National Aeronautics and Space Administration

# LuGRE

LUNAR GNSS RECEIVER EXPERIMENT

***The Lunar GNSS Receiver Experiment (LuGRE)***

Joel J. K. Parker
LuGRE Principal Investigator
NASA GSFC Code 595

ICG Joint Working Group Session on Lunar PNT
June 25, 2024

# LuGRE Overview


## Mission

- NASA HEOMD payload for CLPS “19D” flight
- Joint NASA/Italian Space Agency mission
- “Do No Harm” class
- Firefly Blue Ghost commercial lander
- Transit+surface observation campaign
- Expected surface duration: one lunar day (~12 Earth days)

## Payload objectives

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.
3. Utilize collected data to support development of GNSS receivers specific to lunar use.

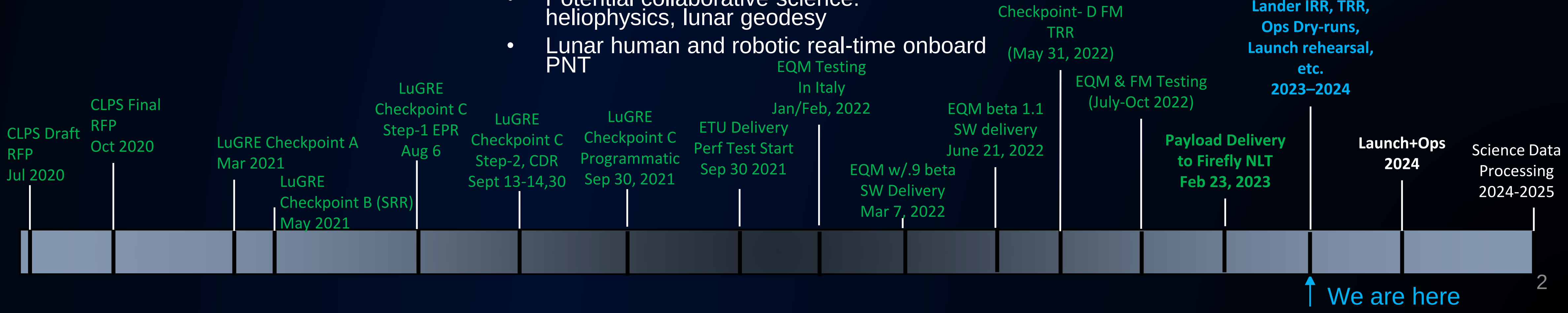
## Measurements

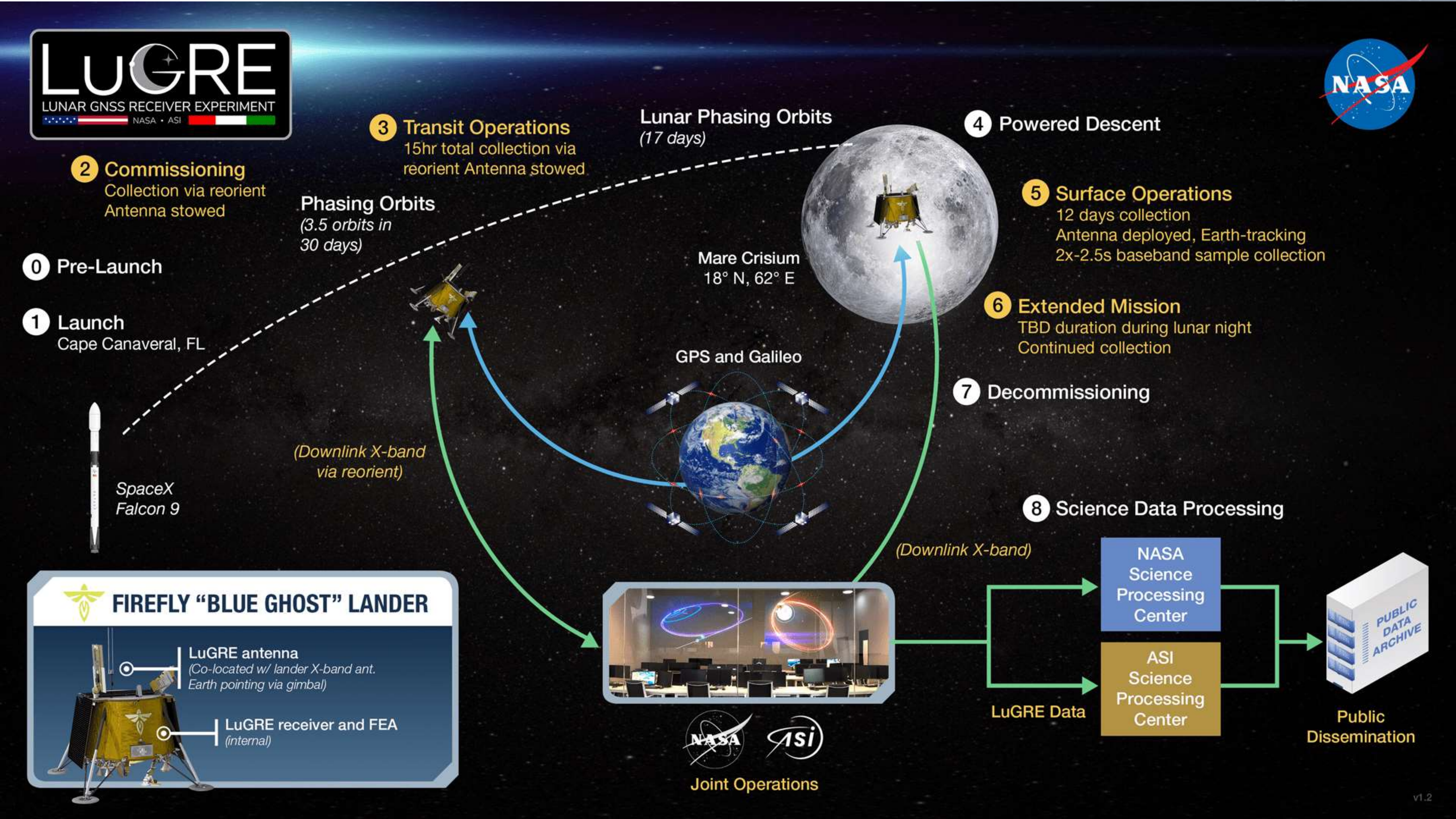
- GPS+Galileo, L1/L5 (E1/E5)
- Onboard products: multi-GNSS point solutions, filter solutions
- Observables: pseudorange, carrier phase, raw baseband samples

## Utilization

- Data + lessons learned for operational lunar receiver development
- Potential collaborative science: heliophysics, lunar geodesy
