



LuGRE

LUNAR GNSS RECEIVER EXPERIMENT

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

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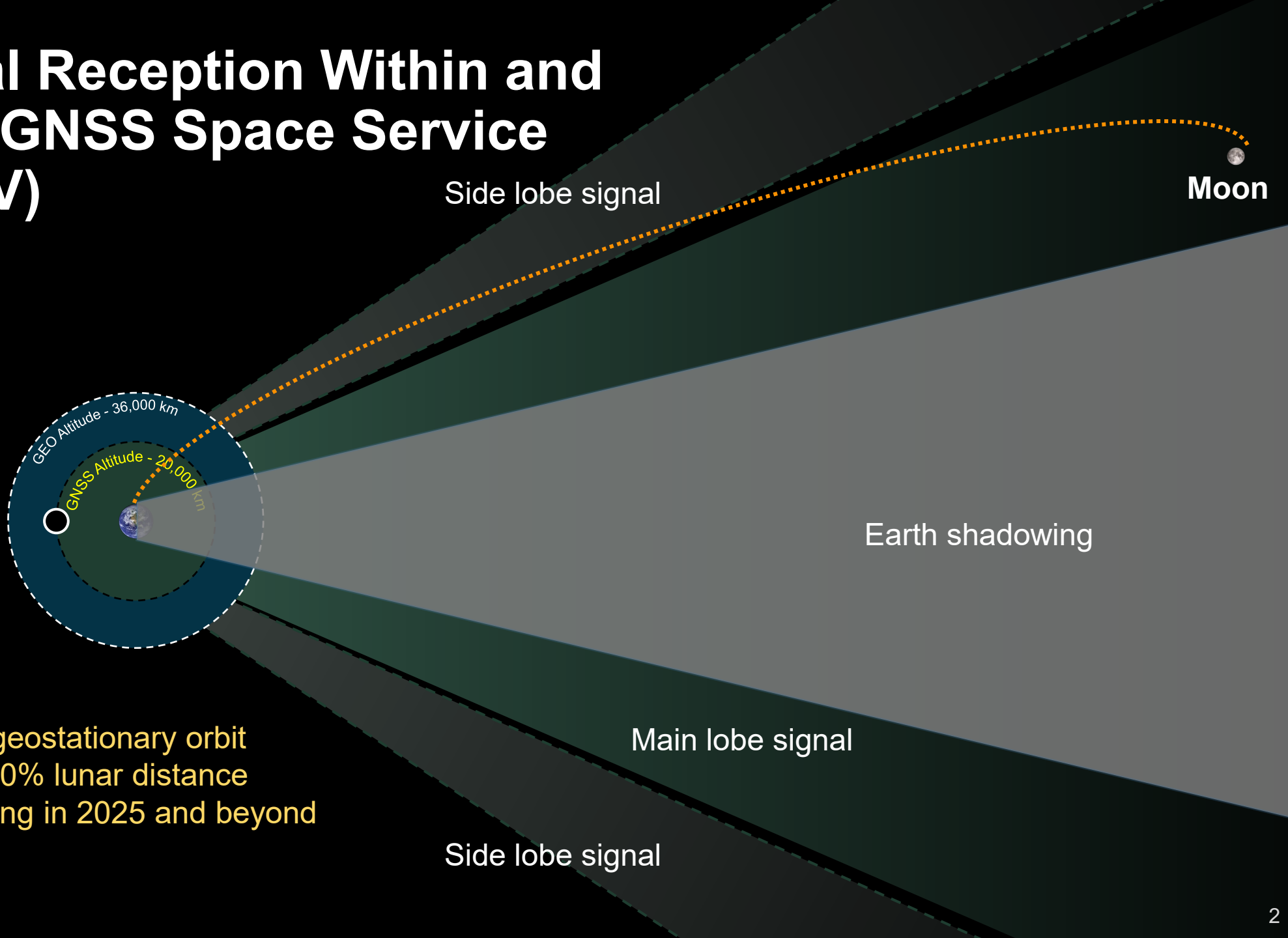
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Multi-GNSS Asia (MGA)

8 March 2026



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

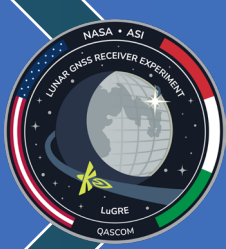


Utilization:

- Broad utilization in geostationary orbit
- Active users up to 50% lunar distance
- Lunar users beginning 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)

