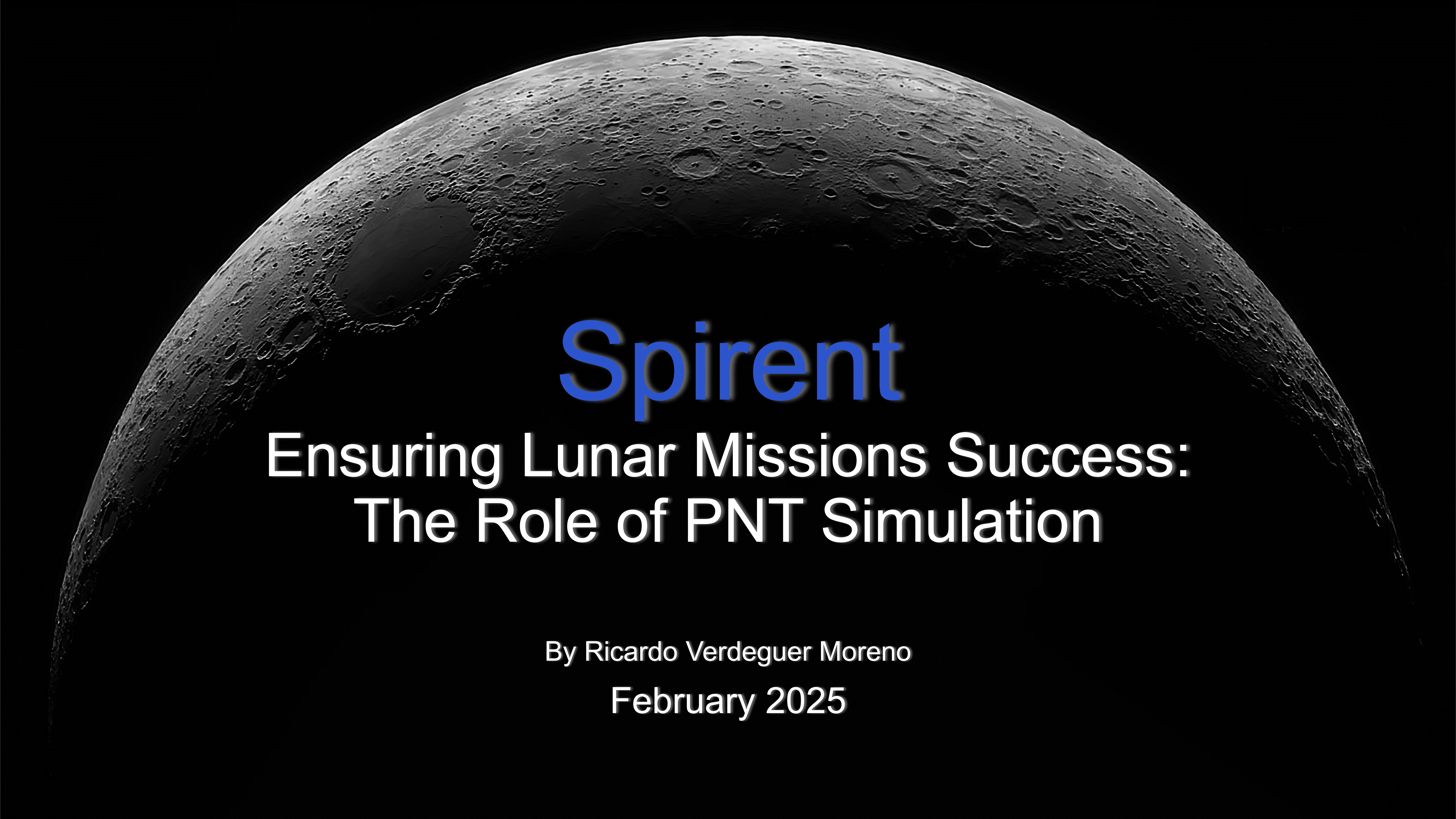


Spirent

Ensuring Lunar Missions Success: The Role of PNT Simulation

By Ricardo Verdeguer Moreno

February 2025

Agenda

1. PNT to the Moon - Phases
2. Simulation Considerations & Achievements
3. Next Steps

Agenda

PNT to the Moon – Phases

Earth-Based GNSS

2023 - onwards

Use of Earth-Based GNSS constellations for PNT in lunar missions.

- Earth-to-Moon transfer
- Orbital navigation and timing

LANS (Initial Services)

2027 - 2035

Dedicated initial lunar orbit GNSS-like constellation to provide South Pole surface and cislunar PNT services.

- Vehicle descent, landing and ascent
- South Pole lunar surface PNT

LANS (Enhanced Services)

2035 - onwards

Enhanced lunar constellation (including additional SVs and lunar surface PNT beacons) to provide full lunar coverage.

- Full lunar surface PNT
- Service integrity

How do we succeed?

Lunar applications, either with Earth-based GNSS signals or LANS, are **pushing the requirements** of GNSS technology further than ever before. Also, the **diversity of applications** is likely to increase.

To successfully bring PNT to the Moon, the design of the various parts of the system, in particular GNSS receivers, must be of a **high standard** that ensures reliable performance. To enable this, it is important that the product development process is based on proper testing from concept to production.

