Flight Experiences and Results of the Lunar GNSS Receiver Experiment (LuGRE)

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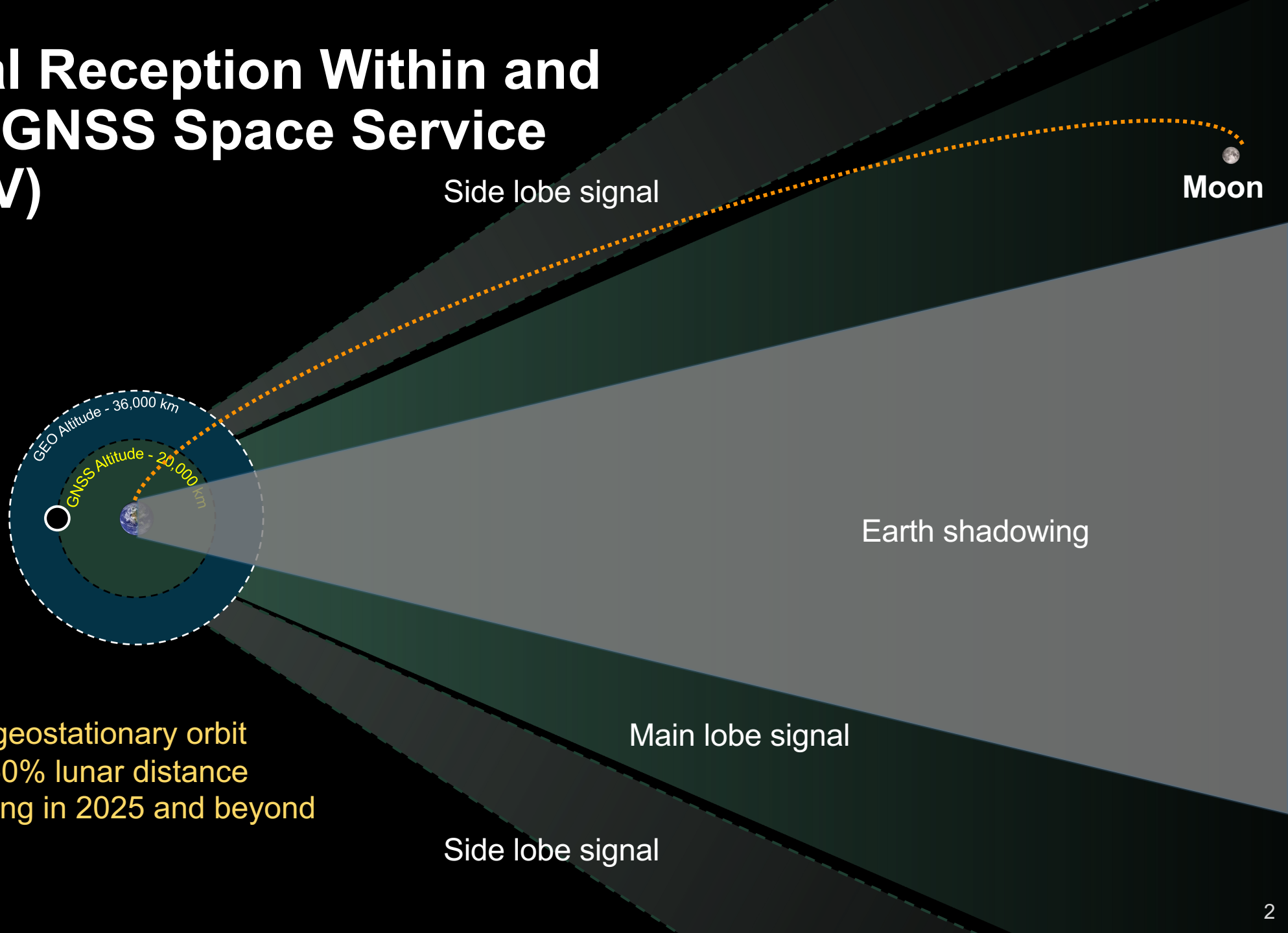
Joint ICG-IOAG Multilateral Cislunar PNT Workshop
12 February 2026

GNSS Signal Reception Within and Beyond the GNSS Space Service Volume (SSV)



Utilization:

- Broad utilization in geostationary orbit
- Active users up to 50% lunar distance
- Lunar users launching in 2025 and beyond

Phased Expansion of Lunar PNT

GNSS-only Lunar demonstrations → **GNSS Lunar Operations** → **GNSS + Lunar PNT Service Demos** → **Broad Infusion**

Relative use of signal sources

Terrestrial GNSS → **Lunar PNT Services (e.g. LunaNet)**

Today — **Time**

Transit use of GNSS and Lunar PNT Services

GNSS Use → **Lunar PNT Use**

Lunar PNT Services (e.g. LunaNet)

Transit Distance

Use of GNSS and lunar PNT services are considered as a key part of the broader navigation ecosystem including ground-based on on-board sources.

Context and Overview

LUNAR GNSS RECEIVER EXPERIMENT

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)
- Observables: pseudorange, Doppler, carrier phase
- Onboard navigation products: multi-GNSS point solutions, filter solutions
- Raw baseband I/Q samples

[Pre-launch plan]

LuGRE
LUNAR GNSS RECEIVER EXPERIMENT
NASA • ASI

0 Pre-Launch

1 Launch
Cape Canaveral, FL

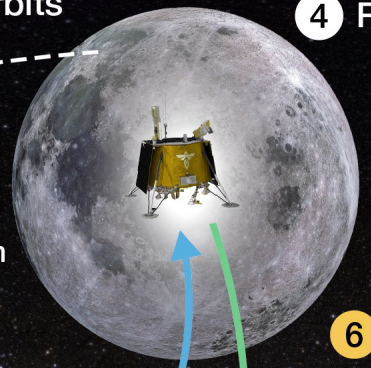
SpaceX Falcon 9

2 Commissioning
Collection via reorient Antenna stowed

3 Transit Operations
15hr total collection via reorient Antenna stowed

Phasing Orbits
(3.5 orbits in 30 days)

Lunar Phasing Orbits
(17 days)



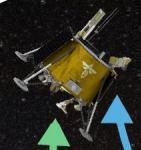
Mare Crisium
18° N, 62° E

4 Powered Descent

5 Surface Operations
12 days collection
Antenna deployed, Earth-tracking
2x-2.5s baseband sample collection

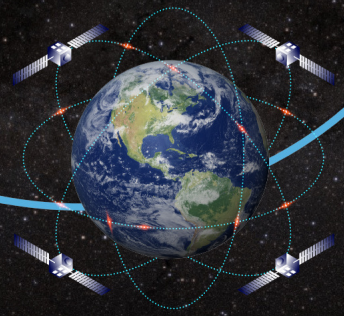
6 Extended Mission
TBD duration during lunar night
Continued collection

7 Decommissioning



(Downlink X-band via reorient)

GPS and Galileo



(Downlink X-band)