Time

Today

Transit use of GNSS and Lunar PNT Services

GNSS Use

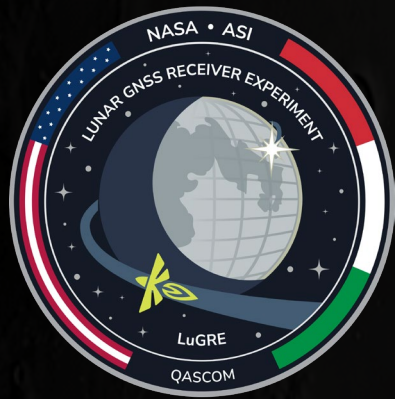
Lunar PNT Use

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



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

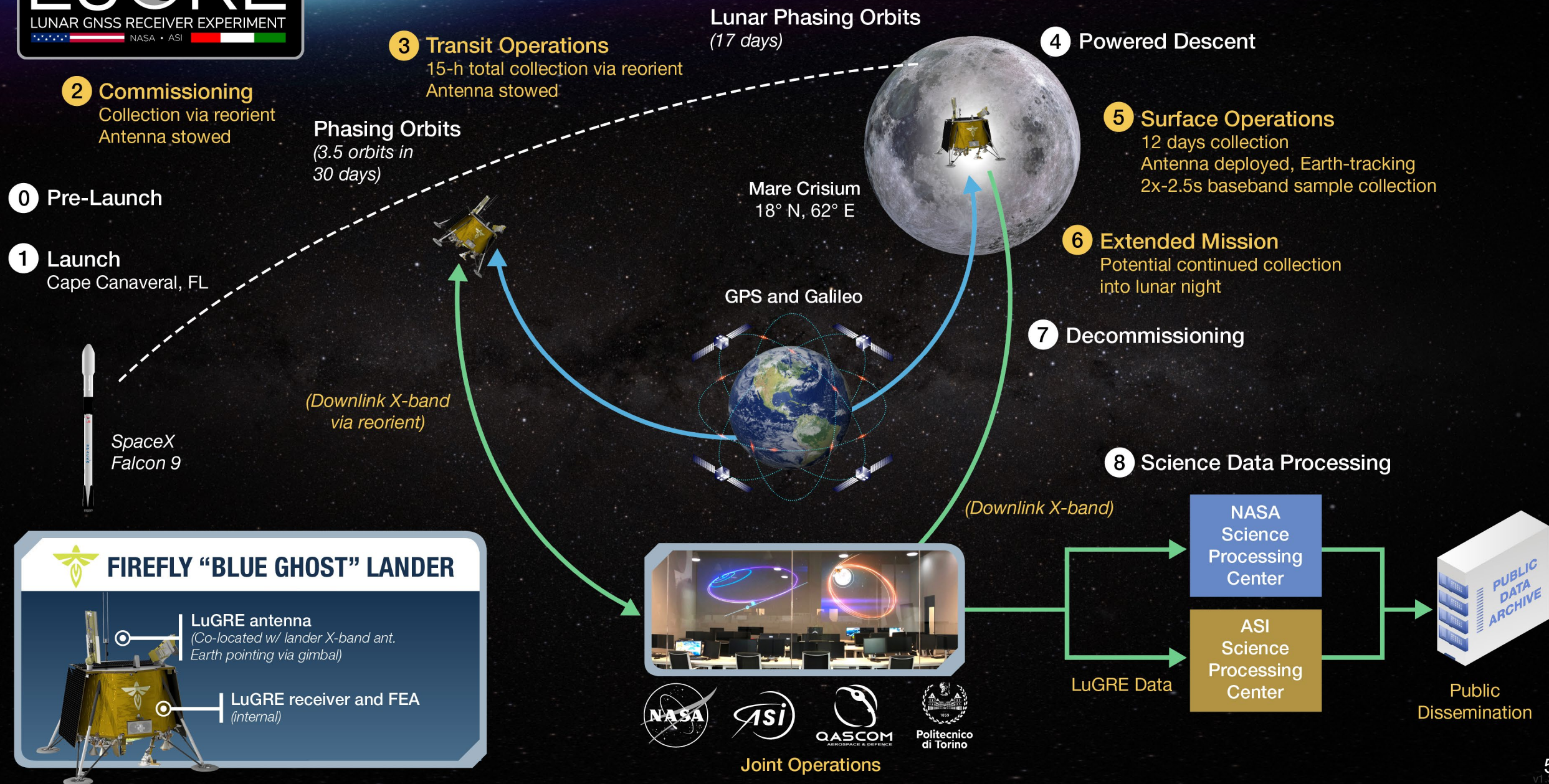


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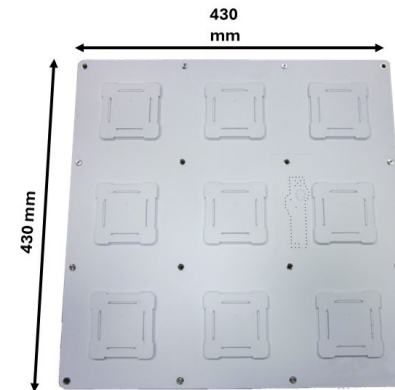
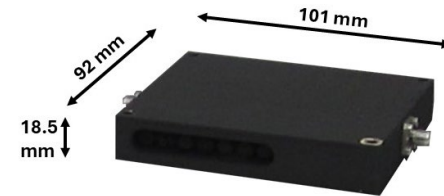
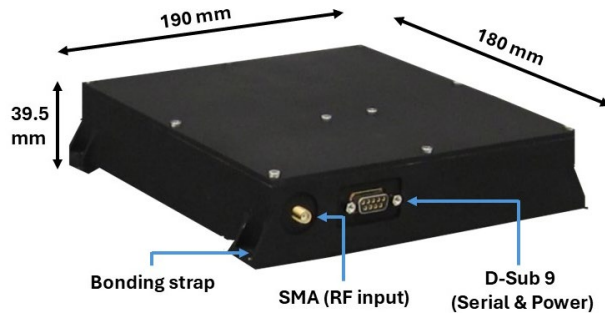
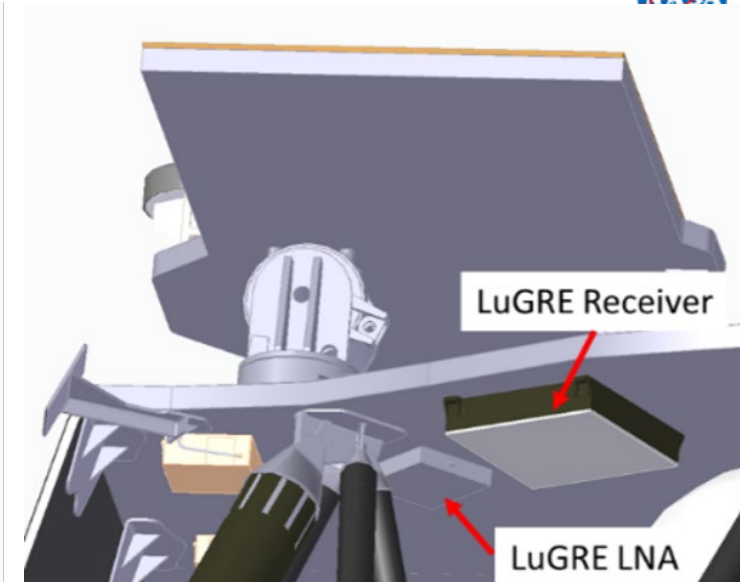
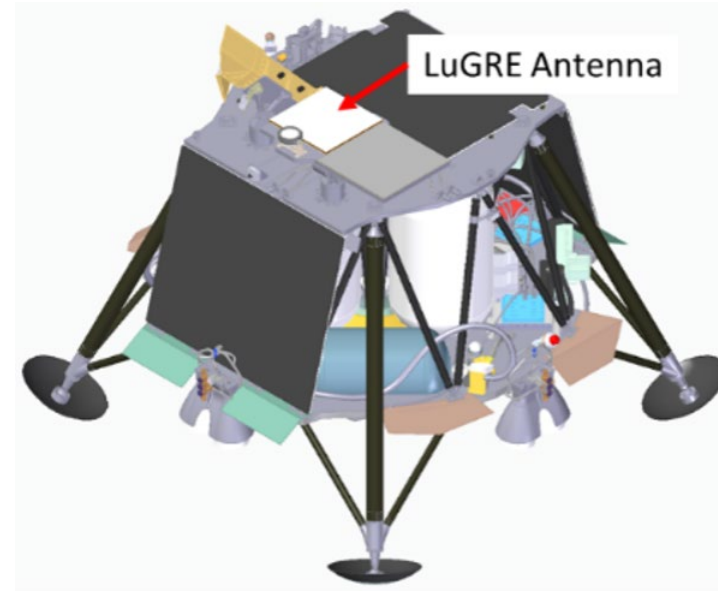
NASA • ASI

[Pre-launch plan]



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.

