clock uncertainties in particular are understood to increase quadratically with altitude and become highly correlated, while lateral uncertainty increases linearly with altitude [26]. Determining the effects of DOP, C/N0, GNSS transmitter state, ionosphere delay, number of acquired signals, and other factors on the PVT solution will help inform the development of receivers and the deployed navigation algorithms for lunar GNSS users.

4.3.2 Onboard Filter Navigation

Investigation ID	Investigation Statement
2-b	Calculate and characterize Kalman filter based navigation solutions onboard throughout the mission.
2-c	Characterize position, velocity, and time uncertainty and convergence properties throughout mission.
2-d	Compute the Dilution of Precision (DOP) metrics from received signals throughout the mission where sufficient signals are available.
3-a	Process GNSS observables (e.g., Doppler, pseudorange) with ground-based tools to predict achievable *onboard* navigation performance.

At high-altitudes, the number of visible GNSS satellites may at times fall below the four-satellite minimum needed for Least Squares estimation to obtain a PVT solution. By incorporating a dynamical model to estimate the future state using an optimal filter such as the Extended Kalman Filter (EKF), PVT solutions can be continuously obtained even when full observability of the receiver state is unavailable. For this reason, the LuGRE receiver is designed to demonstrate onboard real-time navigation using an EKF to generate position, velocity, time, and carrier phase ambiguity estimates from observed weak GNSS signals in the vicinity of the Moon and on the lunar surface.

The EKF onboard the LuGRE receiver is a standard optimal filter with the addition of pre-configured dynamics models for different phases of the mission. Four dynamics models vary the fidelity of the Earth gravity model used in the filter depending on the operating altitude in transit and whether the receiver is located on the lunar surface. The transit phase dynamic model thresholds occur at 0 - 9000 km, 9000 – 50,000 km, and above 50,000 km. A cannonball solar radiation pressure (SRP) model is also built into the dynamics. The receiver clock is modeled using a first order clock model with a zero-derivate clock bias rate and process noise. The internal measurement model is based on the GRAPHIC measurement combination method to mitigate ionospheric delays.

The LuGRE EKF architecture has been designed to allow for in-flight reconfiguration of the receiver as properties of the filter and GNSS observables are observed throughout the mission. This permits flexibility in tuning the initial state and noise covariances used in the filter, as well as updating dynamics models, Earth Orientation Parameters, and other model parameters that influence filter performance. As the mission progresses and the noise environment at high-altitude is better understood, the measurement noise model and initial covariance matrix can be modified to optimize filter performance.

In transit, the 1-hour science periods described in Section 3.3 will pose a challenge for the onboard EKF, particularly at higher altitudes where bulk visibility of GNSS constellation is lower. Several factors will affect the performance of the filter; some are well understood and can be addressed prior to launch, while others will have to be managed and responded to in-flight. For example, the poor DOP of high-altitude GNSS measurements is well understood from prior high altitude GNSS navigation work, and is an inherent challenge for operating in this regime. Challenges related to hardware choices are specific to the receiver design and are more controllable; for example, testing has been performed on the ground to characterize the LuGRE receiver clock and obtain a model of the clock behavior, as shown in FIGURE 3 [19]. A significant unknown the LuGRE mission will address is the GNSS signal environment beyond 29 RE. While MMS data has been used to extrapolate the noise environment beyond 29 RE [34], any unexpected properties observed in-flight, as described in Section 4.2, may require tuning the filter to reflect the observed measurement noise characteristics and improve the filter convergence. The lunar surface phase of the mission will offer longer periods of payload real-time operation mode than during transit. As discussed in previous work, the measurement cadence on the lunar surface has been selected to optimize performance within data downlink volume allocations, balancing both science data-return needs and navigation performance needs [19].

As described in Section 3.4, EKF telemetry is produced by the receiver whenever at least one GNSS signal is tracked in real-time processing mode. The EKF solutions collected in-flight will be analyzed to characterize uncertainty and filter convergence properties as compared to external sources of the true lander state, such as the definitive lander states produced by the Firefly Orbit Determination team. In addition to analyzing the performance of the onboard EKF, raw weak signal GNSS observables will be downlinked for further processing with ground-based tools to predict achievable onboard navigation performance with other flight-like filter architectures, such as the Goddard Enhanced Onboard Navigation System (GEONS), an EKF-based navigation software package with decades of flight heritage.

Filter solution uncertainties and convergence properties will be characterized over transit operational windows and on the surface to evaluate the relationship between the signal environment and filter performance. The outcomes from other investigations described in this paper, particularly those on signal and measurement properties, can help reveal key environmental factors during each operational window, such as signal C/N0, DOP, number of tracked signals, signal frequency, and constellation signal mixture. Additional effects such as filter measurement rate on the surface, stability of convergence, or per-axis navigation accuracy, will be studied. The results of these analyses will support the development of future lunar GNSS receivers and navigation schemes and inform expectations for cislunar navigational performance under a wide variety of scenarios and contexts.