8 Science Data Processing

NASA Joint Operations

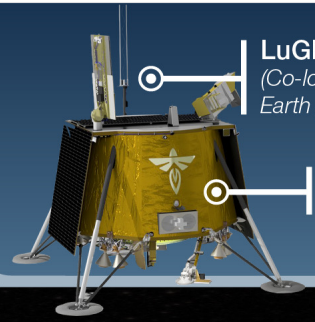
NASA Science Processing Center

ASI Science Processing Center

LuGRE Data

Public Dissemination

FIREFLY "BLUE GHOST" LANDER

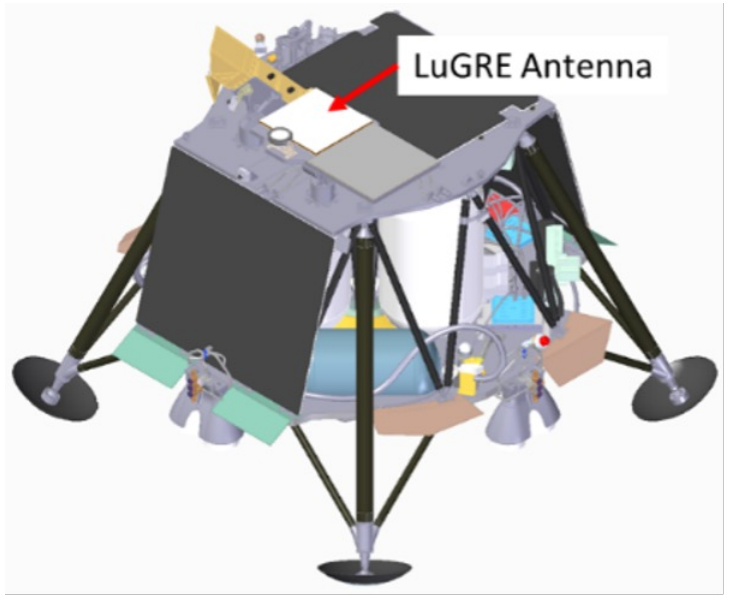


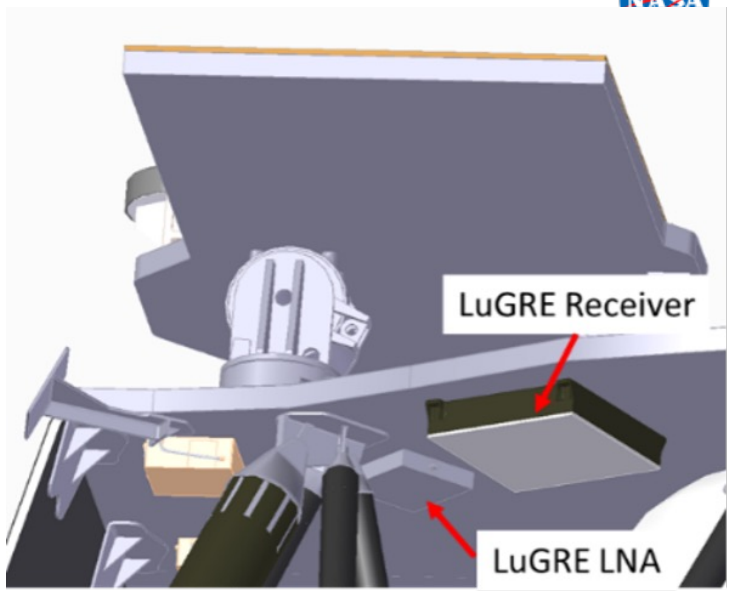
LuGRE antenna
(Co-located w/ lander X-band ant. Earth pointing via gimbal)

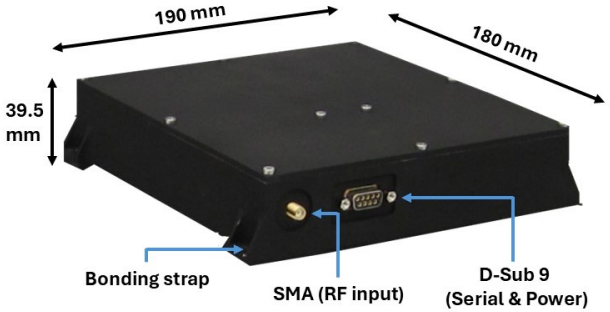
LuGRE receiver and FEA
(internal)

Payload

- Three components:
  HGA → LNA → Receiver
- Integrated separately onto lander
- Total mass: 4.64 kg
- Total peak power: 14 W

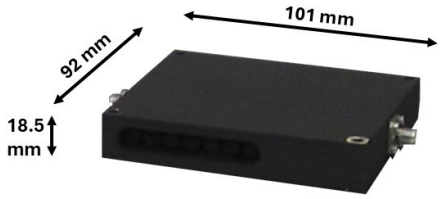






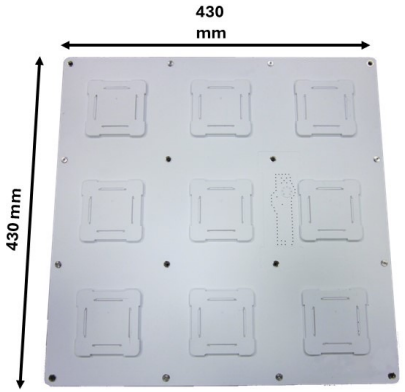
QN400-Space Receiver:

- GPS L1 C/A + L5; Galileo E1BC + E5a
- Mass: 1.3 kg, power: <14 W
- Two cold-redundant receivers
- VCTCXO clock
- Manufactured by Qascom S.r.l.



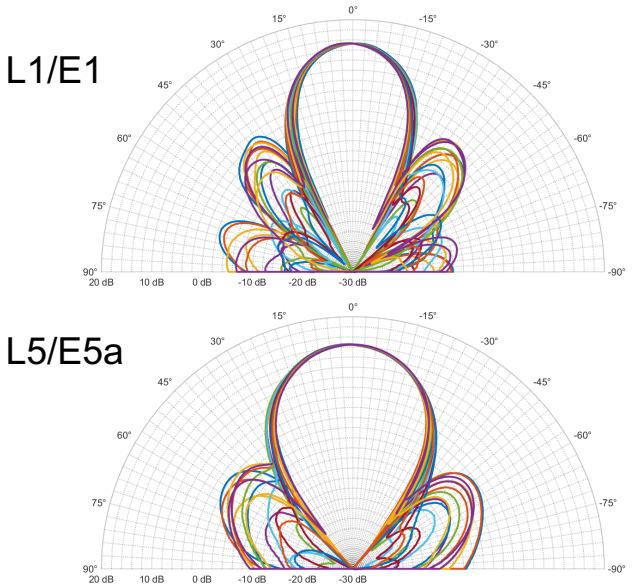
Low Noise Amplifier:

- 40 dB Gain
- ~1 dB Noise Figure
- Manufactured by
  dB Microwave

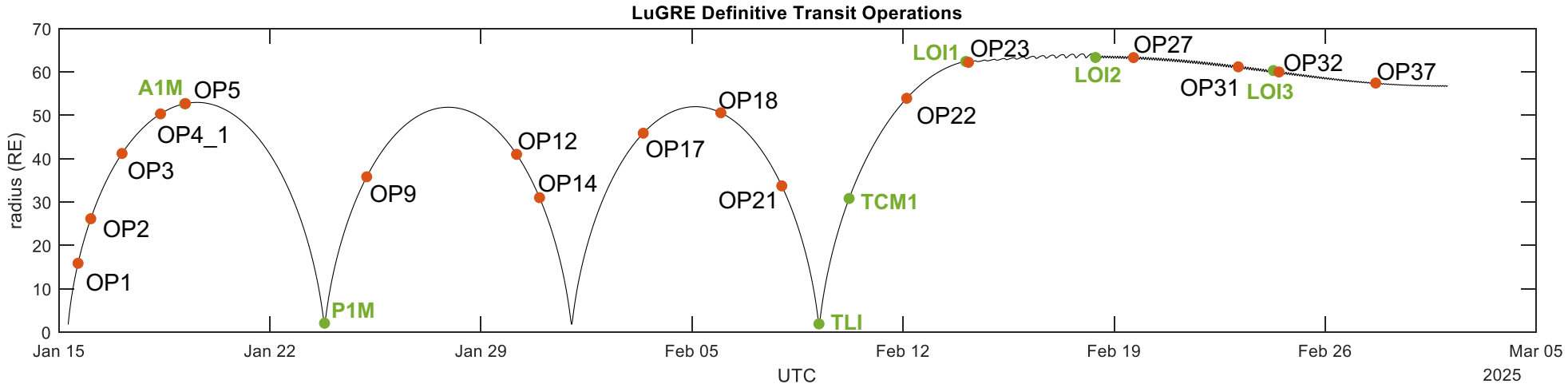


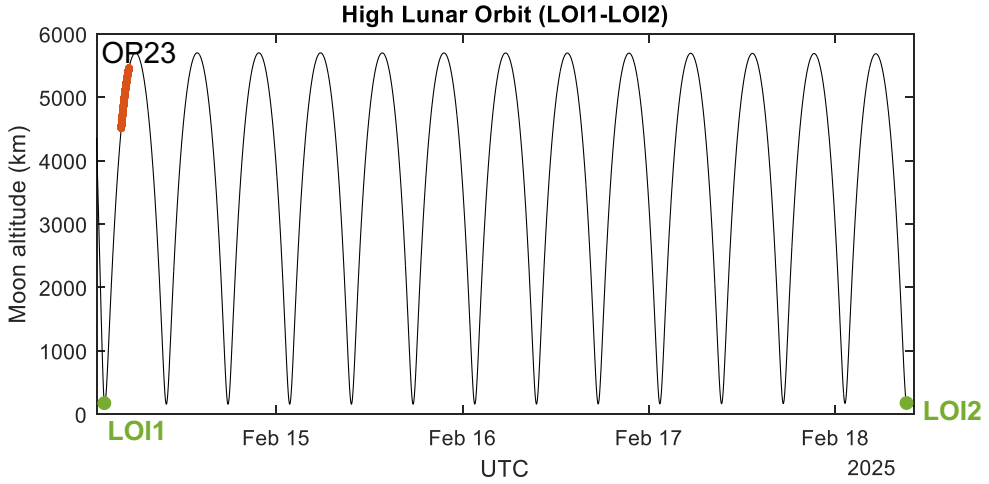
High Gain Antenna:

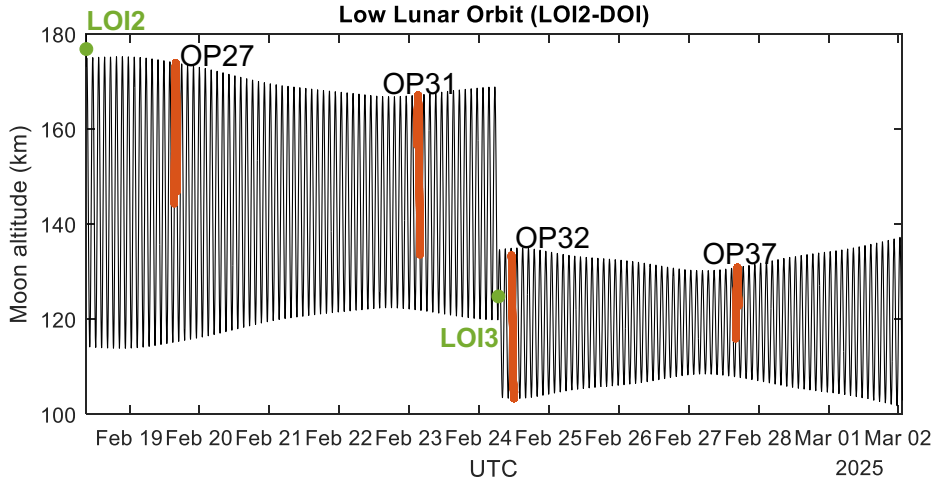
- L1/E1: 15.35 dB, 12° HPBW
- L5/E5a: 14.56 dB, 16° HPBW
- Manufactured by Haigh Farr