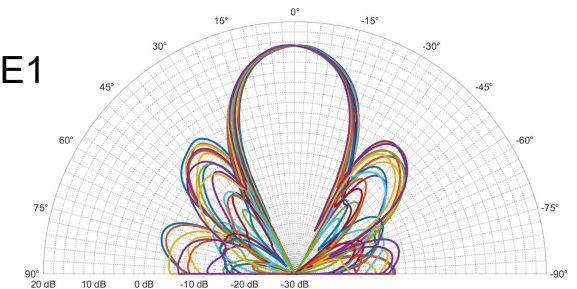
Low Noise Amplifier:

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

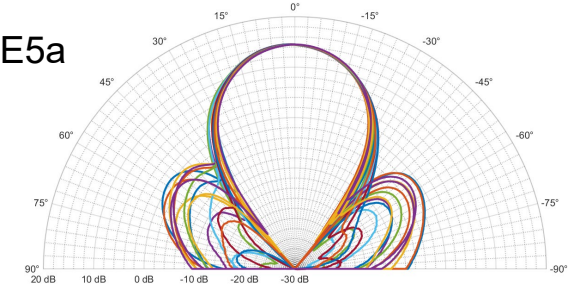
High Gain Antenna:

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

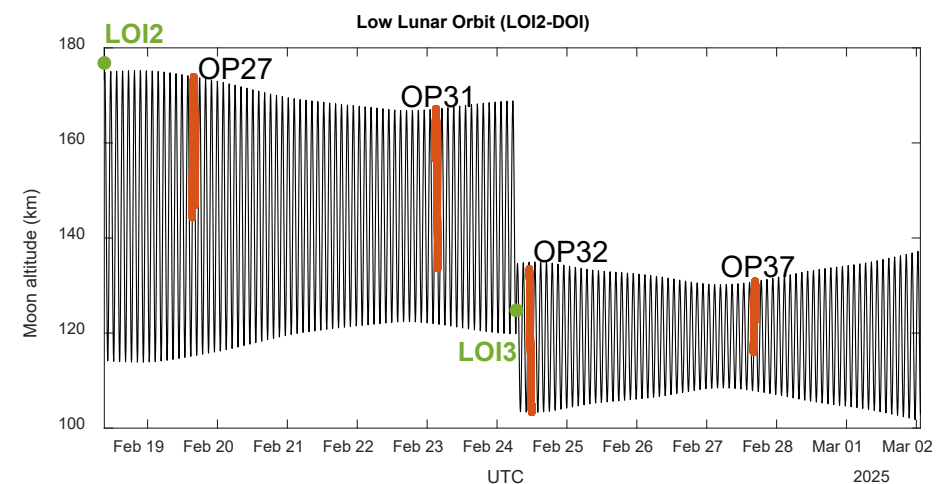
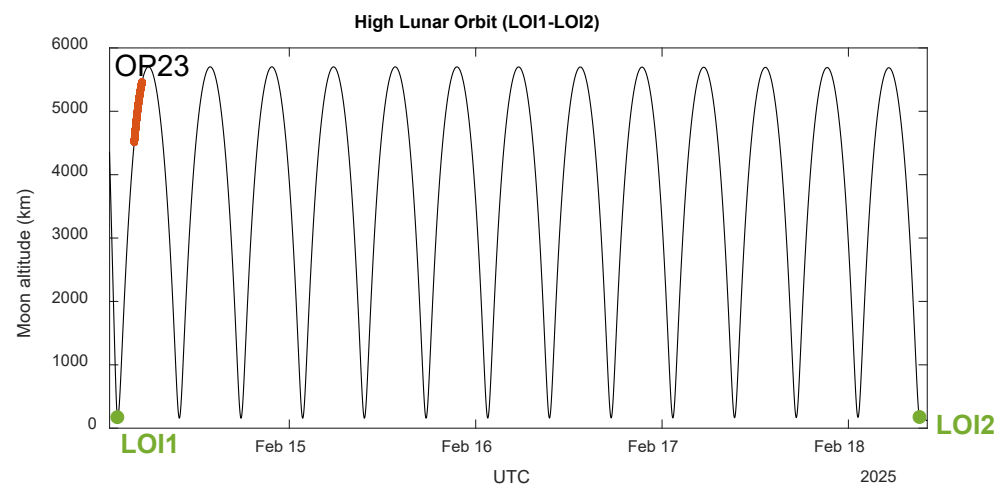
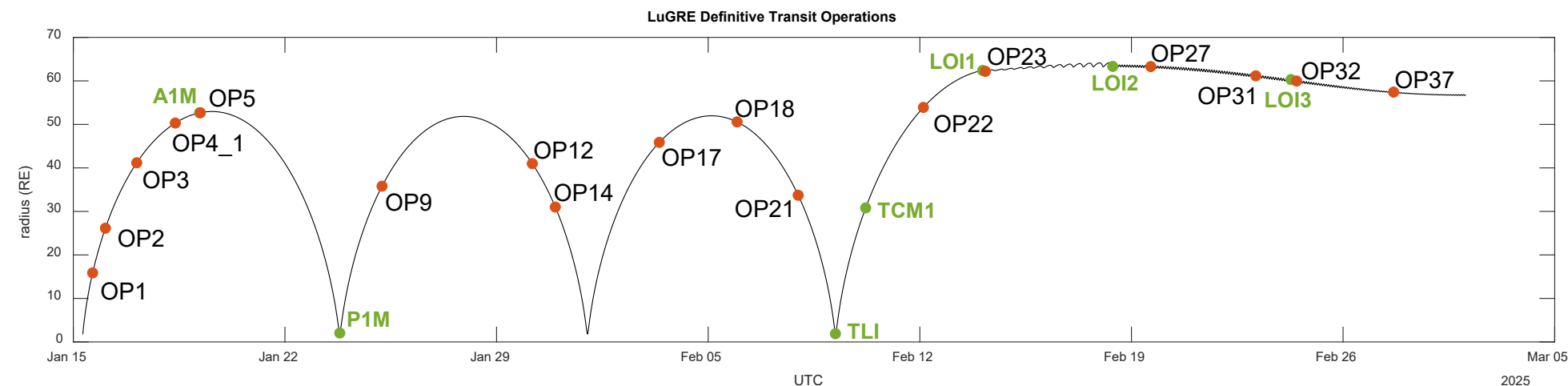
L1/E1