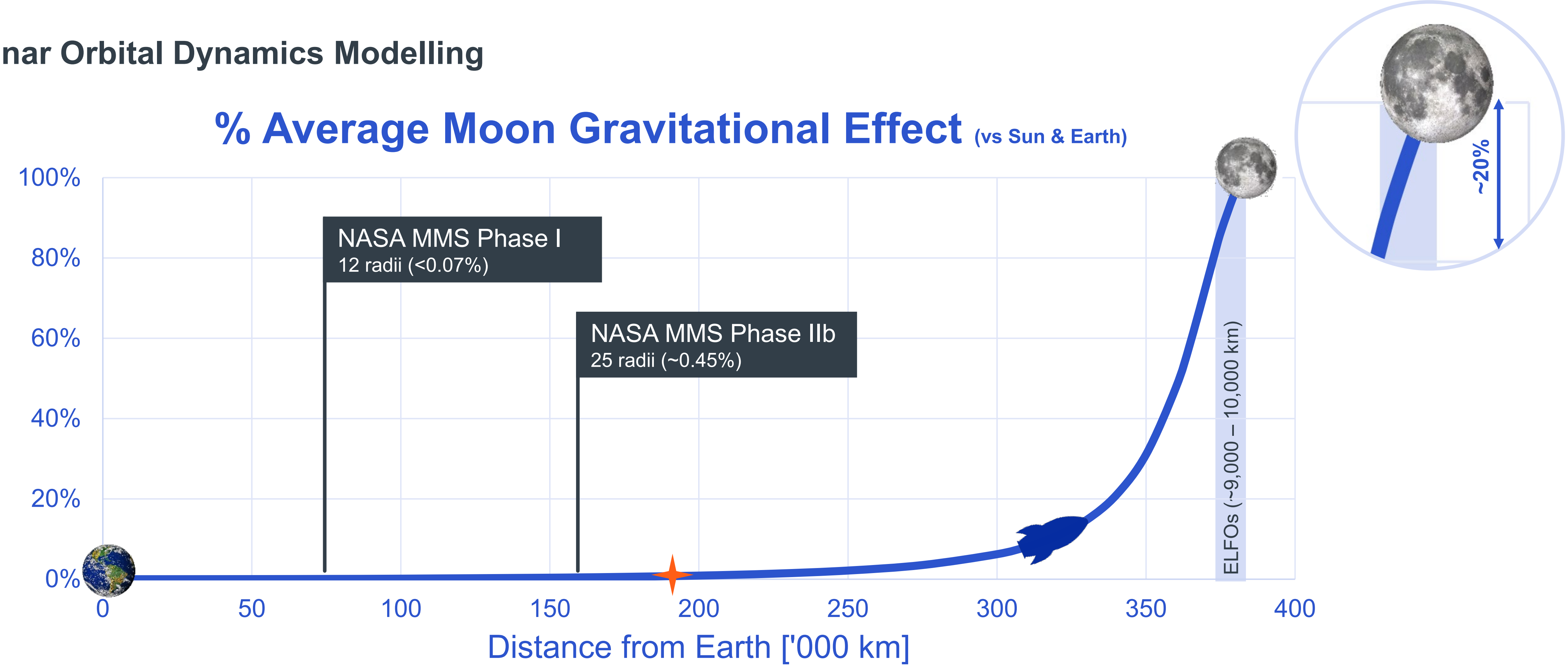
Advantages of Lab Simulation

- Complete control over constellation and signals
- Complete control over environmental conditions
- Fully repeatable
- No unintended interference signals or unwanted signal effects
- Easily test scenarios with constellation errors
- Testing of present and future signals
- Cost-effective testing in laboratory

Agenda

Simulation Considerations

Lunar Orbital Dynamics Modelling

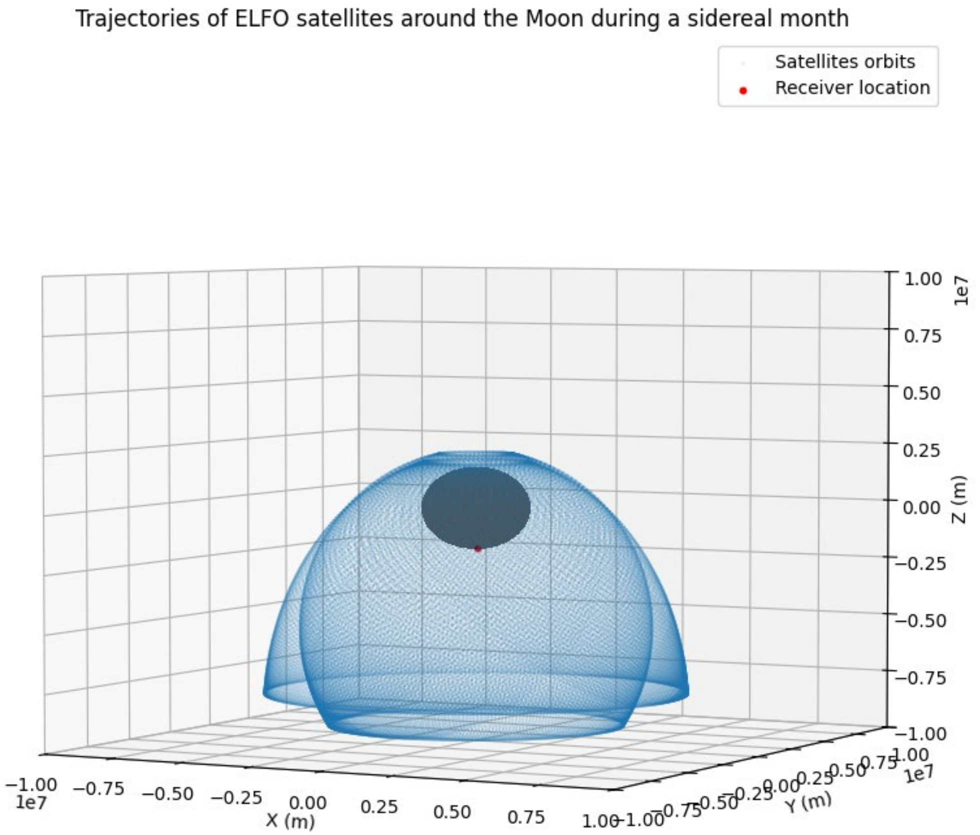


- New dynamics model required to account for the uneven gravitational pull from the Moon, perturbations from other celestial bodies, different solar radiation pressure, etc.