- Lunar human and robotic real-time onboard PNT







LuGRE
LUNAR GNSS RECEIVER EXPERIMENT
NASA • ASI
NASA
0 Pre-Launch
1 Launch
Cape Canaveral, FL
SpaceX
Falcon 9
2 Commissioning
Collection via reorient
Antenna stowed
Phasing Orbits
(3.5 orbits in
30 days)
3 Transit Operations
15hr total collection via
reorient Antenna stowed
Lunar Phasing Orbits
(17 days)
4 Powered Descent
5 Surface Operations
12 days collection
Antenna deployed, Earth-tracking
2x-2.5s baseband sample collection
Mare Crisium
18° N, 62° E
6 Extended Mission
TBD duration during lunar night
Continued collection
7 Decommissioning
GPS and Galileo
(Downlink X-band
via reorient)
(Downlink X-band)
8 Science Data Processing
NASA
Science
Processing
Center
ASI
Science
Processing
Center
LuGRE Data
PUBLIC
DATA
ARCHIVE
Public
Dissemination
FIREFLY "BLUE GHOST" LANDER
LuGRE antenna
(Co-located w/ lander X-band ant.
Earth pointing via gimbal)
LuGRE receiver and FEA
(internal)
NASA
ASI
Joint Operations
v1.2

# LuGRE Payload

## Payload characteristics

### 1. High-altitude GNSS receiver

- Qascom receiver, GPS+Galileo L1/E1 + L5/E5
- Cold redundant configuration
- Mass: 1.3 kg
- Power: 13 W