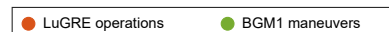
L5/E5a



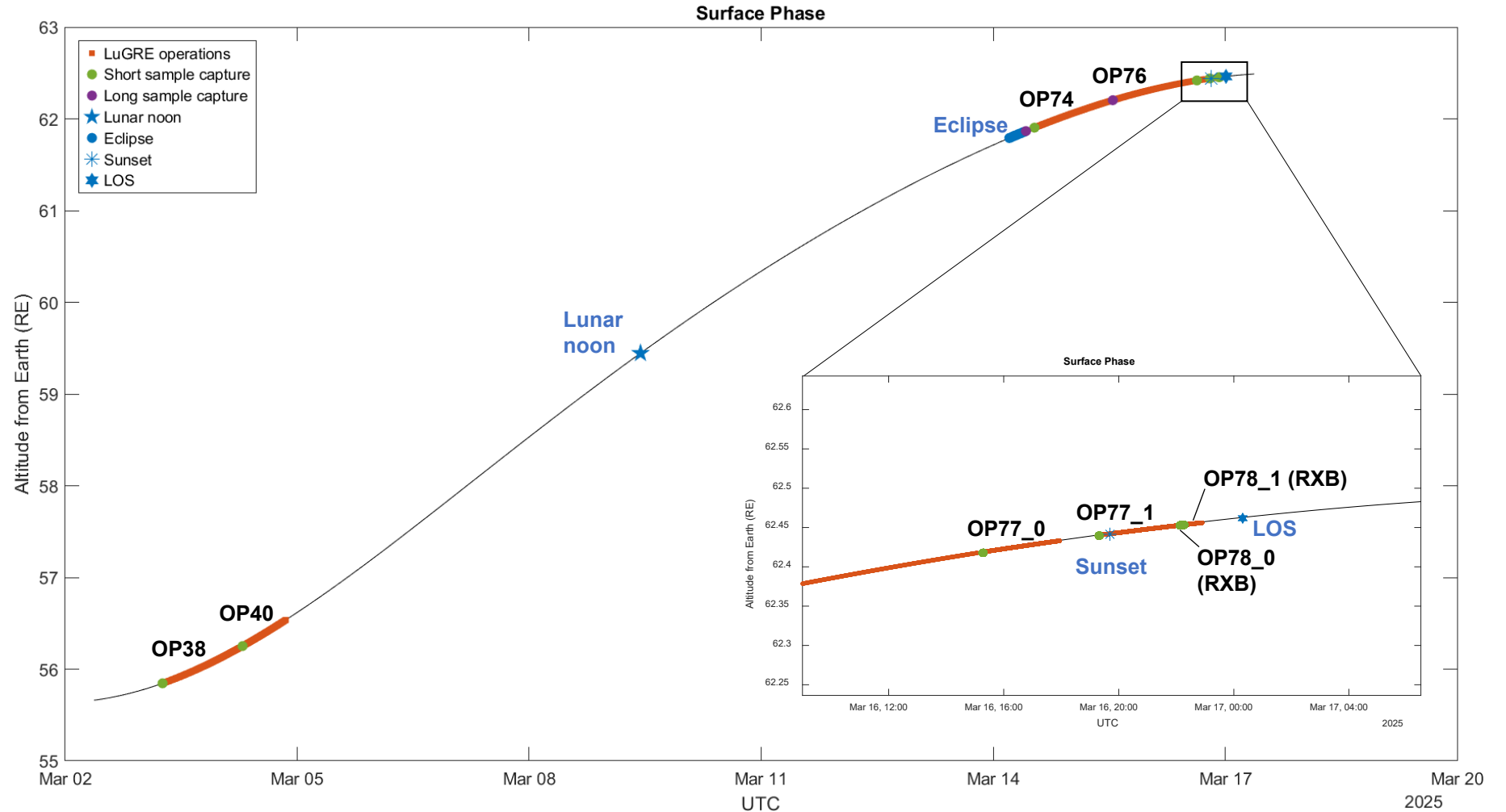
As-Flown Operations—Transit



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

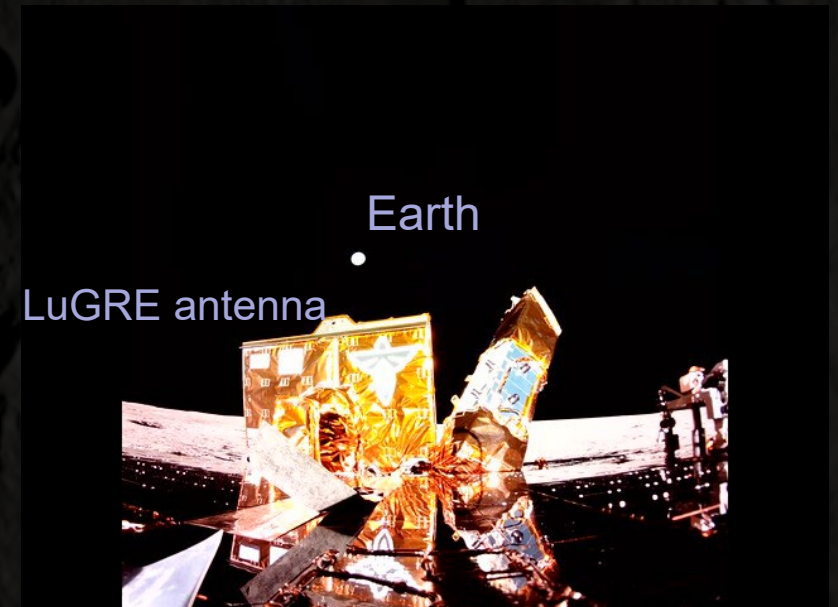
- 2 during the commissioning phase
- 9 during the Earth-centered phasing loops
- 5 in lunar orbit