✦ [Record-Breaking NASA Mission Advances High-Altitude GPS | NASA]

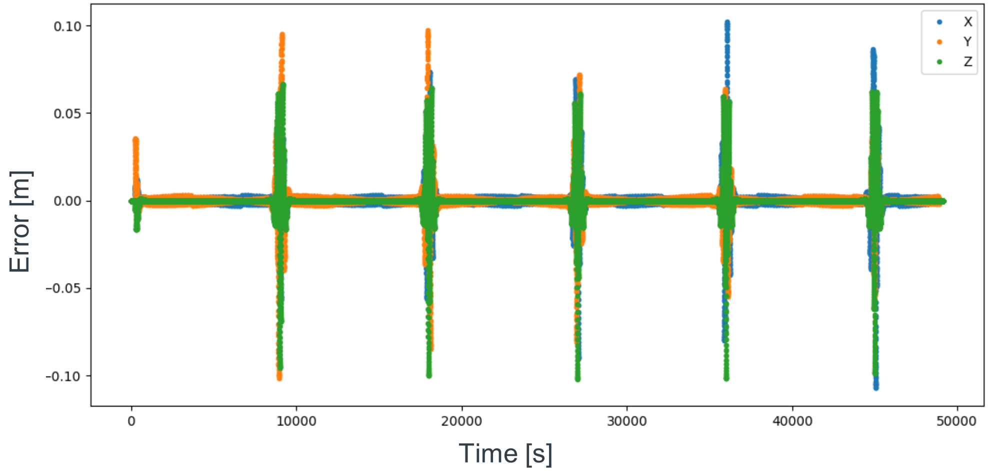
Achievements

Lunar Orbital Dynamics Modelling

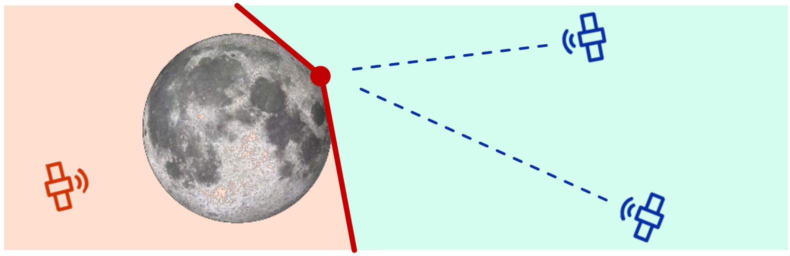


- Successfully created and imported into our Software SP3 files containing ELFO satellite orbits.

- Validated our SP3 Lagrange interpolation algorithm with 5-min SP3 update interval against external orbital data.

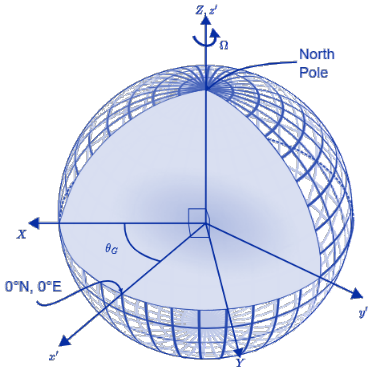


- Use of elevation masks on the receiver antenna to account for Moon obscuration effects, satellite visibility and vehicle rotation.



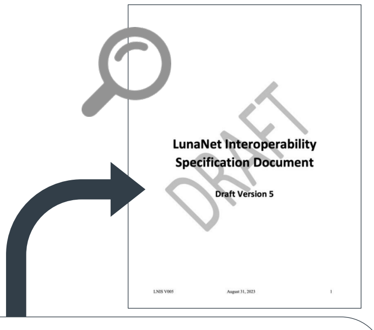
Simulation Considerations

Selenodetic Reference Systems[1]



Two reference frames are needed:

- **Body-fixed reference frame** for the main body perturbation modelling and for the expression of the broadcast navigation message, to estimate position without implementing the rotations of the inertial frame (e.g., ECEF)
- **Inertial reference frame** for precise time resolution (including relativistic effects) and the numerical integration of the equations of motion (e.g., ECI)



LunaNet Interoperability Specification includes an Applicable Document 5 (AD5) to define an interoperable LRS & Lunar Time System set with associated criteria (e.g. tolerances).