As-Flown Operations—Transit



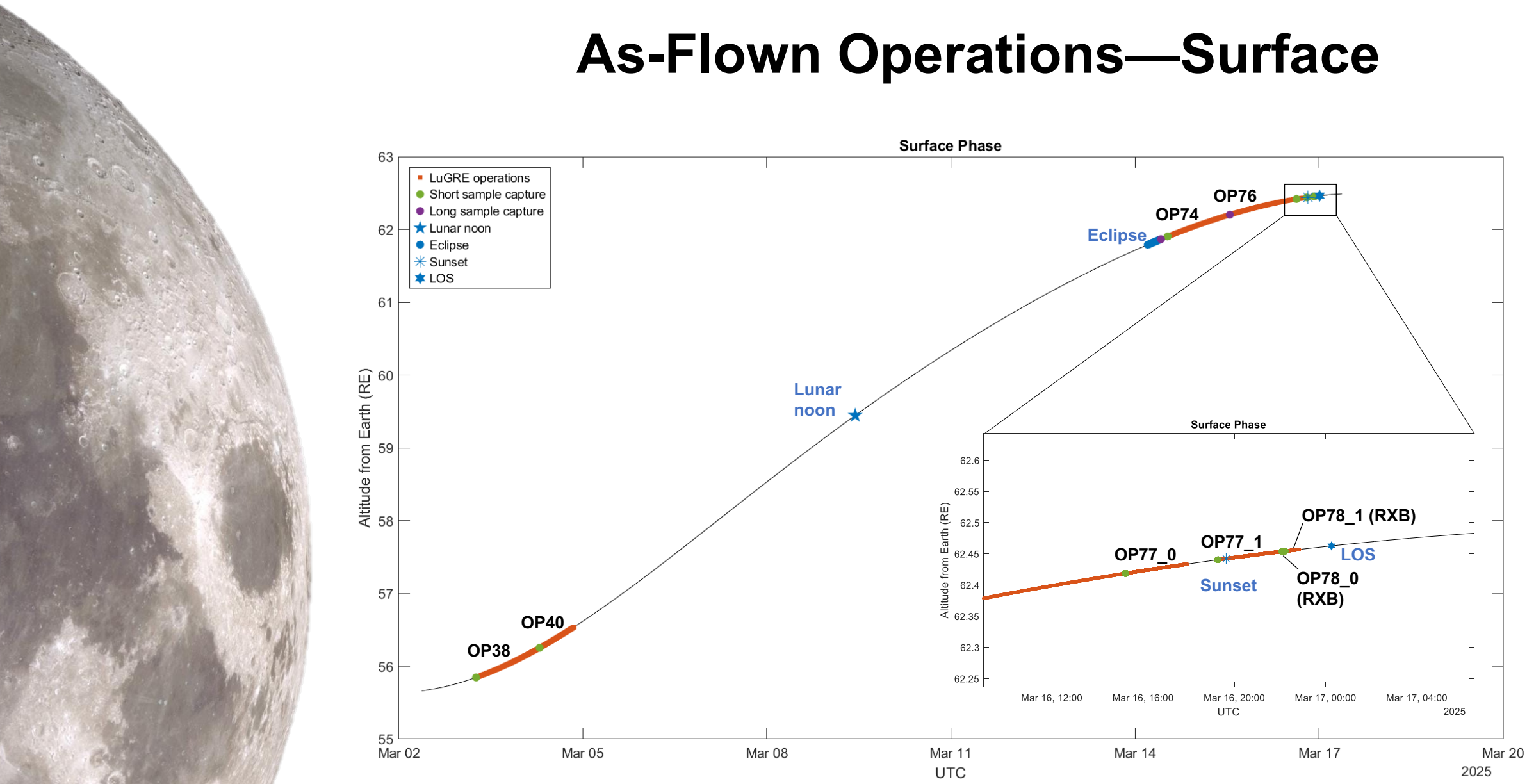




LuGRE operations BGM1 maneuvers

Each transit operation = 1 hr duration

As-Flown Operations—Surface



LOS = loss of signal

LuGRE Mission Highlights

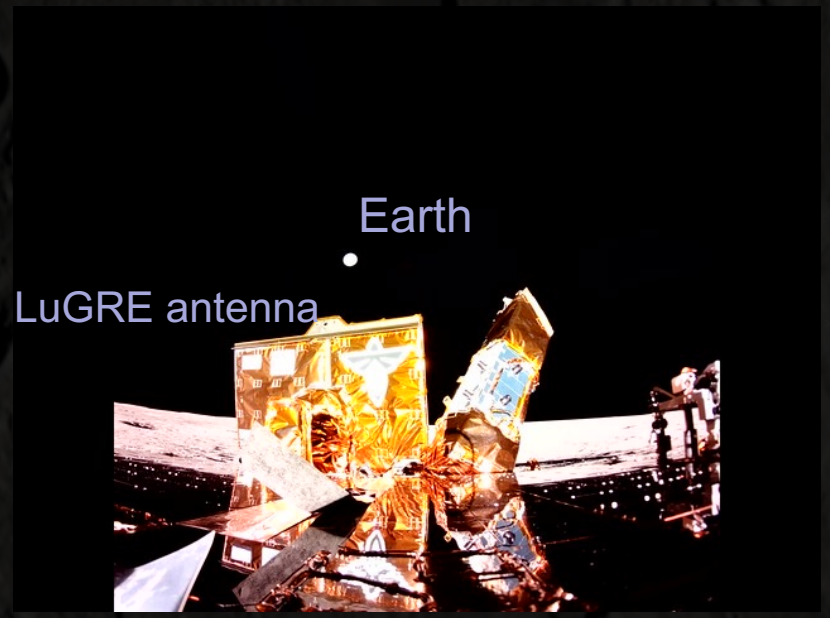
TOTAL OPERATION TIME: >111 hours,
- Operation time on surface: >95 hours (>85%)

TOTAL DATA VOLUME COLLECTED
- Approximately 12s of IQ sample batches
- More than 106 hours of GNSS measurements in real-time processing mode.

16 TOTAL OPERATIONS IN TRANSIT
- 2 during the commissioning phase
- 9 during the Earth-centered phasing loops
- 5 in lunar orbit

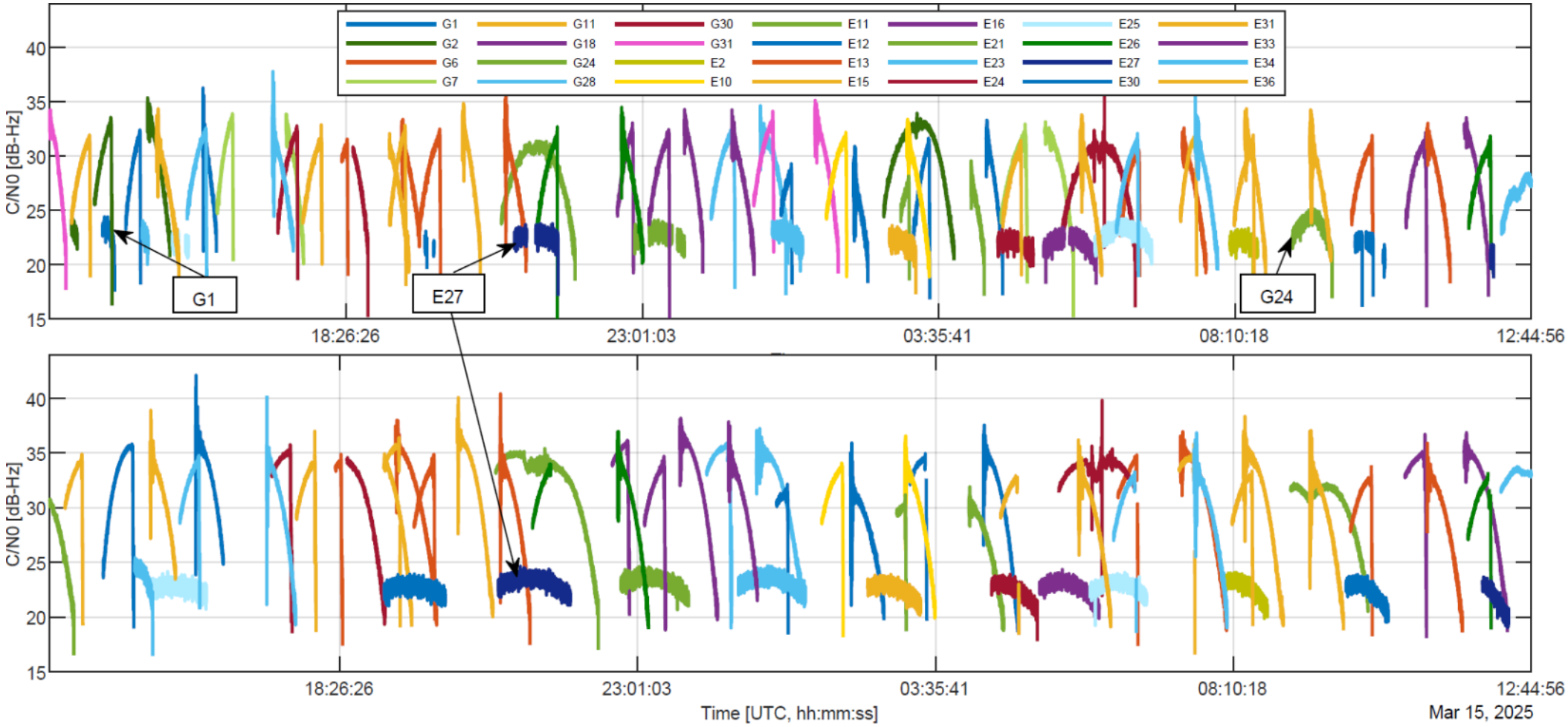
DATA COLLECTED IN TRANSIT
- 14 IQS samples' batches collections
- 14 real-time measurements

SURFACE TIME: 95+ hours
Nearly 93 hours were spent in real-time processing mode.