### 2. Low-noise amplifier (LNA)

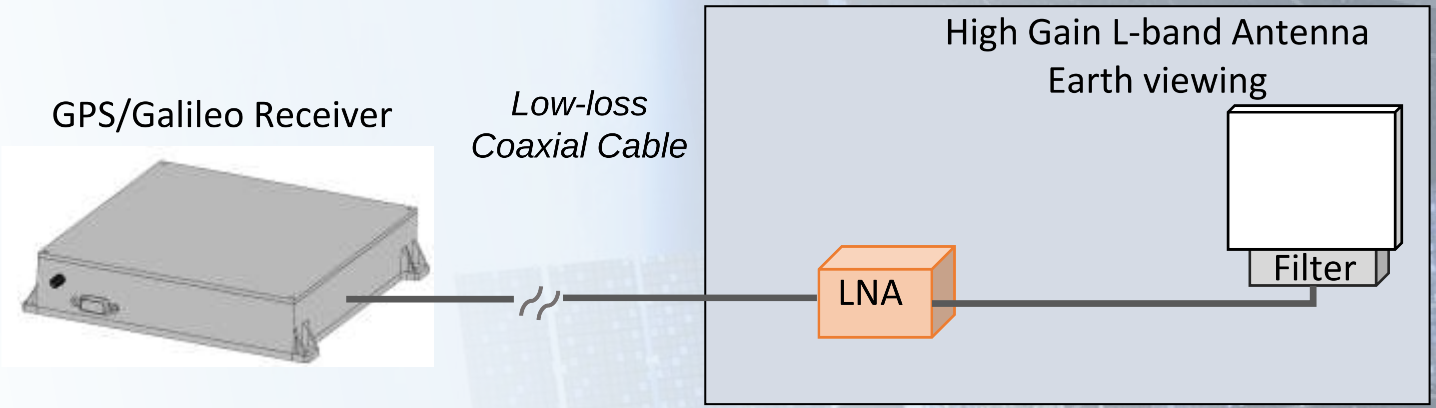
- Mass: 0.85 kg
- Power: 0.7 W

### 3. High gain L-band antenna + Filter

- Requires Earth pointing for GNSS reception
- 16 dBi peak gain, >10deg FOV
- Mass: 2.1 kg
- Power: 0 W (passive)