DATA COLLECTED IN TRANSIT

- 14 IQS samples' batches collections
- 14 real-time measurements

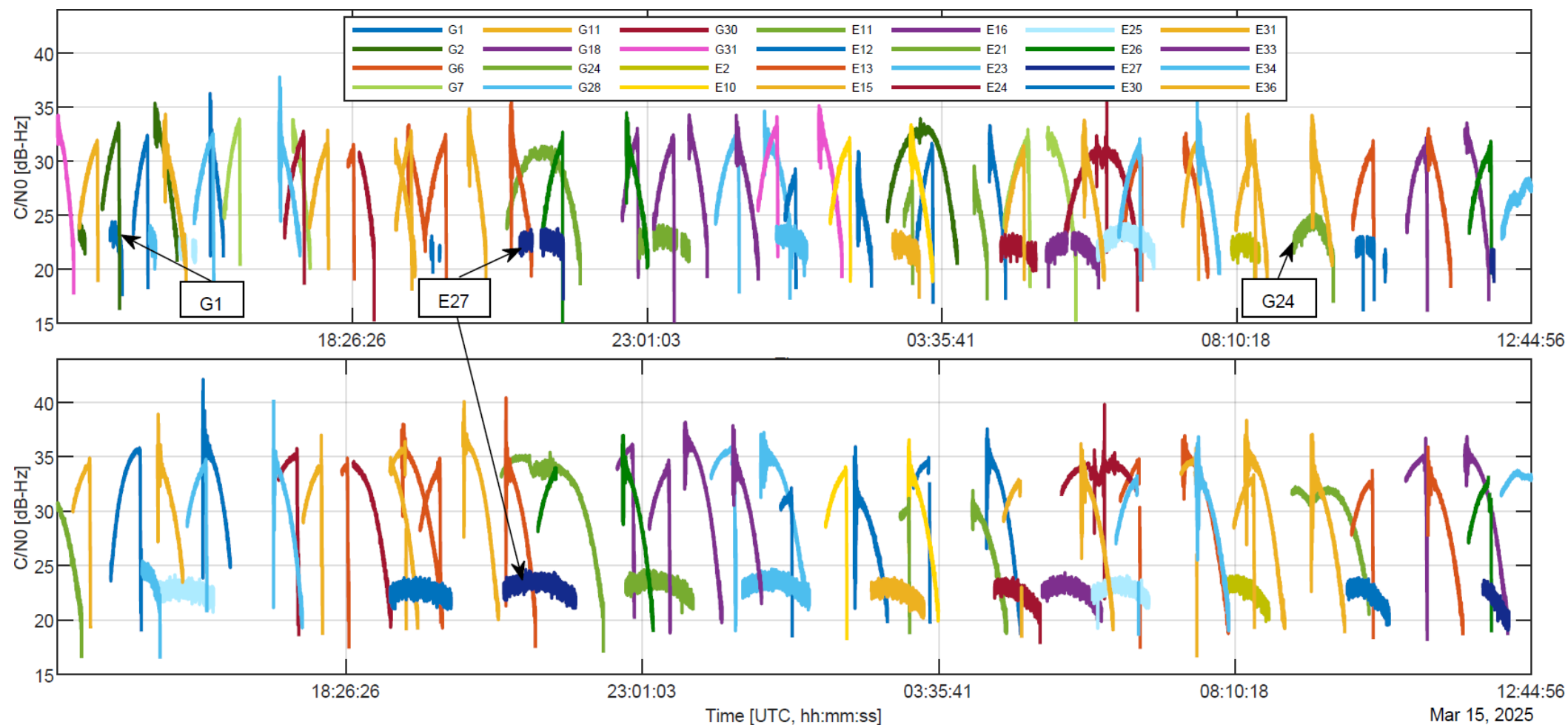
SURFACE TIME: 95+ hours

Nearly 93 hours were spent in real-time processing mode.



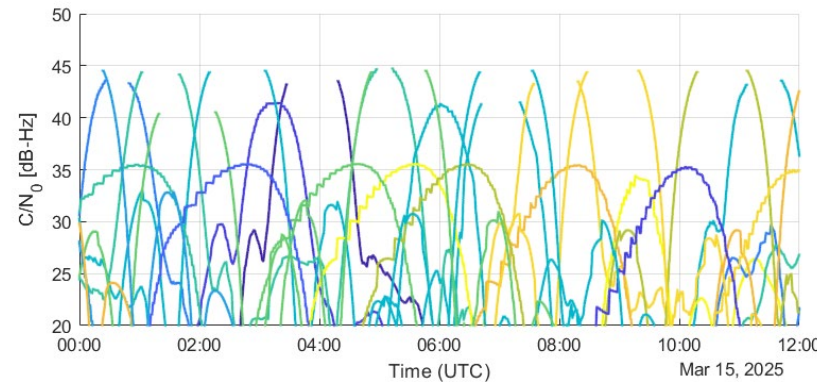
Results: Signal Strength

- 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

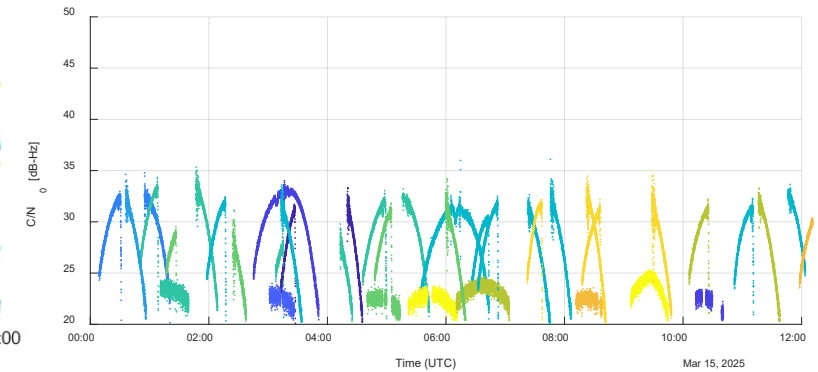


Results: C/N0 Level Analysis

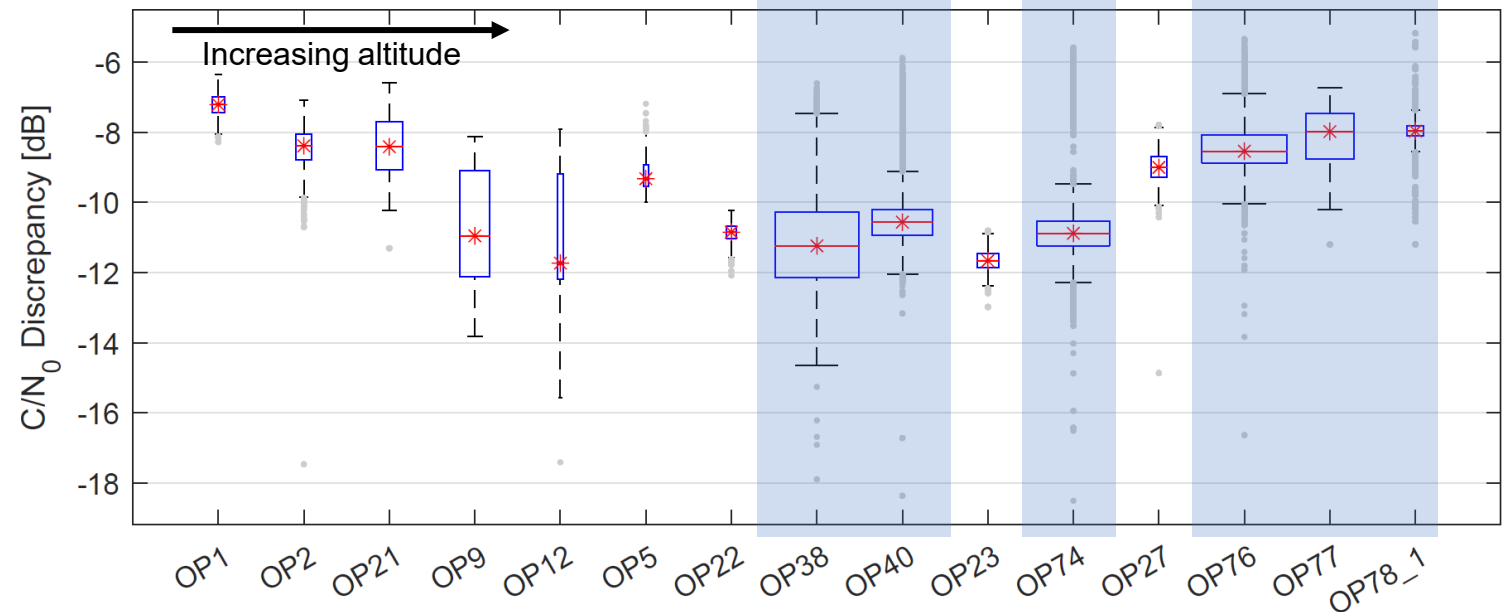
- In-flight C/N0 estimates are lower than predicted by LuGRE planning sim, and lower than literature shows.
- Simulation validated with MMS link budget and flight data
- Characterization of discrepancy focused on best-known EIRP signals: GPS L1 signal, block IIR-M & IIIA vehicles
- Discrepancy is 7–12 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