4.3.3 Postprocessed Orbit Determination

Investigation ID	**Investigation Statement**
3-c	Process GNSS observables (e.g., Doppler, pseudorange) with ground-based tools to predict achievable *ground-based post-processed* navigation performance.
4-b	Evaluate accuracy of lunar surface solution compared to and augmented by NGLR measurements

GNSS observables collected over the length of the mission will be processed on the ground with ground-based tools to predict achievable post-processed navigation performance. Ground-based data processing techniques, algorithms, and methodologies will be applied to this data to obtain higher quality solutions than the real-time onboard navigation algorithm. Approaches such as pruning of data outliers, smoothing filtered solutions, combining with overlapping tracking pass data, trading combinations of GNSS frequencies, constellations, and observables will be explored to achieve higher solution accuracies. The limited operational time windows in transit may prove challenging for the onboard filter to converge sufficiently at higher altitudes. The GNSS data from these operational windows can be combined across multiple operations through an approach such as Batch Least Squares to obtain a higher quality orbit determination solution. This methodology, in tandem with data pruning and observable trades, can also be applied to the GNSS data collected during the long span operations on the lunar surface.

Augmented navigation solutions may also be obtained and studied by utilizing measurements collected by other sensors simultaneously with LuGRE operations. For example, the Next Generation Laser Rangefinder (NGLR) instrument is an additional payload onboard BGM-1, demonstrating technology that is capable of producing range measurements with millimeter-level accuracy [25]. Combining these high accuracy range measurements with the GNSS observables collected by LuGRE presents a valuable research opportunity for demonstrating advanced cislunar navigation, particularly due to the known range bias that arises when using high-altitude GNSS solutions alone. Similarly, Firefly has planned support for near-continuous tracking from the Swedish Space Corporation for BGM-1. Incorporating range and Doppler observables from this tracking data provides the opportunity to further augment navigation solutions, demonstrating a more robust approach to performing navigation that is available to near-term space-based GNSS users.

4.4 Opportunistic Science Investigations

During the investigations discussed above, interesting behavior may be observed that can provide insight into other phenomena that isn't directly related to navigation or GNSS use. Several example investigations are described here. The viability of these investigation is largely unknown until flight data is collected, but they are proactively identified so the mission design preserves the opportunity for further study if at all possible.

4.4.1 Lunar Dust

Investigation ID	Investigation Statement
4-c	Assess the effects of lunar dust environment on GNSS signal strength.

Apollo-era robotic spacecraft missions, including Surveyor-7 and the Apollo human spaceflight missions, observed a "Horizon Glow" above the lunar surface, attributed to dust being levitated above the lunar surface via electrostatic charging. The electrostatic charging is postulated to result from interactions with the local plasma environment (nightside) and electrons discharged from solar ultraviolet and x-ray emissions (dayside). Scientific dynamic "fountain" models have been presented [62] which depict how sub-micron dust particles are able to rise to ~100 km above the lunar surface and then fall back to the surface, dependent upon solar lighting conditions and localized shadowing. With these particles composed primarily of FeO, temporal changes in GNSS signal strength can be expected on the lunar surface as the sun proceeds from rising to setting. Since lunar dust particle motion is also impacted by local shadowing effects, GNSS signals traversing through these shadowed areas are expected to exhibit different signal strength properties than GNSS signals that are not shadowed.

This investigation has the potential to support both planetary science objectives (dust propagation modeling and the scope of the lunar ionosphere) and PNT engineering objectives (GNSS link budget impacts). In low lunar orbit, radio occultation soundings as the GNSS signal approaches or moves away from the limb of the Moon can support science investigations on the height and density of lunar dust propagation as well as its contributions to the lunar ionosphere, while also allowing engineers to understand how close to the lunar limb GNSS signals can reliably be employed. On the lunar surface, it will investigate signal strength and stability from initial landing, i.e., the heavily shadowed early part of the mission, to maximum solar elevation and finally to lunar sunset. If there is an extended mission, it is desirable to continue these investigations into lunar night. Additionally, through lunar surface feature maps, it might also be possible to better understand the transient effects of shadowing on lunar dust rise and its expected GNSS signal degradation. Other studies can investigate post-landing dust settling and dust plumes that might be purposely or inadvertently caused by other payloads. To support this investigation, signals across all frequency bands (GPS L1/E5, GAL E1/E5a) should be collected, at varying points along the lunar day.

4.4.2 Multipath

Investigation ID	Investigation Statement
1-f	Evaluate the presence and, if possible, characteristics of multipath due to the Blue Ghost lander and/or the lunar surface.

Various methods have been employed in GNSS receivers at either the measurement level or the signal processing level to detect multipath, i.e., the signal distortion created by the superposition of GNSS signal replicas with different delays and amplitudes onto the line-of-sight GNSS signals.