Results: Signal Strength

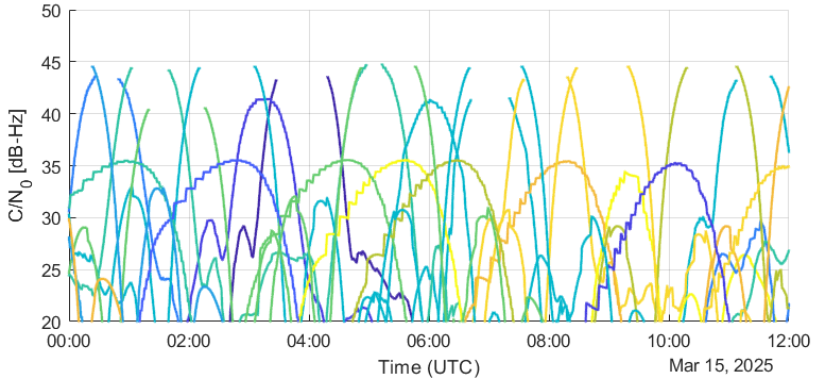
- Plots show received C/N0 for 24hr on lunar surface (61.9 RE alt. and above)
- Mixture of GPS, Galileo, L1/E1, L5/E5a throughout
- Distinct separation between mainlobes and sidelobes



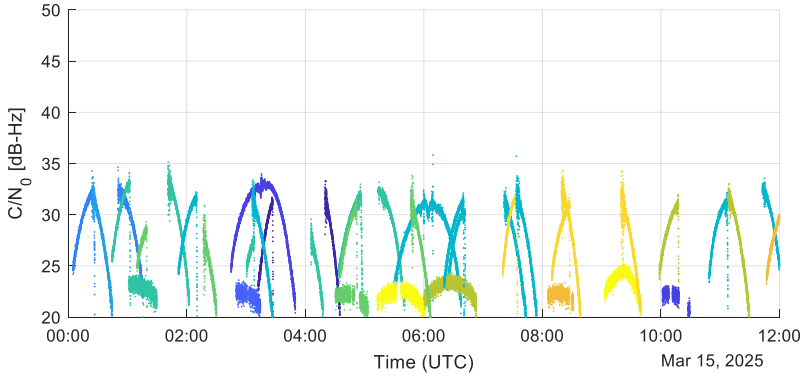
Successful tracking at all altitudes – GPS and Galileo, L1 and L5

Results: C/N0 Level Analysis

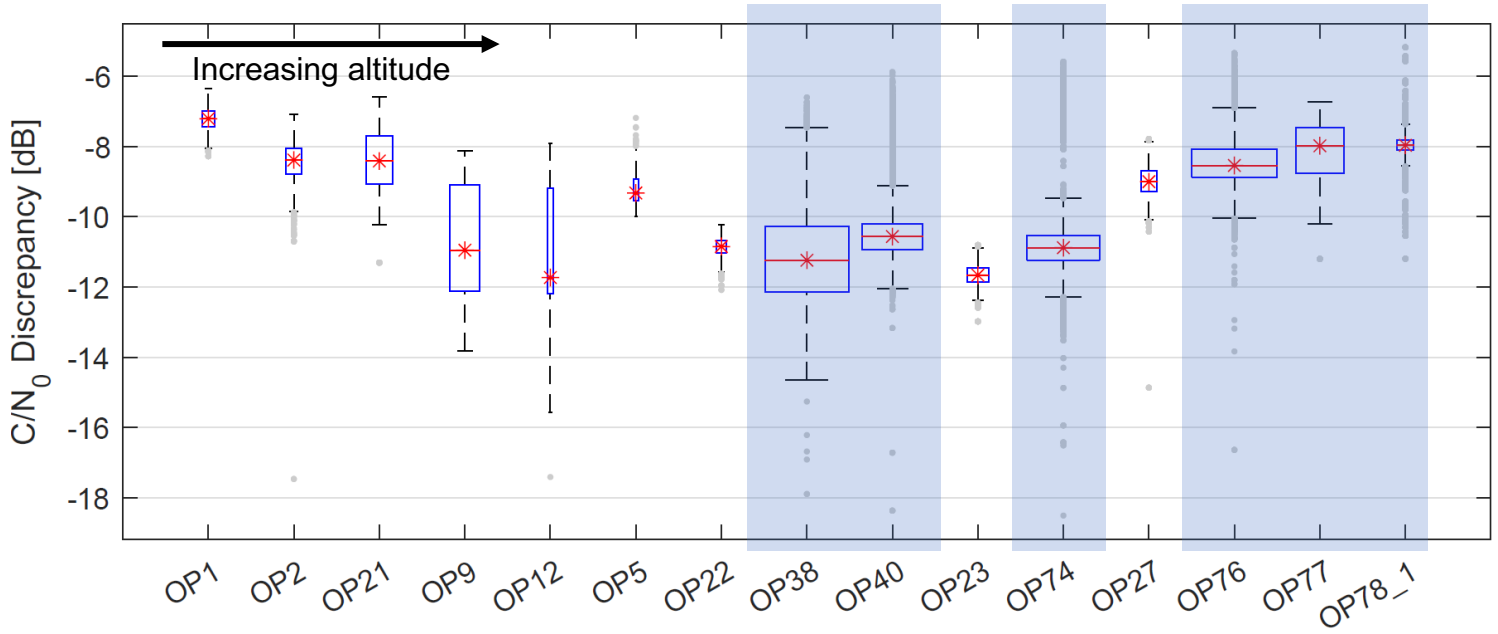
- In-flight C/N0 estimates are lower than predicted by LuGRE planning sim, and lower than literature shows.
- Simulation validated with MMS link budget and flight data
- Characterization of discrepancy focused on best-known EIRP signals: GPS L1 signal, block IIR-M & IIIA vehicles
- Discrepancy is 7–12 dB. No apparent correlation to altitude, temperature, mission phase.
- Root causes are under investigation. Behavior suggests causes related to specific flight system, not inherent to lunar environment.



Simulated



In-Flight

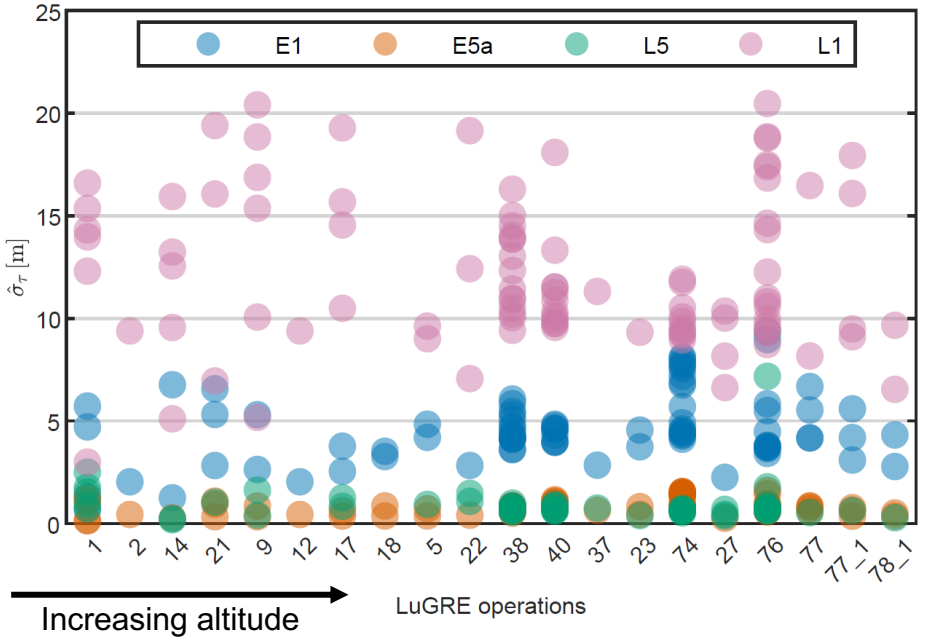


Low C/N0 under investigation.
Data suggests mission-specific cause, not due to lunar environment.