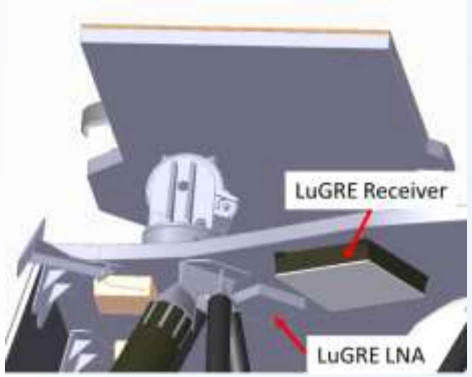
## Total resource allocations

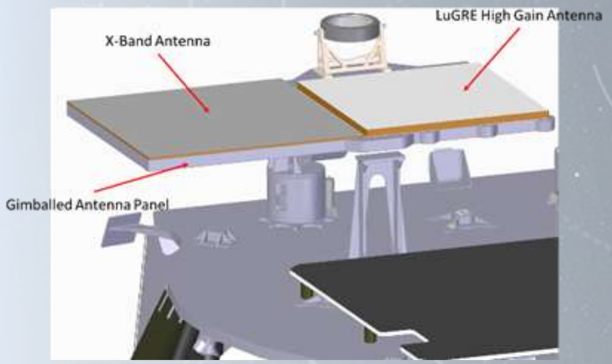
- Mass: 4.64 kg
- Power: 14 W



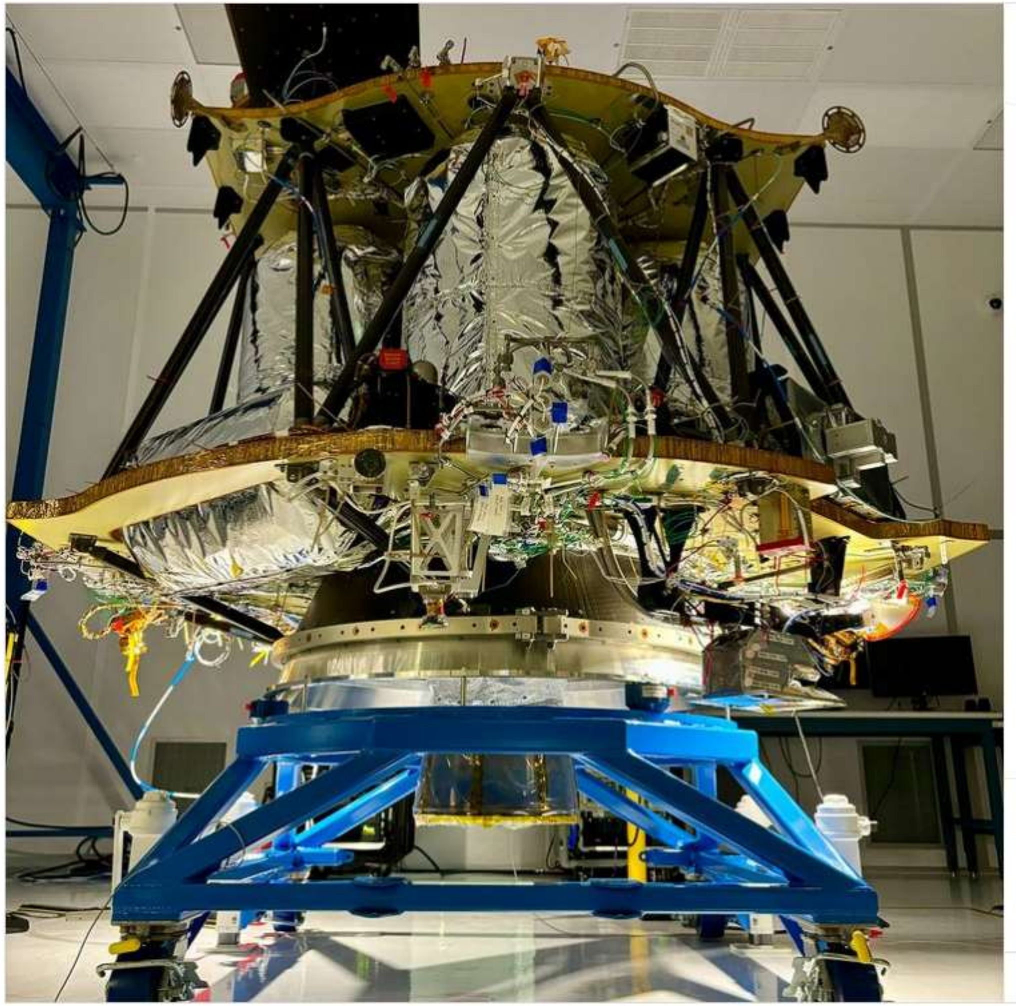

## Operations Concept

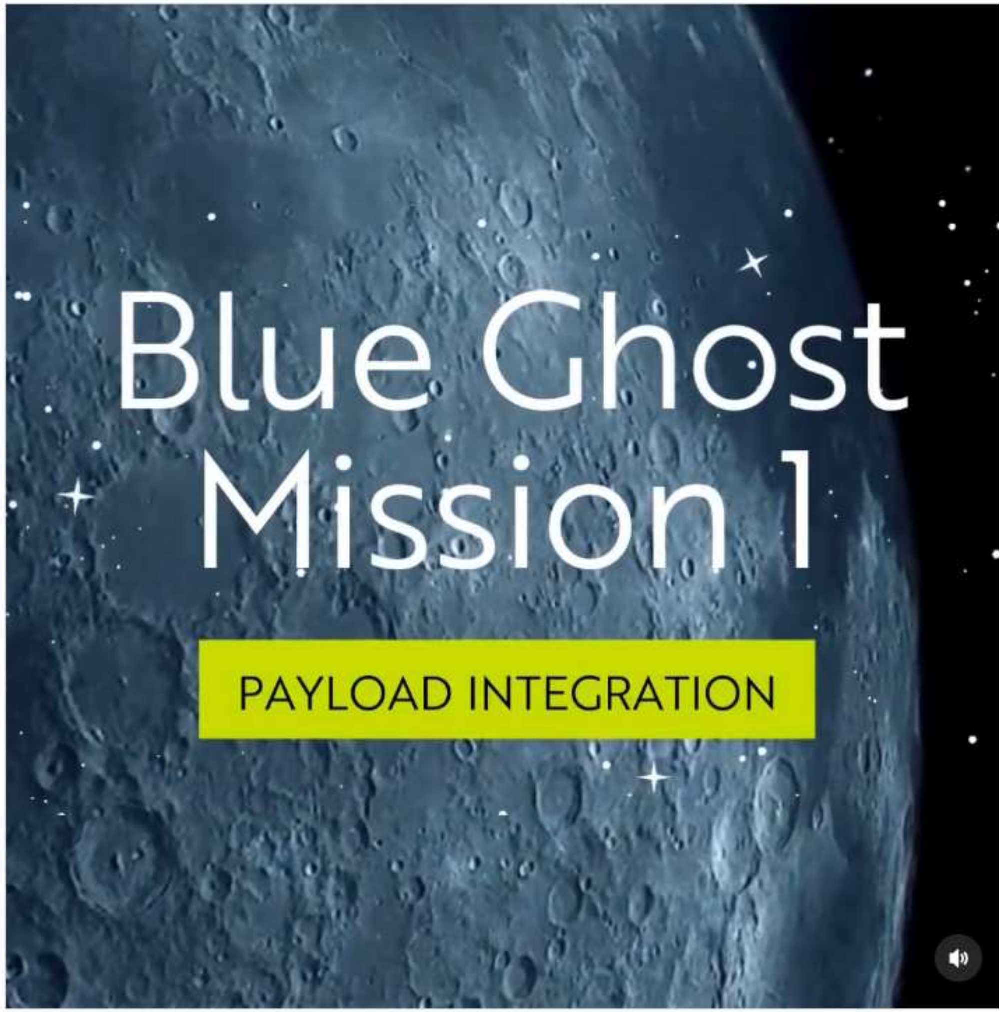
- Transit: checkout, 15hr operations, GNSS measurement downlink
- Surface: continuous operations, GNSS measurement downlink
- Baseband sample collection, <2.5s duration, 2x during surface ops



# Lander Images





# LuGRE Outcomes

| Characterize the GNSS signal environment | Characterize navigation performance | Share collected data | Facilitate adoption of capability |
|---|---|---|---|

**Characterize the GNSS signal environment**

- GPS+Galileo, L1+L5, E1+E5a
- Signal availability
- DOP
- $C/N_0$
- Observables
  - Pseudorange
  - Carrier phase
  - Doppler
- Raw baseband I/Q samples
- Transmit antenna patterns
- Multipath, surface environment

**Characterize navigation performance**

- Point solutions
- Onboard Kalman filter states
- Time to first position fix
- Formal errors, convergence
- Comparison to independent sources (lander, LRR)
- Application of GGTO