At the measurement level, the presence of multipath can be estimated from the pseudorange errors studied in investigation 1-d. A combination of these pseudorange errors and scenario geometry (antenna, spacecraft/lander body, positions of the GNSS satellites) will be used to detect the presence of non-line of sight (NLOS) signals. At the signal-processing level, raw in-phase and quadrature samples may allow for the implementation of multipath detection and identification post-processing techniques. These mostly rely on multicorrelator architectures that can identify signal correlation function distortion at the PRN chip level. These techniques may not be feasible with the anticipated data, however, due to the limited duration and the potential inability to reach a tracking loop steady state.

Other techniques (e.g., [56]) involve averaging the received signal after the tracking loop synchronizes the incoming and local codes. By averaging samples from one code period with corresponding samples in subsequent periods (whether the averaged samples are exactly one code period apart or offset by some fractional chip, i.e., “dithered”), the code itself can be perceived in the time domain. Chip shape distortions can be analyzed to detect the presence of multipath and potentially estimate its properties (e.g., the number of reflections, the amplitude and phase of reflections).

4.4.3 GGTO

Investigation ID	Investigation Statement
2-f	Investigate the benefits of the use of GGTO for high-altitude multi-GNSS navigation solutions.

A chief benefit to using a multi-GNSS receiver in cislunar space is to maximize the number of signals available for inclusion in the navigation solution. However, at lunar distances, visibility maybe limited to only a few signals from a mixture of constellations, in which case the time offsets between constellations cannot be immediately calculated. The Galileo broadcast message contains the Galileo to GPS Time Offset (GGTO) parameter, which contains a ground-estimated value for the time offset between the timescales of these two constellations.

This investigation will experimentally assess the use of the GGTO parameter and demonstrate its value for obtaining multisystem interoperable GPS+Galileo solutions when few satellites of the same constellation are visible. Using the GGTO, a minimum number of four pseudoranges are needed to form an instantaneous least-squared GPS+Galileo solution, instead of five. However, the broadcast value of the GGTO is the result of an estimation process performed on the ground using clock models and real measurements, and it may be inaccurate or outdated. This experiment will obtain least-squares solutions using multi-constellation measurements, considering in particular the meaningful case in which less than four satellites from one of the constellations are available (and then a least squares solution would not be possible using such a constellation only). Comparisons of accuracy can then be done at lunar distance using a minimum set of pseudoranges with the GGTO, versus using an additional pseudorange measurement.

5 FUTURE WORK

BGM1 is scheduled for launch at the end of 2024, with the mission concluding in Q1 of 2025 upon final loss of lander power on the lunar surface. Lower level “quicklook” LuGRE science investigations will be performed prior to and during each operation period to verify as quickly as possible that the data being collected is sufficient to meet science needs and whether plans must be adjusted. The more complex science investigations will be performed in the months following the mission when final lander data (such as definitive ephemerides) is made available to the payload teams. Future papers will present and discuss the outcomes of the investigations defined in this paper.

Outside of the core internal science team composed of members of NASA, ASI, and Politecnico di Torino, an external mission advisory group has been selected. This group is composed of members of the GNSS community who may be able to offer additional insight and perspective just prior to mission operations to ensure that the needs of the broader GNSS science and technology community are being met. As of the writing of this paper, the scope of this advisory group is still being defined.

One of the core tenets of the LuGRE mission is that all data collected over the course of the mission will be released to the public six months after the conclusion of BGM1. Data will be shared and preserved at an archival database to be agreed upon by the NASA TO19D project scientist and the LuGRE science team prior to launch. Each dataset will be assigned a Digital Object Identifier (DOI), allowing researchers and the public to easily reference and cite the data in their work.

6 CONCLUSIONS

Before GNSS usage can be embraced as a widespread and trusted solution for lunar position, navigation and timing, the capability must be proven and well understood at lunar distances. The Lunar GNSS Receiver Experiment (LuGRE) will provide flight data essential for this effort, capturing raw snapshot data and tracking GNSS signals at altitudes higher than have ever been achieved, as well as in lunar orbit and on the lunar surface. The primary objectives of LuGRE are to 1) receive GNSS signals at the Moon, return data, and characterize the lunar GNSS signal environment; 2) demonstrate navigation and time estimation using GNSS data collected at the Moon; and 3) utilize collected data to support development of GNSS receivers specific to lunar use.

Science investigations in support of these guiding objectives have been defined, detailed, and prioritized to assist in development of the LuGRE science program. The definition of these investigation goals and the properties of the inputs necessary for their success serve as guideposts to ensure that as mission requirements develop and the concept of operations evolves, the driving objectives of the mission are upheld and will be fulfilled by the specific plan executed by the LuGRE project.

LuGRE mission data will be made available to the public to aid in analysis and receiver development, including raw IQS data, GNSS observables, and supporting data necessary for understanding the context in which these datasets were collected. Analyses from the defined science investigations will be published for the GNSS and PNT communities, as well as lessons learned that may be useful in aiding future lunar GNSS users in their own implementations.

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