Body-Fixed Lunar Reference Systems

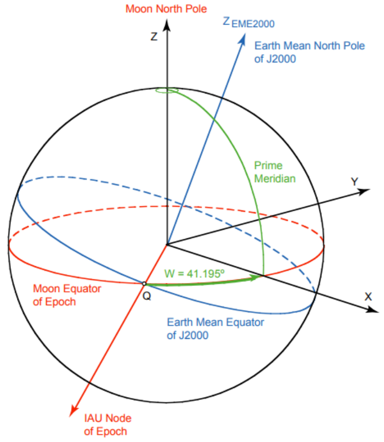
- **Mean Earth Rotation (MER)** – mean direction to Earth (X) and mean Lunar spin (Z): mainly used for cartography

Do not coincide
Systems differ about 1 km

- **Principal Axis (PA)** – aligned with principal axis of inertial of the Moon: important for orbit propagation

Lunar Inertial Reference Systems

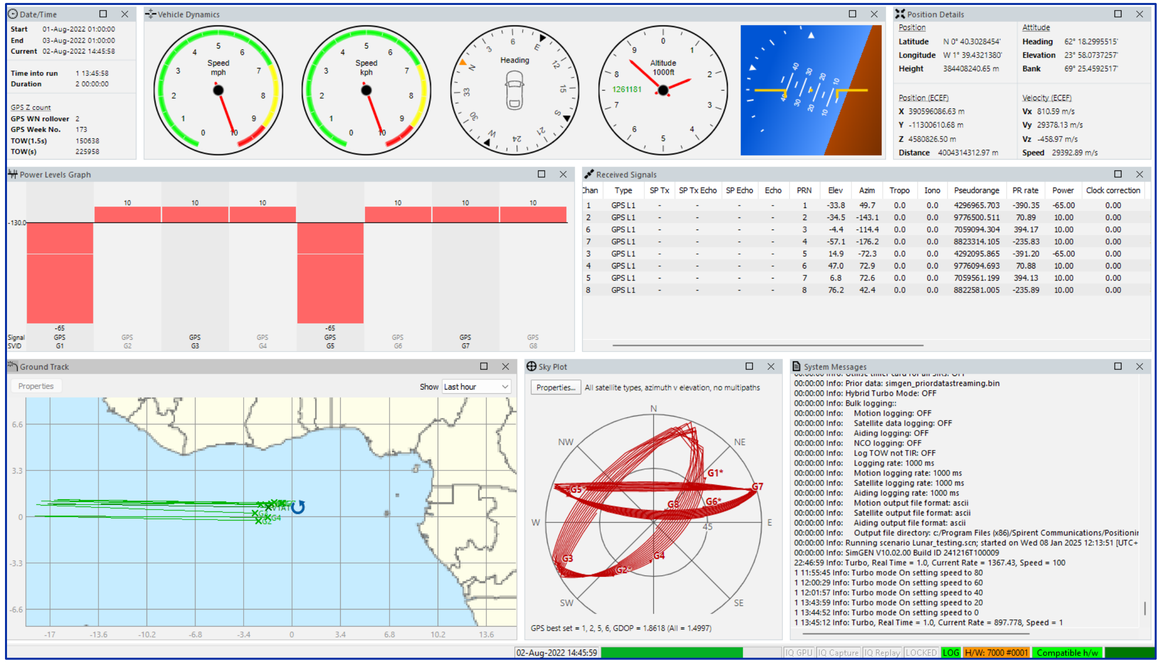
- Recommendation is to use a frame that is aligned to the Moon equator at a reference epoch to ease integration of lunar orbits
- Roncali[2] contains a complete list of Moon-Centred inertial frames



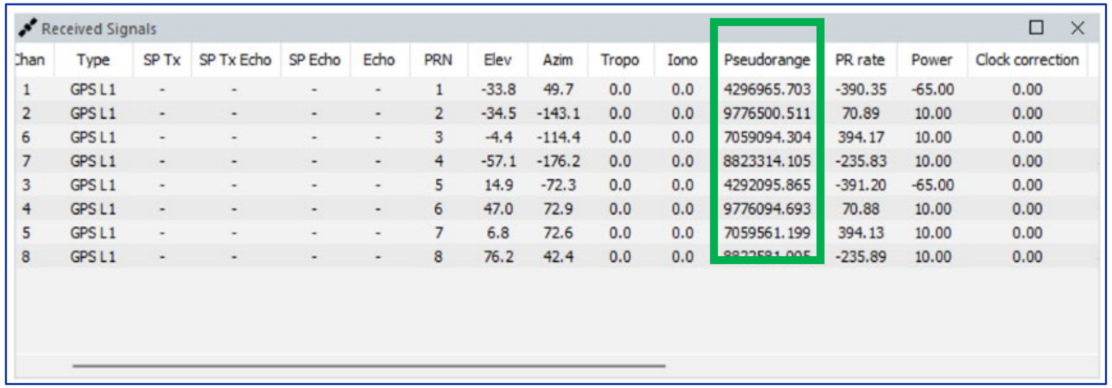
Simulation Considerations

First Lunar Simulation

8 lunar-orbiting satellites distributed across 2 ELFO orbits received by a vehicle on the surface of the Moon



- Expected pseudoranges (~3,000 to 10,000km) for eccentric orbits with A_0=6540 km.



Chan	Type	SP Tx	SP Tx Echo	SP Echo	Echo	PRN	Elev	Azim	Tropo	Iono	Pseudorange	PR rate	Power	Clock correction
1	GPS L1	-	-	-	-	1	-33.8	49.7	0.0	0.0	4296965.703	-390.35	-65.00	0.00
2	GPS L1	-	-	-	-	2	-34.5	-143.1	0.0	0.0	9776500.511	70.89	10.00	0.00
6	GPS L1	-	-	-	-	3	-4.4	-114.4	0.0	0.0	7059094.304	394.17	10.00	0.00
7	GPS L1	-	-	-	-	4	-57.1	-176.2	0.0	0.0	8823314.105	-235.83	10.00	0.00
3	GPS L1	-	-	-	-	5	14.9	-72.3	0.0	0.0	4292095.865	-391.20	-65.00	0.00
4	GPS L1	-	-	-	-	6	47.0	72.9	0.0	0.0	9776094.693	70.88	10.00	0.00
5	GPS L1	-	-	-	-	7	6.8	72.6	0.0	0.0	7059561.199	394.13	10.00	0.00
8	GPS L1	-	-	-	-	8	76.2	42.4	0.0	0.0	8822581.005	-235.89	10.00	0.00

- Simulation includes satellite and lunar orbits as well as vehicle real-time orientation (i.e., Euler angles wrt local Earth-based horizontal).