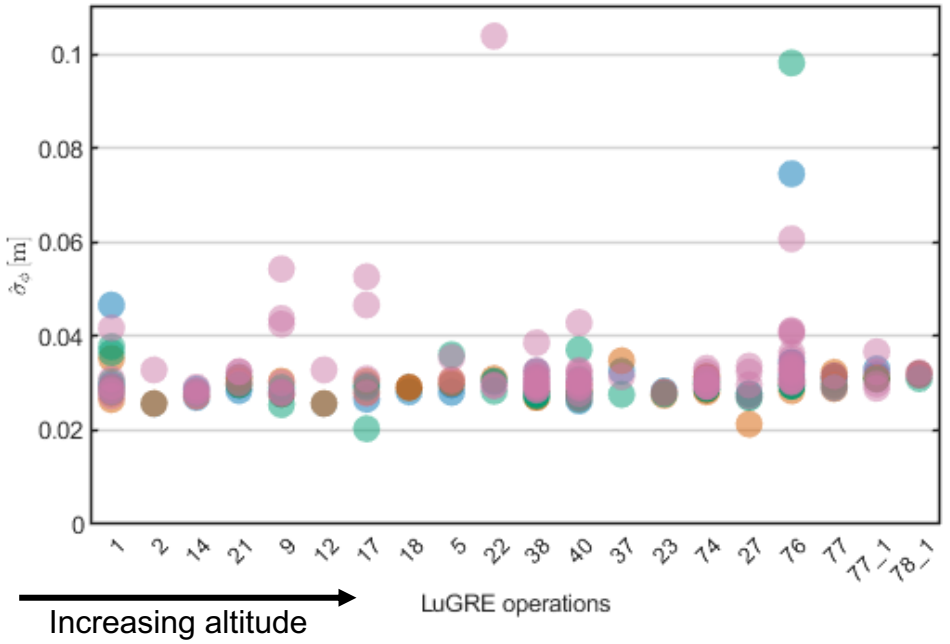
Results: Measurement Quality

- Standard deviation of detrended code and carrier-phase measurements to isolate short-term variations due to receiver noise
- Statistics accumulated for each PRN over full operation window. Correlations to other factors like C/N0 remains to be investigated.
- In general, results show measurement quality in all mission phases comparable to typical terrestrial receivers
- Measurement noise behavior is as expected
  - L5/E5a measurements show lower measurement noise than L1/E1
  - Carrier-phase noise two orders of magnitude less than code measurement noise

Code measurements



Carrier-phase measurements

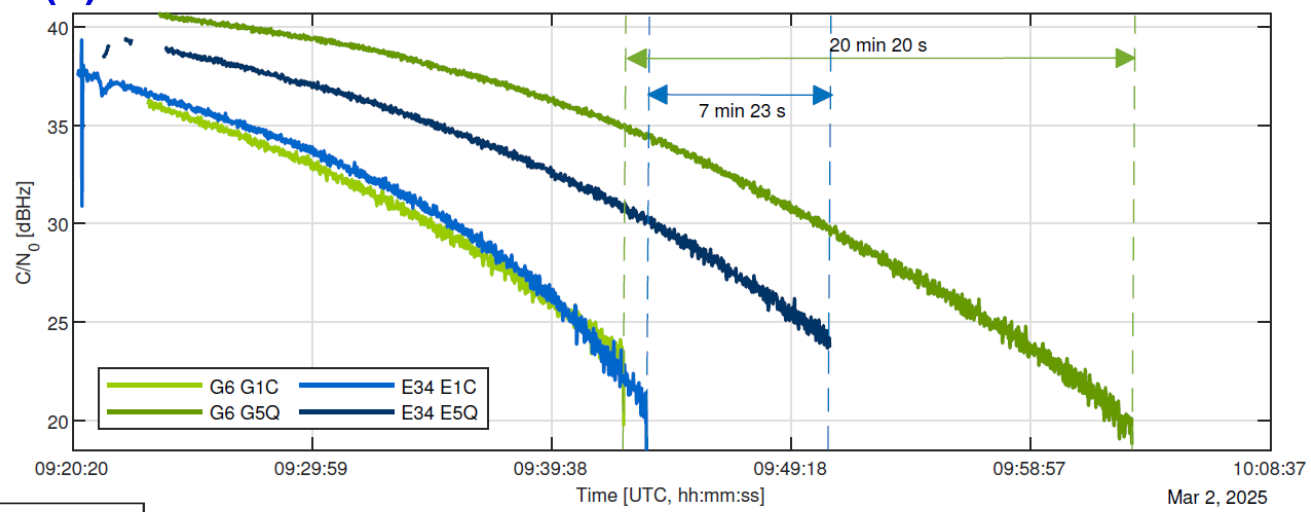


Measurements are high-quality; comparable to typical terrestrial behavior.

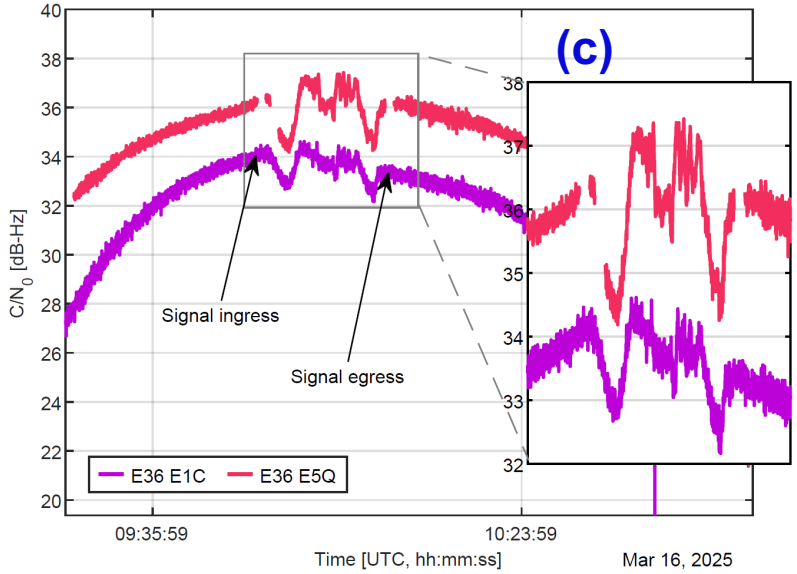
Observations

- GPS and Galileo L1/E1 and L5/E5a signals can be acquired, tracked, and used for navigation at the Moon – using both main lobes and side lobes.
- Measurements are high-quality, consistent with measurements from typical terrestrial receivers.
- L5/E5a offers better C/N0 and longer trackable signals than L1/E1. **(a)**
- Phasing significantly affects main lobe visibility, esp. for Galileo. **(b)**
- Ionospheric signature visible in C/N0. **(c)**

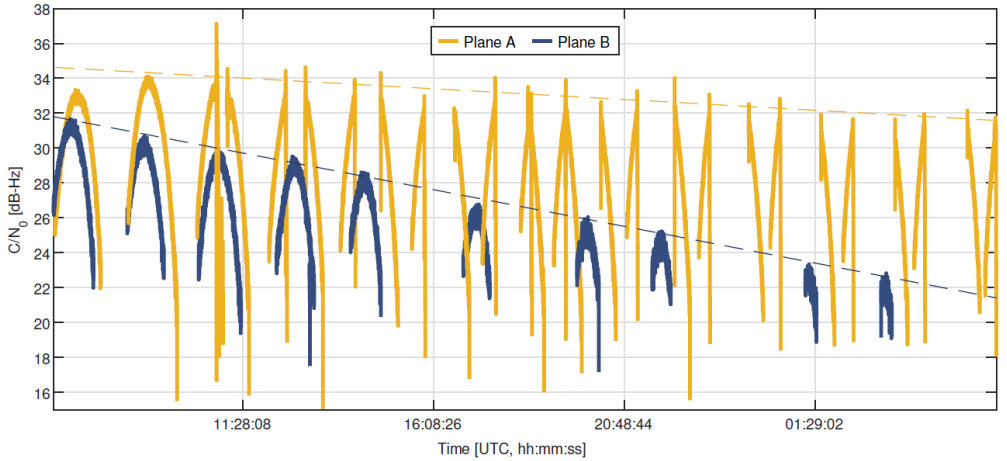
(a)



(c)



(b)



Data provides rich set of observations and lessons learned.