**Share collected data**

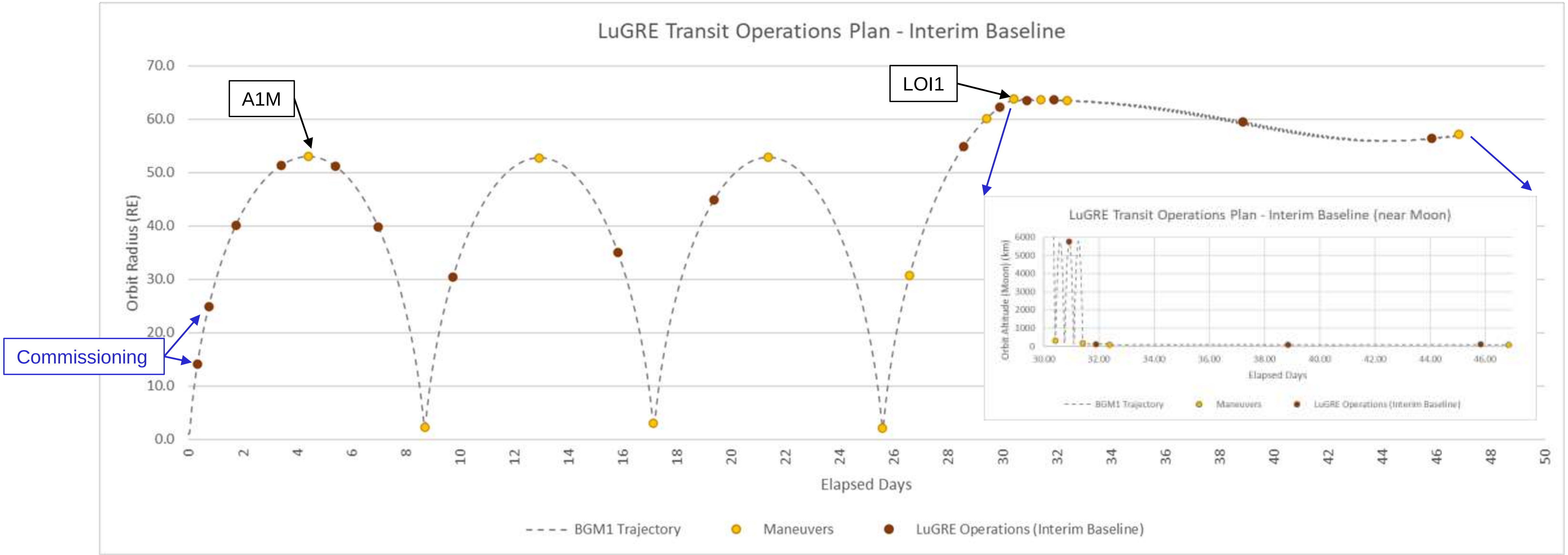
- GNSS receiver developers
- LuGRE science partners
- NASA missions (Artemis, Gateway, science)
- Commercial landers
- International space agencies
- GNSS community
- Science community
- Public

**Facilitate adoption of capability**

- Raw data availability
- LuGRE team reports + papers
- Calibration of lunar GNSS simulation models
- Application to future mission navigation studies
- Lessons learned to GNSS hardware and software developers