- Signal received includes vehicle motion and Doppler shifts. Power levels have been set to “Fixed” in this scenario.

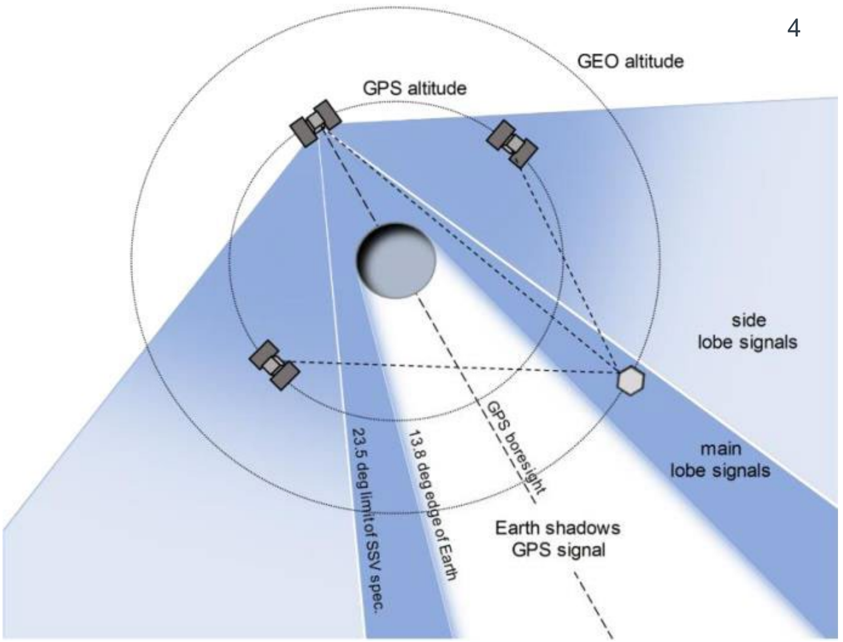
Simulation Considerations

Realistic Tx Antenna Patterns & SV Dynamics Modelling[3]

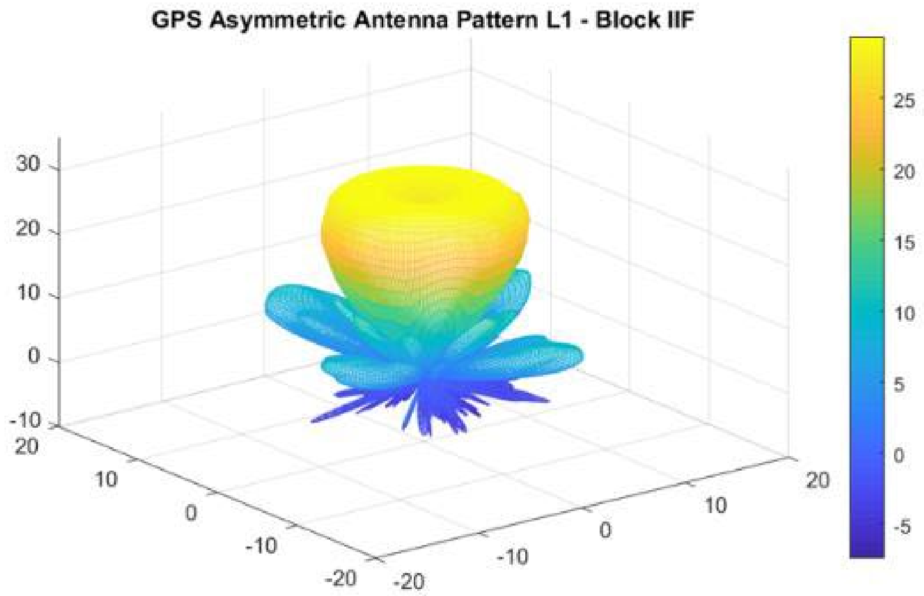
- Implementing Tx antenna pattern data for accurate representation of side lobe signals
- Yaw attitude representation for each SV plays an important role in the determination of the power levels received beyond MEO orbits → Account for Z-axis rotation performed to orientate solar panels
- Receiver antenna Modelling → Earth-pointing, high Gain. E.g., boresight gain of 15 dBi at L1 and 11.5 dBi at L5

GPS IIR/IIM&III antenna patterns are publicly available for Earth and Space service.

Galileo Reference Antenna Pattern (GRAP) model became available in 2024.