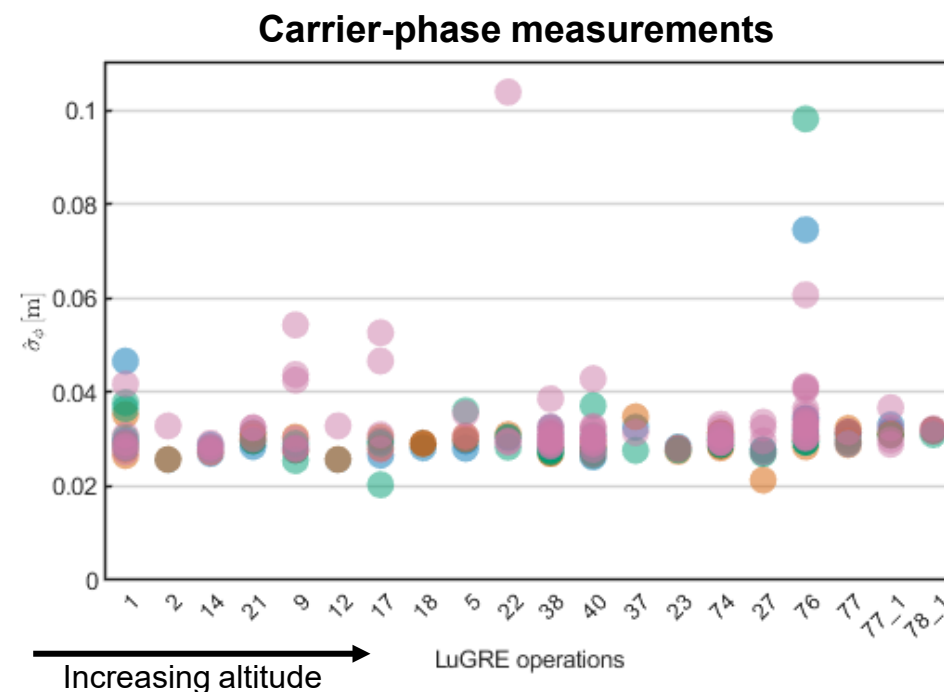
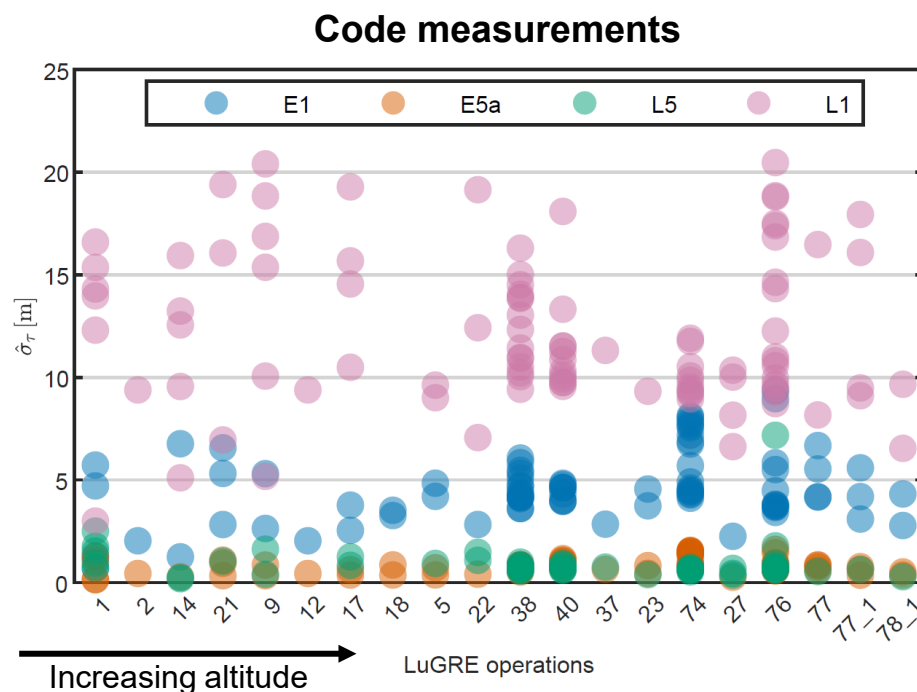
In-Flight



Lunar surface operations

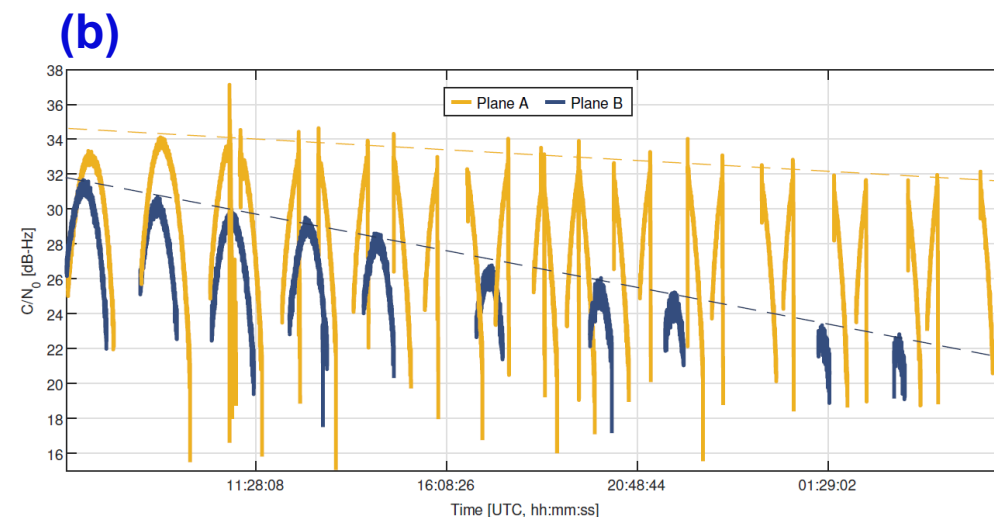
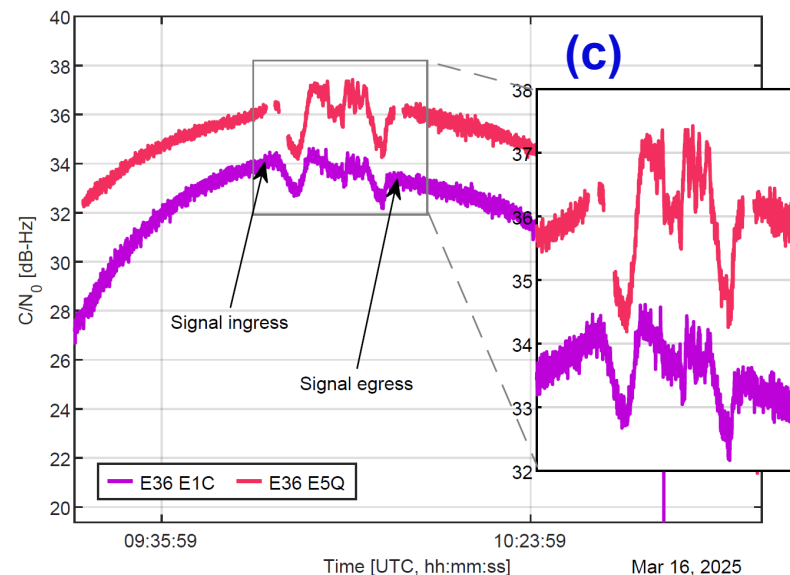
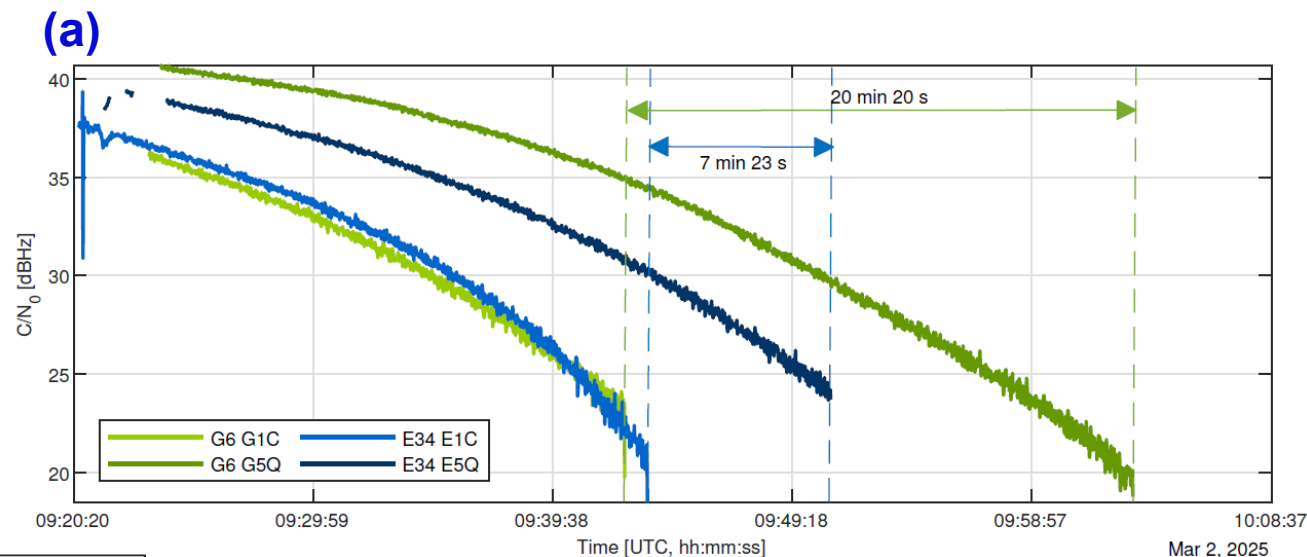
Results: Measurement Quality