*Specific investigations are coordinated via LuGRE Science Team

# Sample Transit Operations Plan

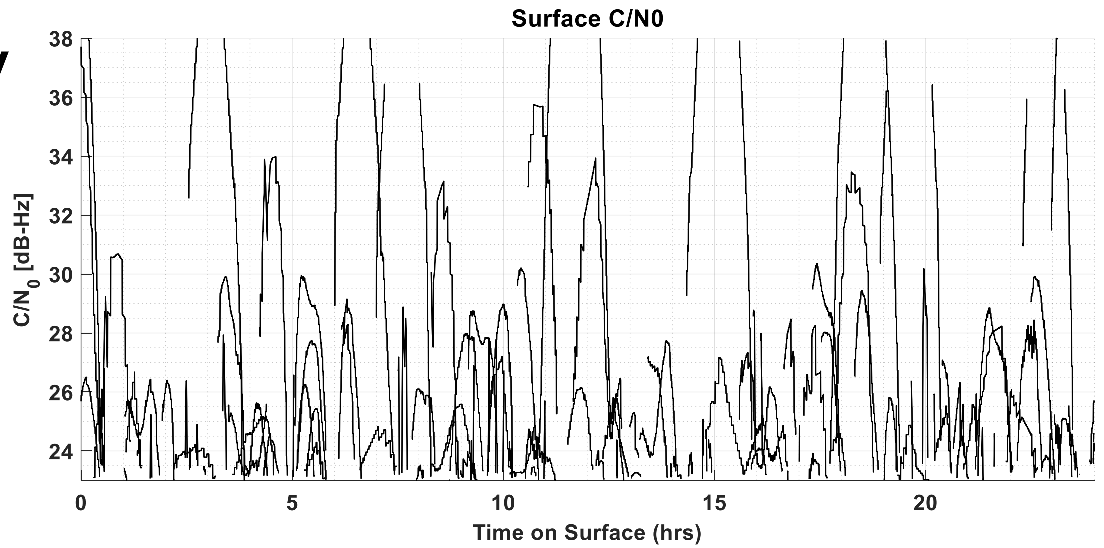


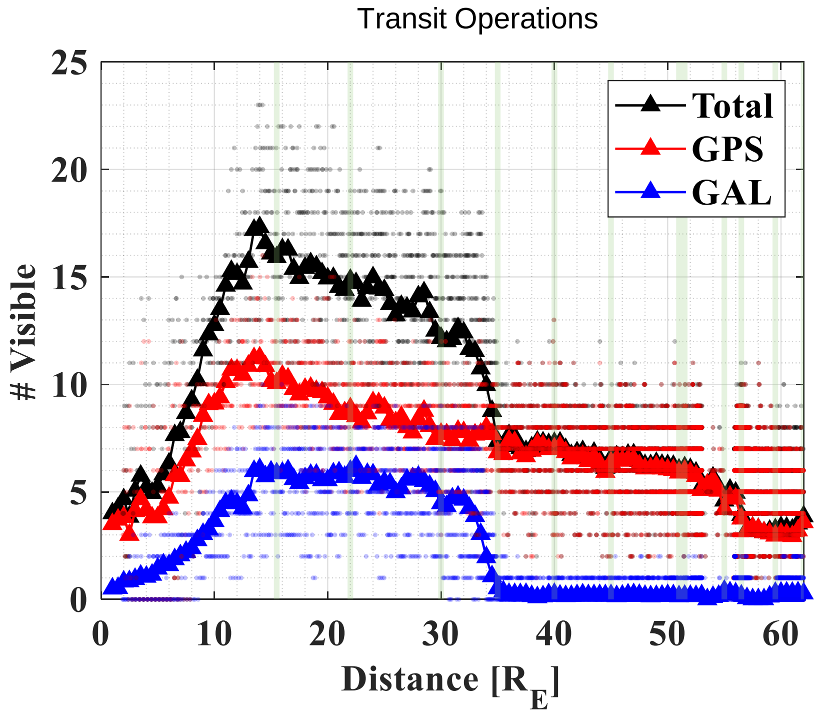

Trajectory as of Oct 2022

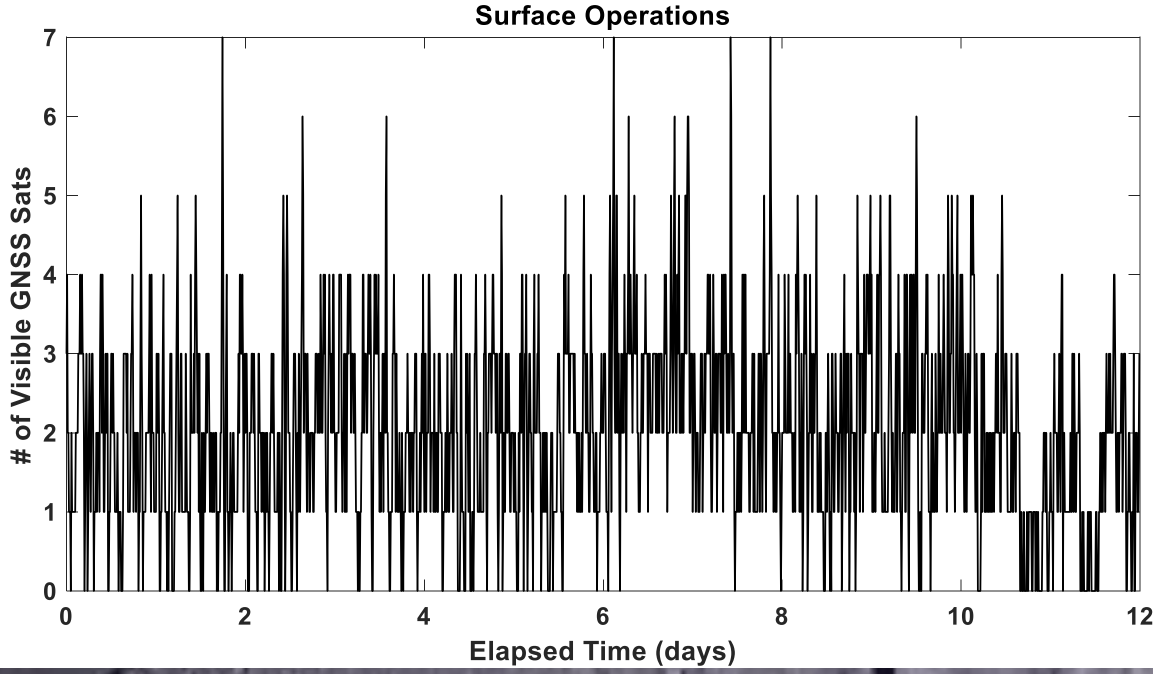
- In transit, Lander must reorient to point LuGRE antenna toward Earth
- Baseline 15x 1-hr opportunities are allowed; more may become available as design matures
- Operations may be single-mode (real-time operations) or mixed mode (sample capture + real-time operations)
- On surface, operations are continuous except 1hr on/1hr off for ±24 hr around lunar noon