4



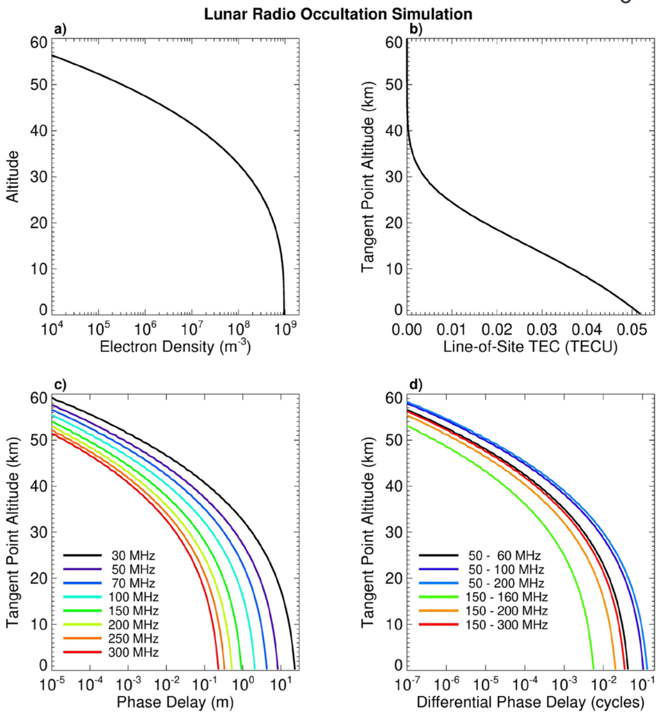
Simulation Considerations

Signal Propagation[5]

Earth-Based GNSS

- Further sophistication of Earth ionospheric models required for calculating the Total Electron Count (TEC) as signals may cross ionosphere twice → Thin-shell model not sufficient for these applications.

[6]



LANS

- The gas concentration in the lunar exosphere is approximately $2 \times 10^5 cm^{-3}$ during the lunar night, and $10^4 cm^{-3}$ during the lunar day.
- The TEC of the exosphere is extremely low, often in the order of 0.01 TECU → Earth TEC ranges from a few to 100 TECU.
- The effect of the lunar exosphere is neglectable for Earth-Based GNSS PNT solutions. However, the consequences for lunar PNT and LANS imply the need for transmission of signals exclusively with the direct line-of-sight, due to the lack of significant reflection and diffraction effects.

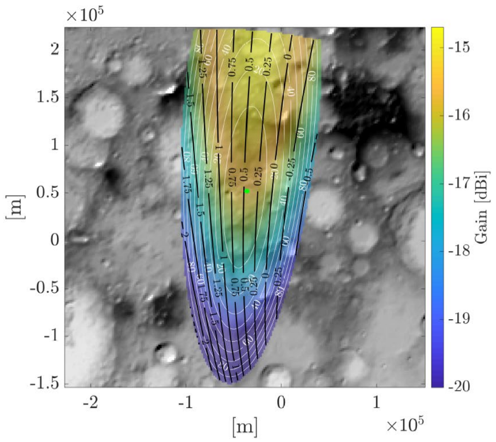
Simulation Considerations

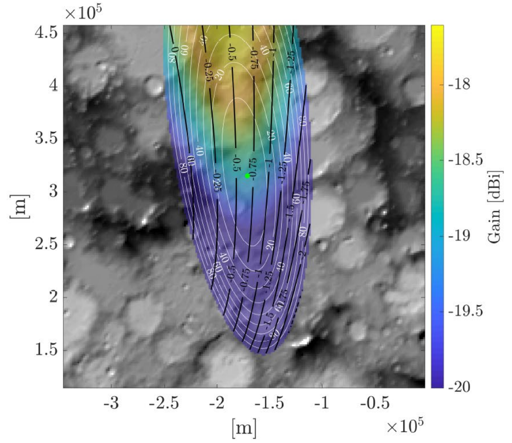
Multipath[7]

- Most of the electrical characteristics of the moon core and regolith have been directly obtained and the estimates seem to vary.
- Research values indicate that core and regolith permittivity and conductivity are similar to some ceramic materials.

	Permittivity	Conductivity
Core	$\varepsilon_1 = 5$	$\sigma_1 = 5 * 10^{-4}$ mhos/m
Regolith	$\varepsilon_2 = 3$	$\sigma_2 = 5 * 10^{-6}$ mhos/m

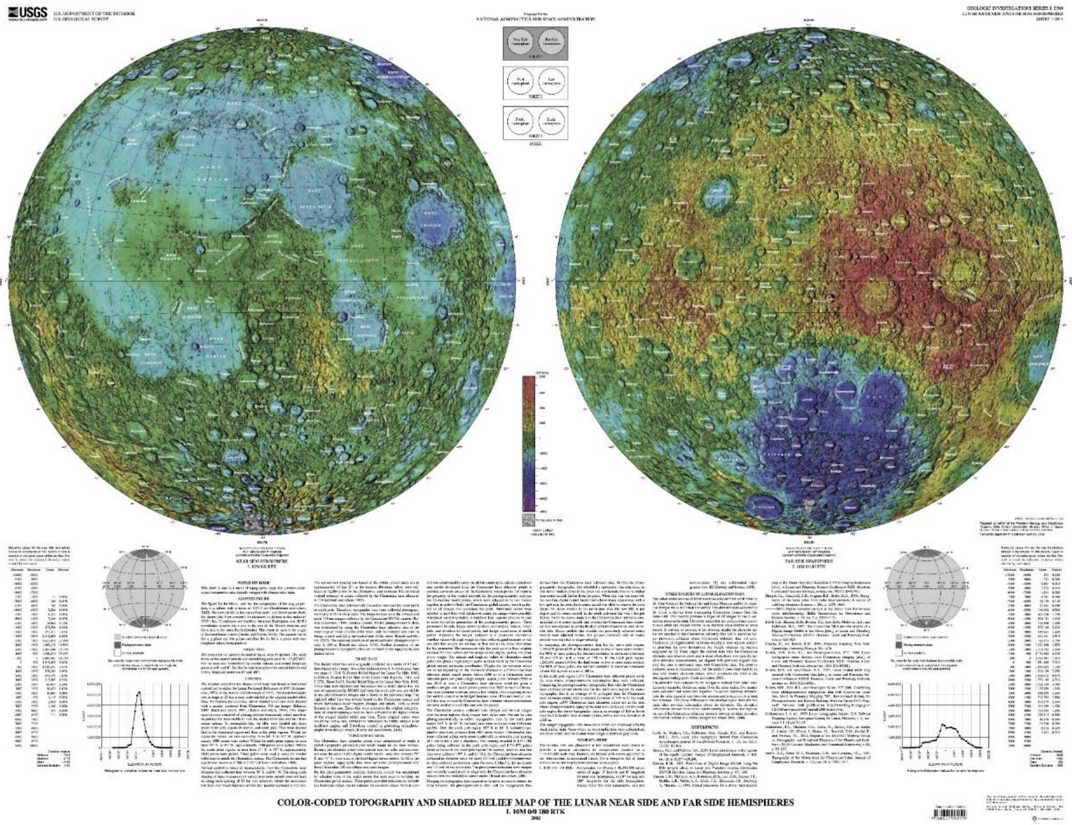
- Opportunistic multipath measurements at the Lunar South Pole with communications between LRO and DSN show the potential impact of multipath in S-Band communication, with 0-2 kHz doppler shift and signal delays of a few microseconds.