- 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



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)



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>

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

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



A photograph of a sunset on the Moon. The horizon is a straight line across the middle of the frame. Above the horizon, a bright, glowing sun is partially obscured by a dark, circular shadow, creating a ring-like effect. The sky is a deep, dark blue. The lunar surface below the horizon is covered in a layer of dark, reddish-brown soil and rocks, with some lighter patches of sand. The overall scene is dimly lit, with the primary light source being the setting sun.

LuGRE represents the dawn of lunar applications of GPS and GNSS.

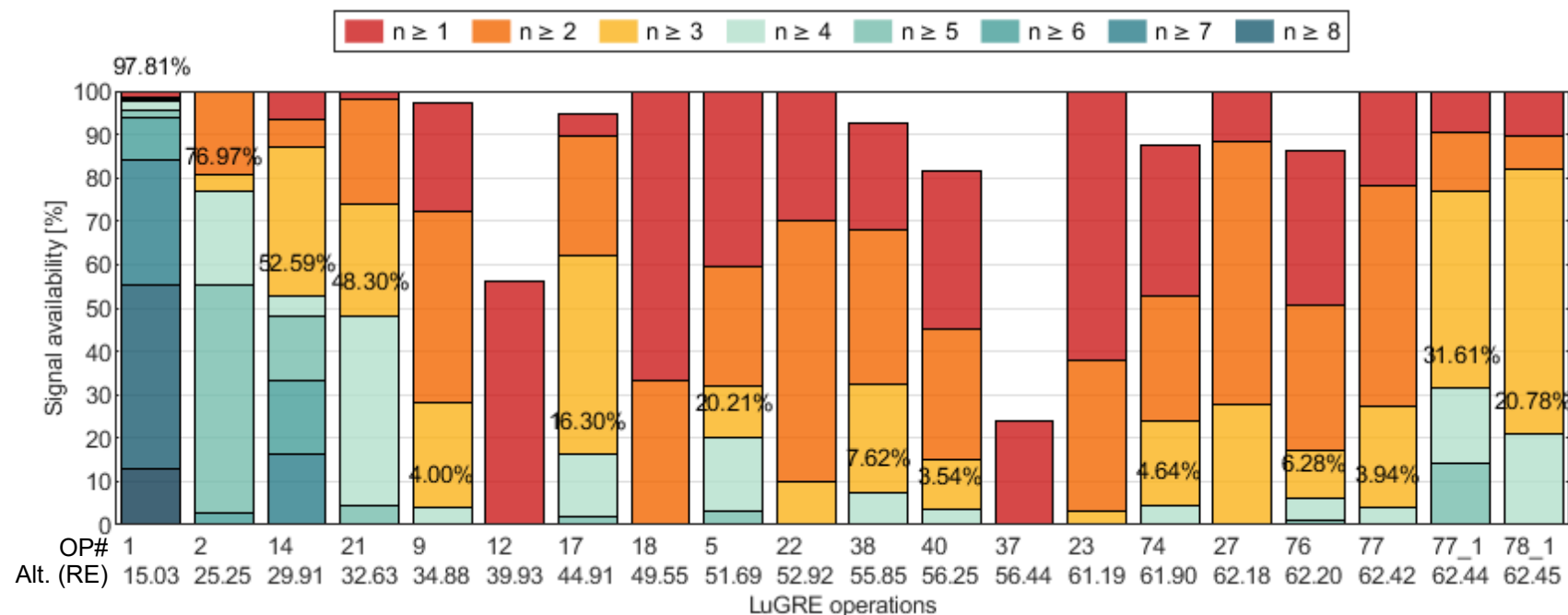
GNSS will enable and enhance low-cost, high-flexibility lunar missions using signals already available and proven in Earth orbit and cislunar space.

LuGRE and lunar GNSS are steppingstones to future PNT systems at the Moon – which will enable the next generation of lunar missions with high-accuracy PNT needs.