Data Release

- Open dataset now available
- Contents include raw telemetry for acquisition, measurements, PVT solutions, IQ samples, and ancillary data.
- Publication accepted by journal NAVIGATION:

  "GNSS Reception at the Moon: First Results of the Lunar GNSS Receiver Experiment (LuGRE)"

- Link to data: https://doi.org/10.5281/zenodo.16411686

ID	Level[a]	Description	Coverage
TLM_ACQ	L0	Receiver ACQ (acquisition) message, in raw binary and text forms.	All real time processing (RTP) operations, 1 Hz rate
TLM_RAW	L0	Receiver RAW (measurements) message, in raw binary and text forms.	All real time processing (RTP) operations, 1 Hz rate
TLM_NAV	L0	Receiver NAV (least-squares PVT solutions) message, in raw binary and text forms.	All real time processing (RTP) operations, 1 Hz rate
IQS_L1	L0	In-phase/quadrature sample capture binary data, L1 and E1 bands	All sample capture (SC) operations, (variable parameters)
IQS_L5	L0	In-phase/quadrature sample capture binary data, L5 and E5a bands	All sample capture (SC) operations, (variable parameters)
OPTABLE	Ancillary	Detailed operations table	Full mission
ICD	Ancillary	Binary data format ICD	N/A

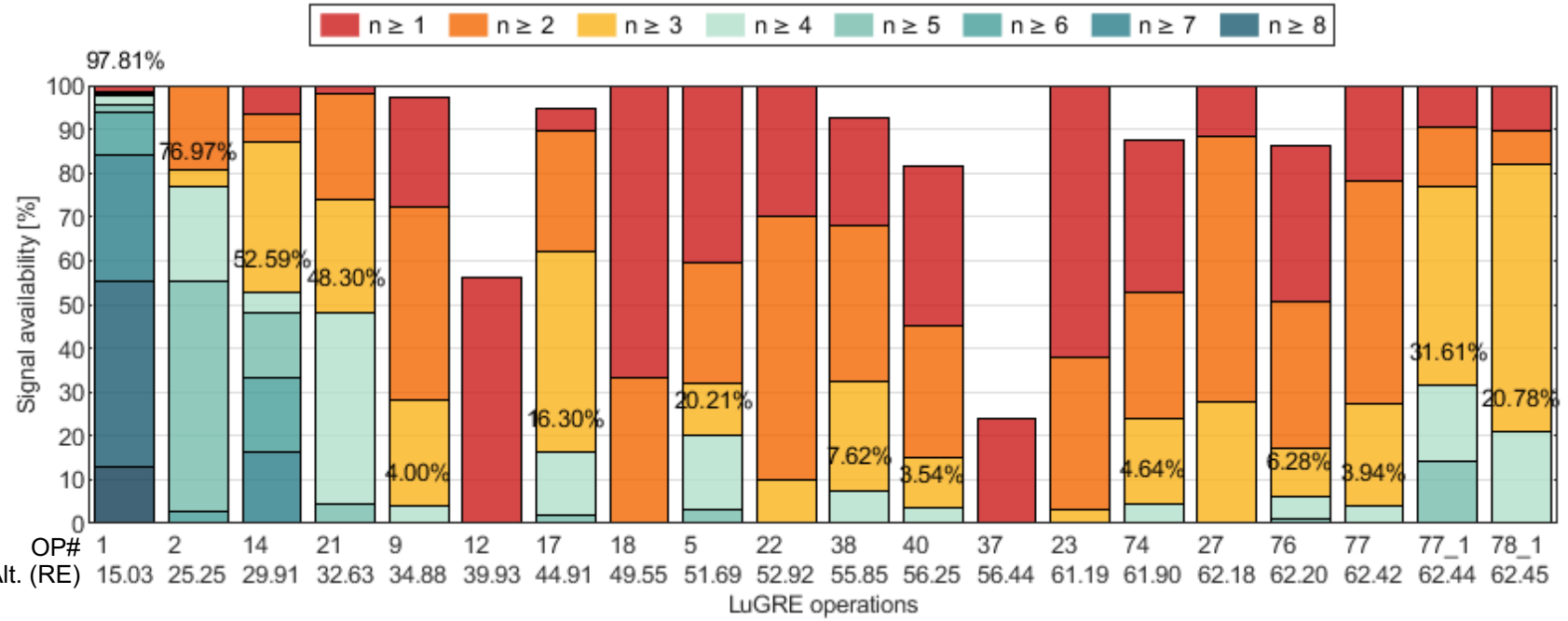
LuGRE initial data products

LuGRE legacy: data and results shared with all to enable the future of lunar GNSS.


Sunset on the Moon from Blue Ghost Mission 1
16 Mar 2025

Results: Signal Availability

- High degree of availability of at least one signal across full altitude range
- PVT availability (4+ unique signals) decreased with altitude, but remained even during long-duration lunar surface operations
- L5/E5a contributed to PVT availability: 1–5% increase in long-duration lunar surface operations



PVT availability (4+ unique signals)

Lunar surface operations

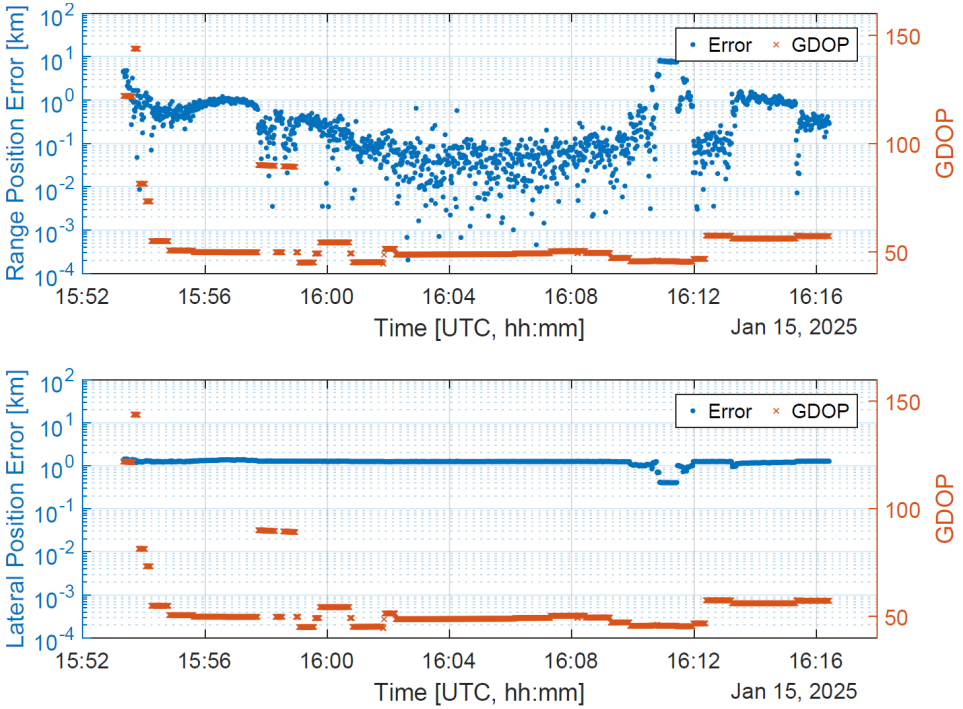
Metric / OP ID	1	2	14	21	12	17	5	23	74	27	76	77	77_1	78_1
L1/E1 (%)	97.81	61.35	0.00	3.70	52.59	0.00	13.10	1.44	1.43	1.43	0.87	3.00	4.09	20.48
L1/E1+L5/E5 (%)	97.81	76.97	20.21	4.00	52.59	16.30	48.30	7.62	3.54	4.64	5.94	3.94	31.61	20.78
Gain (%)	0.00	15.62	20.21	0.30	0.00	16.30	35.20	6.18	2.11	3.21	5.07	0.94	27.52	0.30