Simulation Considerations

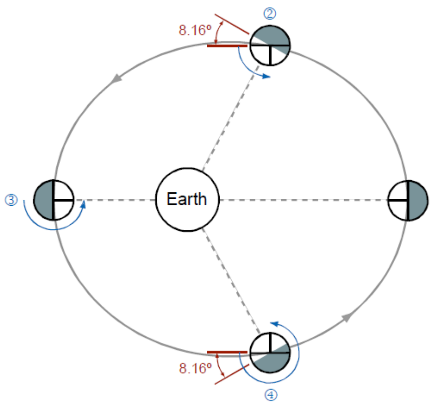
Topography[8]



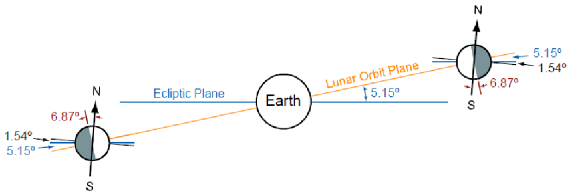
- The maximum and minimum variations are approximately +8 km/-9 km with both extremes occurring on the far-side of the Moon (relative to a sphere with a radius of 1737.4 km)

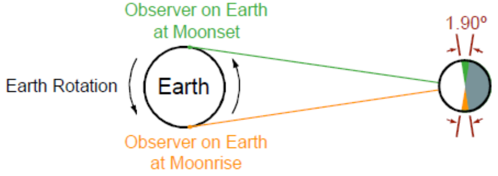
Librations[2]

- Earth and Moon motion that allows observers to see slightly different parts of the Moon's surface at different times



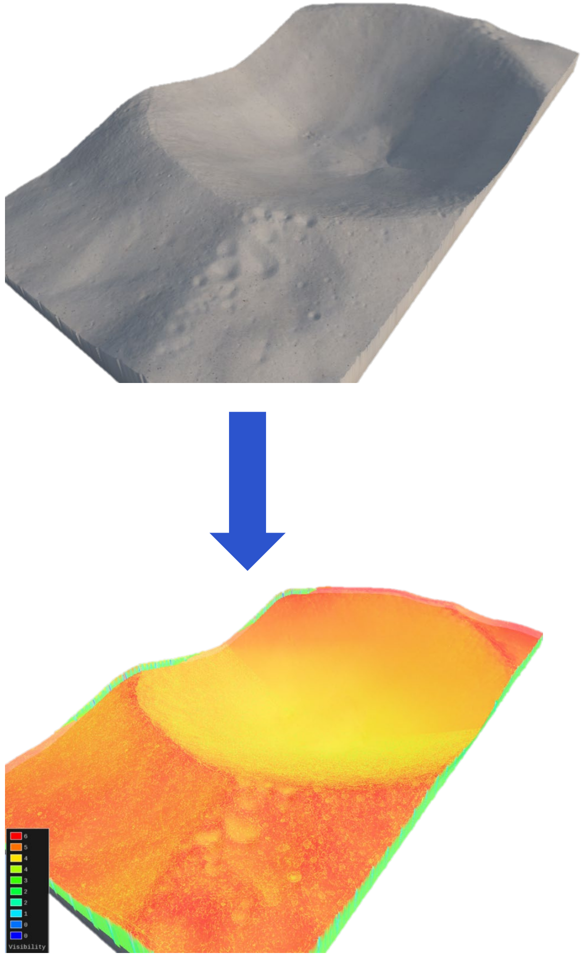
- **Longitude librations** → Relative velocity of the Moon with respect to the Earth is not constant because its orbit is elliptical
- **Latitude librations** → Moon's equator is inclined to the plane of its orbit 6.69 degrees, generating an apparent "nodding" motion
- **Diurnal librations** → Rotation of the Earth causes observers to see the Moon from different angles