Backup

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

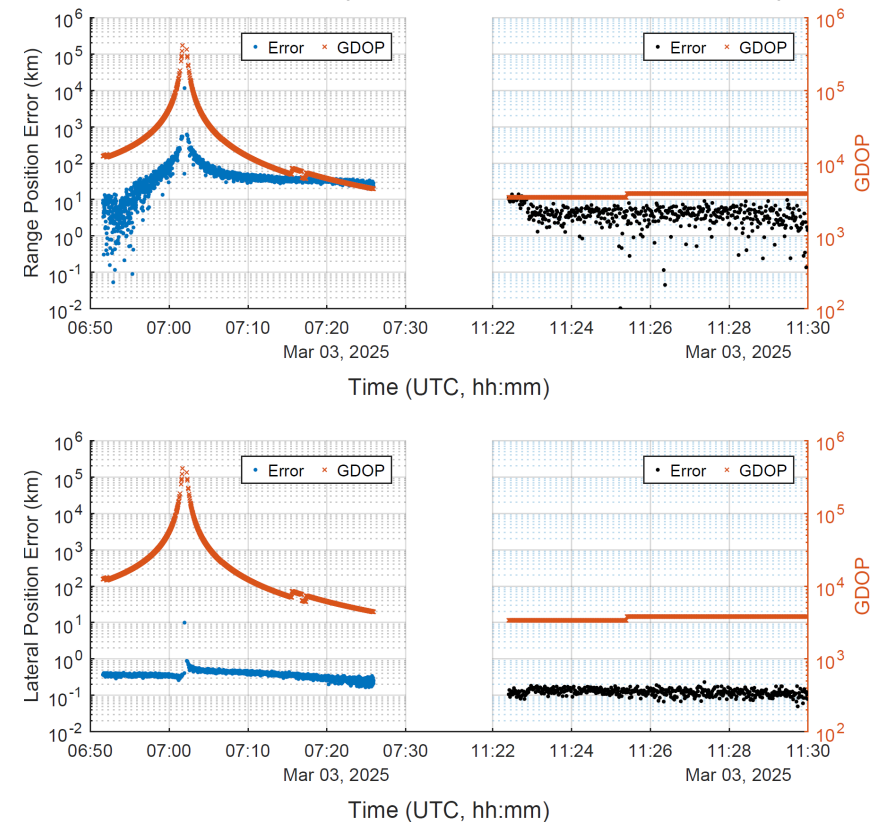


PVT availability (4+ unique signals)										Lunar surface operations				
Metric / OP ID	1	2	14	21	12	17	5	23	74	27	76	77	77_1	78_1
L1/E1 (%)	97.81	61.35	0.00	3.70	52.59	0.00	13.10	1.44	1.43	1.43	0.87	3.00	4.09	20.48
L1/E1+L5/E5 (%)	97.81	76.97	20.21	4.00	52.59	16.30	48.30	7.62	3.54	4.64	5.94	3.94	31.61	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

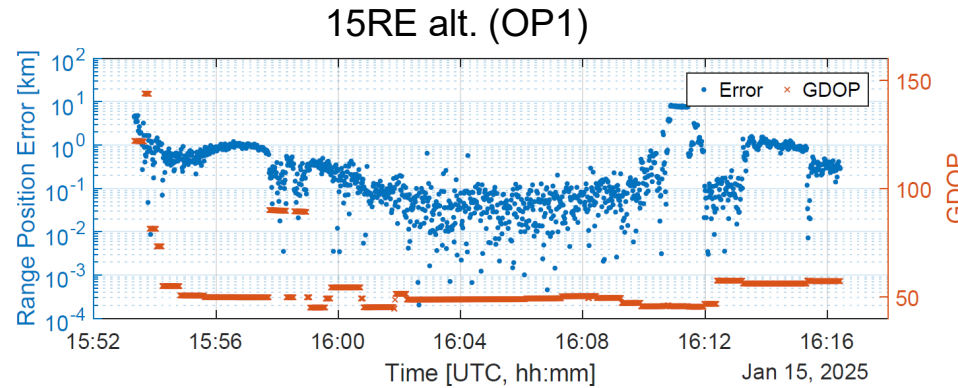
Results: State Estimation (PVT)



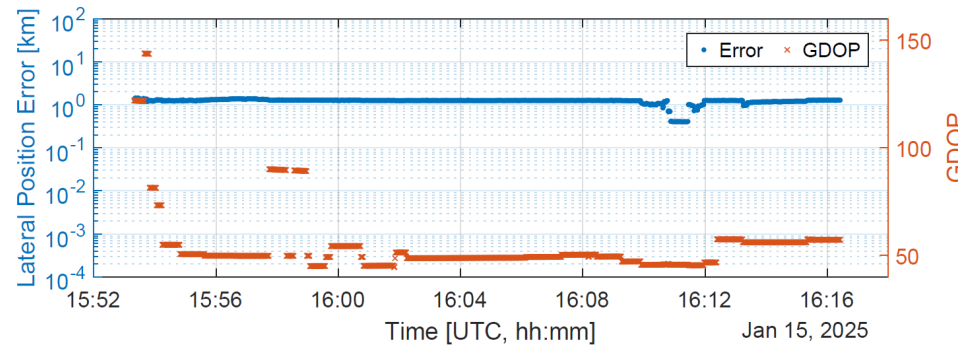
Lunar surface (OP38, two PVT instances)



Range
position
error



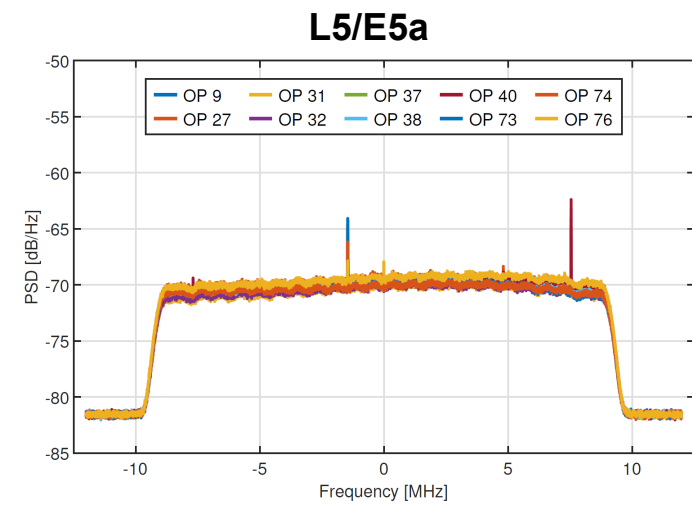
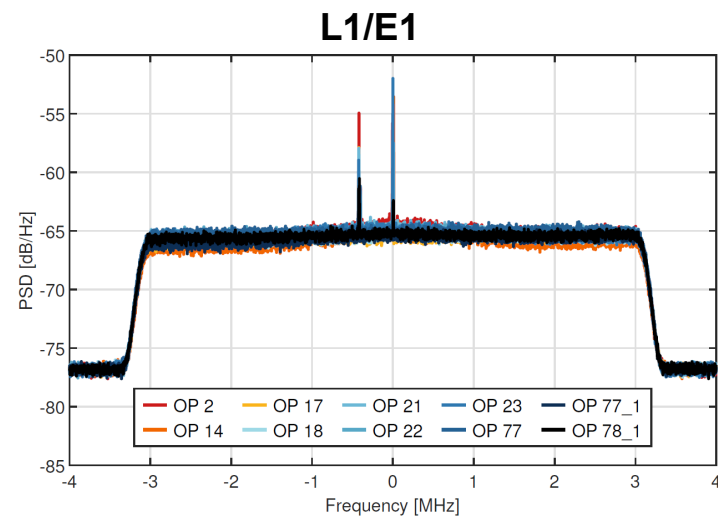
Lateral
position
error
(RSS)



- 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/N₀

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