# Mission Performance: C/N0, Visibility

- Signal visibility extends to 60+ RE and is available on lunar surface.
- 4+ SV visibility achieved often in transit and at Moon (>10% of time)
  - Indicates occasional point solution availability
- GPS visibility greater than Galileo, likely due to conservative Galileo assumptions
- C/N0 peaks >30 dB-Hz for main lobes, ~26 dB-Hz for side lobes



# Signal Level

**"Obtain signals"**

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

**"Determine the signal strength"**

- Investigation 1-a**: Measure the signal strength** throughout the mission and empirically evaluate link budget model
- Investigation 1-b: **Determine signal availability** throughout the mission.

**"Use that observed signal strength to inform knowledge of other things"**

- Investigation 3-d : **Calibrate ground models** with LuGRE data to enable predictions of achievable navigation performance for future missions.
- Investigation 4-a: Empirically **calculate portions of GPS and Galileo transmit antenna gain patterns** using available measurements.
- Investigation 1-g: Investigate signal strength and stability **on the lunar surface** as compared to similar observations in lunar orbit.

# Measurement Level

**"Get the Measurements"**

- Investigation 1-e: Measure **Doppler-shift and Doppler-rate** profiles throughout the mission
- Investigation 1-c: Measure **pseudorange** from visible satellites during all planned operations periods.

**"Characterize them"**

- Investigation 1-d: Evaluate **pseudorange error** from visible satellites during all planned operations periods.

LuGRE science plan Adopted early 2023

# Navigation Level

**"Demonstrate navigation"**

- Investigation 2-a: Calculate and characterize **least-squares** multi-GNSS point solutions throughout the mission where sufficient signals are available.
- Investigation 2-b: Calculate and characterize **Kalman filter** based navigation solutions onboard throughout the mission.
- Investigation 2-c: Characterize position, velocity, and time uncertainty and **convergence properties** throughout mission.
- Investigation 2-d: Compute the **Dilution of Precision (DOP) metrics** from received signals throughout the mission where sufficient signals are available.
- Investigation 2-e: Compare onboard navigation solutions to **external sources** of lander state knowledge

**"Perform some nav. experiments"**

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

# Unique Analysis

**"Bonus science"**

- Investigation 2-f: Investigate the benefits of the **use of GGTO** for high-altitude multi-GNSS navigation solutions
- Investigation 1-f: Evaluate the presence and, if possible, characteristics of **multipath** due to the Blue Ghost lander and/or the lunar surface.
- Investigation 4-c : Assess the effects of **lunar dust** environment on GNSS signal strength.

**Priority**

- = P1
- = P2
- = P3

Complexity

Processing Levels

# Conclusions

- The Moon is the next frontier in space use of GNSS. NASA is pursuing multiple open, collaborative activities. **The first demonstrations are around the corner.**
- Lunar use of GNSS is enabled by decades of underlying activities to specify the SSV, release relevant data, and coordinate multi-GNSS interoperability. **A continued commitment is essential to support future activities.**
- LuGRE is a joint NASA/ASI project that will demonstrate GNSS-based PNT in transit to the Moon and on the lunar surface, paving the way to future development.
  - **LuGRE will create an initial public dataset with the intention to jump-start development of GNSS-based navigation at the moon.**