Results: State Estimation (PVT)

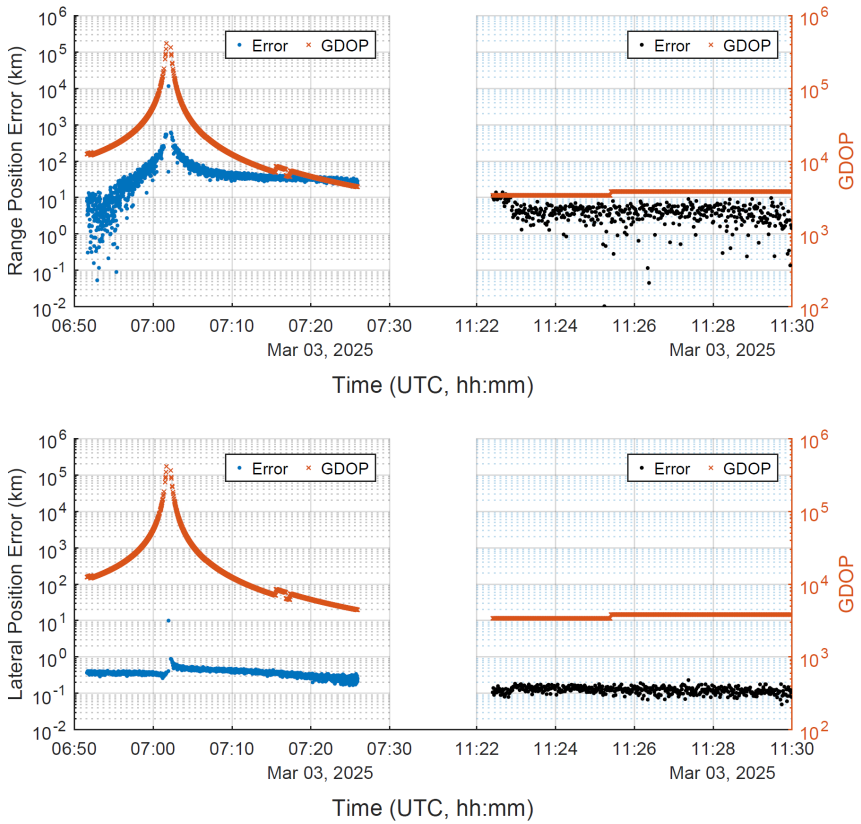
Range position error

Lateral position error (RSS)

15RE alt. (OP1)



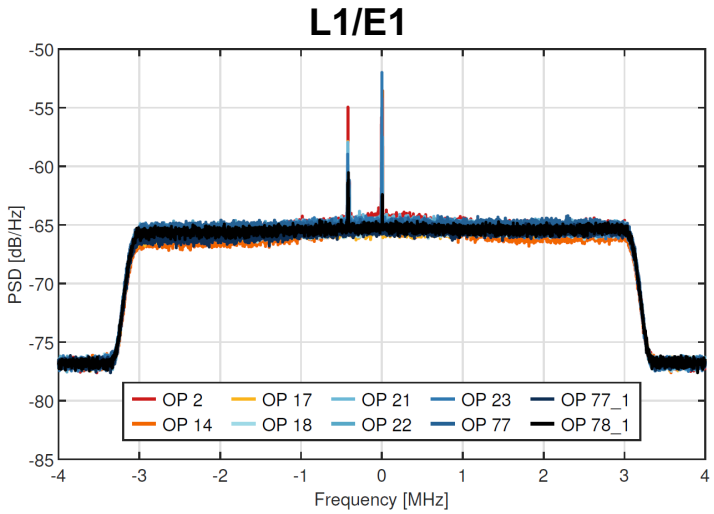
Lunar surface (OP38, two PVT instances)

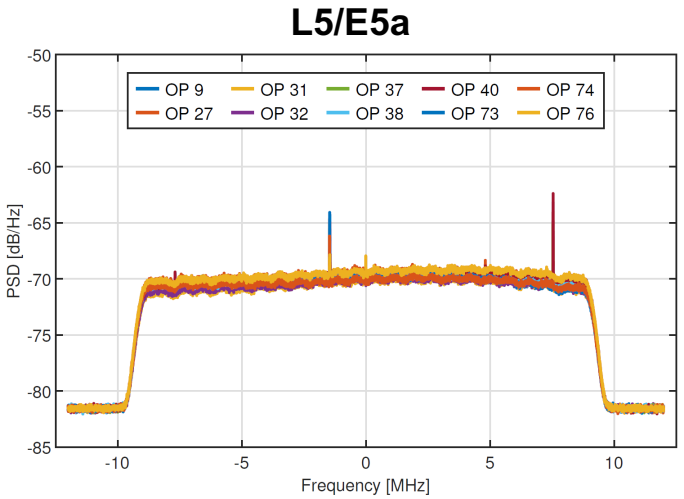


- LuGRE receiver calculated both least-squares PVT and Kalman filter POD solutions. Analysis of POD solutions is future work.
- Plots describe PVT solution position error with respect to Firefly definitive ephemeris and GDOP
- At 15RE, behavior is as expected – GDOP near 50, position errors around 1km in all directions
- On lunar surface, both a dynamic and a steady-state case are shown.
  - Dynamic case is caused by temporary alignment of GNSS planes as seen by receiver – DOP discontinuity causes highly elevated range position error.
  - Steady-state case shows effect of correlation between range and clock bias states – range error ~10km, lateral error ~100m

Results: IQ Sample Capture

- LuGRE captured IQ samples during nearly all operations – 12s of samples total
- Configurable parameters:
  - Bands: L1/E1 only, L5/E5a only, dual-band
  - Sample rate: 8–12 Msps (L1/E1), 24 Msps (L5/E5a)
  - Quantization: 4–8 bits/sample
  - Duration: 200–800 ms (transit+surface) + 2000 ms (2x on surface)
- Executed immediately before or after real-time processing experiment
- Sample data will be part of public dataset
- Welchplot shows spurious peak in both frequencies, likely caused by EMI
- Addition of cascading notch filter in postprocessing to exclude peak results in acquisition C/N0 increase of <0.2 dB – shows that this peak does not significantly affect overall signal strength seen during operations.





EMI peak can be removed via cascading notch filter; shows EMI has little impact on C/N_0

Signal, PRN	Est. C/N_0 (dB-Hz)			Doppler Shift (kHz)			C/N_0 Increase due to Filtering (dB)
	IQS	ACQ	Filtered IQS	IQS	ACQ	Filtered IQS	
GPS L1 C/A, 18	39.21	40.81	39.30	-10.800	-12.448	-10.800	0.09
GPS L1 C/A, 24	37.03	40.63	37.19	-3.100	-4.7477	-3.100	0.16