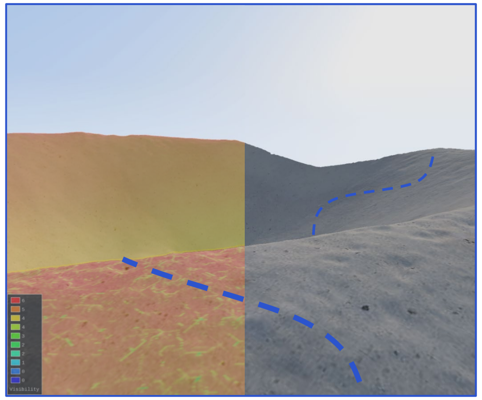
Achievements

Terrain Modelling



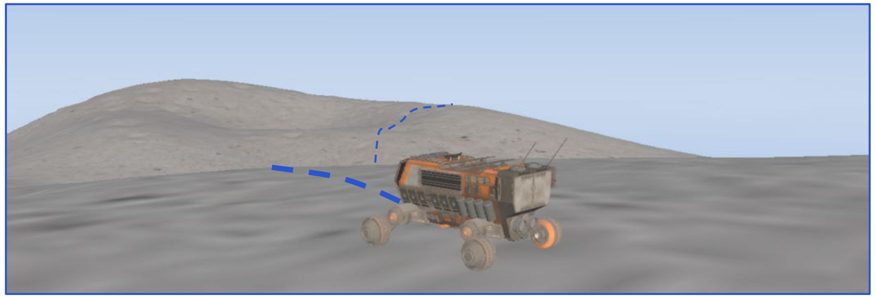
- We are collaborating on research to assess the signal reception characteristics of the lunar navigation constellation on the Moon's surface. Leveraging our advanced 3D capabilities, we analyse obscuration, multipath effects, satellite visibility, and dilution of precision (DOP) along specific trajectories.

- We are also generating heatmaps with information for the following sites:
  - Connecting ridge: -89.090 284°, -136.468 801°
  - Shackleton rim: -89.423 127°, -149.036 243°
  - Peak near Shackleton: -88.825 732°, 141.842 773°



- We are refining an optimization equation to determine the most efficient routes for rovers at various locations near the Moon's South Pole. This process accounts for satellite visibility, multipath effects, dilution of precision (DOP), and mission-specific requirements.

- The results and conclusions from this research will be published at ION GNSS+ 2025.

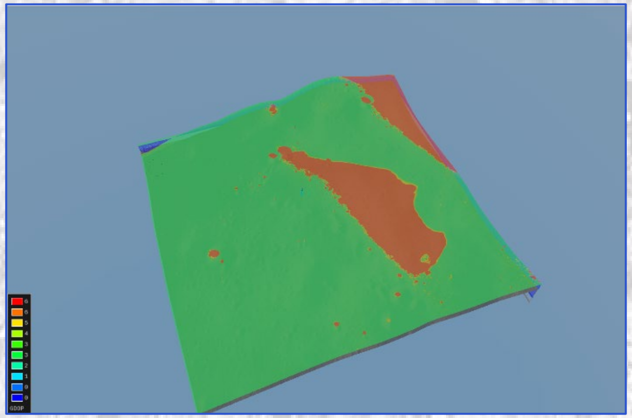


Agenda

1. **PNT to the Moon - Phases**
2. **Simulation Considerations**
3. **Next Steps**

Next Steps

- Expand and enhance our simulation building blocks based on subsequent LunaNet releases – including selenodetic spatial and time reference systems, real-time satellite orbit generation and embedded Moon gravitational models.
- Present our upgrade path for early-adopters that will become available as software updates of their current hardware platform.



- We are open to collaborate in joint research using our tools and share results with the wider community.
- Exploring opportunities to integrate new or existing third-party tools to add value and further enhance our lunar simulation test setup.

References

1. Laurenti, M., Stallo, C., Bellardo, V., Marty, J. C., Giordano, P., Zoccarato, P., Schoenemann, E., Swinden, R., & Traveset, J. V. (2022). Reference Frames Analysis for Lunar Radio Navigation System. *Proceedings of the International Technical Meeting of The Institute of Navigation, ITM*, *2022-January*, 606–615. https://doi.org/10.33012/2022.18170

2. Roncoli, R. B. (2005). *Lunar Constants and Models Document*.

3. Delépaut, A., Giordano, P., Ventura-Traveset, J., Blonski, D., Schönfeldt, M., Schoonejans, P., Aziz, S., & Walker, R. (2020). Use of GNSS for lunar missions and plans for lunar in-orbit development. *Advances in Space Research*, *66*(12), 2739–2756. https://doi.org/10.1016/j.asr.2020.05.018

4. Donaldson, J. E., Parker, J. K., Moreau, M. C. & etal., 2018. Characterization of On-Orbit GPS Transmit Antenna Patterns for Space Users. Miami, Florida, Proceedings of the 31st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2018), pp. 1208-1245

5. Manning, R. M. (2008). *Long-Range Transhorizon Lunar Surface Radio Wave Propagation in the Presence of a Regolith and a Sparse Exospheric Plasma*. http://www.sti.nasa.gov

6. Watson, C., Jayachandran, P. T., Kashcheyev, A., Themens, D. R., Langley, R. B., Marchand, R., & Yau, A. W. (2023). Radio Instrument Package for Lunar Ionospheric Observation: A concept study. Radio Science, 58, e2023RS007666. https://doi.org/10.1029/2023RS007666

7. Sanchez, M., Rodriguez-Alvarez, N., Kahan, D., Morabito, D. D., & Elliott, H. M. (2020). *Multipath Measurements at the Lunar South Pole from Opportunistic Ground-based Observations — Part I: Experiment Concept.*

8. USGS (2017). *Moon Clementine Topographic Maps*.

9. Spirent (2024). PNT X Datasheet. Available at: PNT X Simulation System Datasheet - Spirent