Spirent

Taking PNT to the Moon

October 2023

Agenda

1. PNT to the Moon - Phases
2. Simulation Challenges
3. Simulation Solutions
4. References

Agenda

1 **PNT to the Moon - Phases**

1.1 Earth-Based GNSS

1.2 LANS (Initial Services)

1.3 LANS (Enhanced Services)

2 **Simulation Challenges**

3 **Simulation Solutions**

4 **References**

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

PNT to the Moon – Phases

Earth-Based GNSS

2023 - onwards

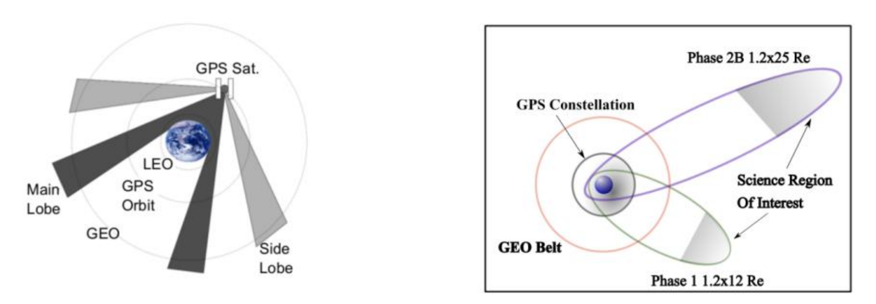
Use of Earth-Based GNSS constellations for PNT in lunar missions.

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

Receiver Technology[1]

- High-sensitive acquisition and tracking algorithms
- Compact design (inc. power)
- In-flight FW/SW upgradability
- Reliability on long missions

Missions



NASA MMS – 2015[2]

- Highest operational use of GPS
- Acquisition and tracking of sidelobe signals
- Vehicle spinning at 3 RPM ► 4 antennas

SpacePNT NaviMoon[3] for **ESA Lunar Pathfinder[4]**

NASA-ISA LuGRE[5] for **Blue Ghost Mission I[6]**

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PNT to the Moon – Phases

LANS (Initial Services)

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- Vehicle descent, landing and ascent
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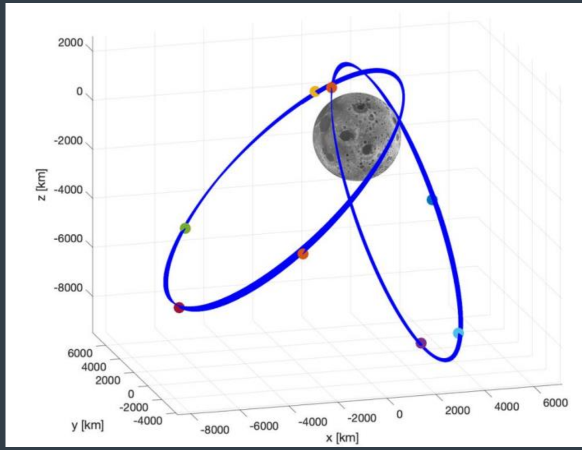
[8]



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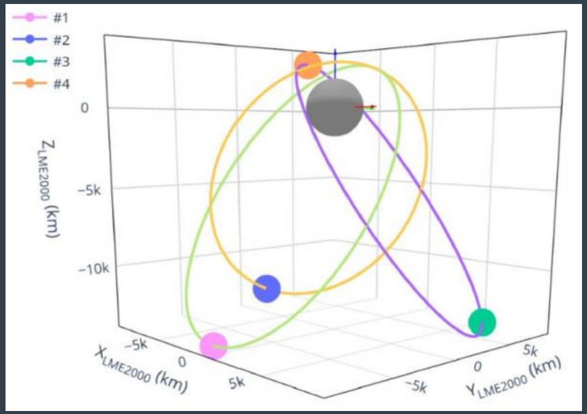


General Requirements

- Real-time horizontal positioning accuracy less than 40-50 meters at the lunar South Pole region at any time
- Accurate orbit and clock determination
- Compliant with LunaNet standard[9] to become LNSP
- Use of Elliptical Lunar Frozen Orbits (ELFO)
- S-Band signals at 2492.028MHz
- BPSK Modulation

Missions

NASA LCRNS, JAXA LNSS & ESA Moonlight

PNT to the Moon – Phases

LANS (Enhanced Services)

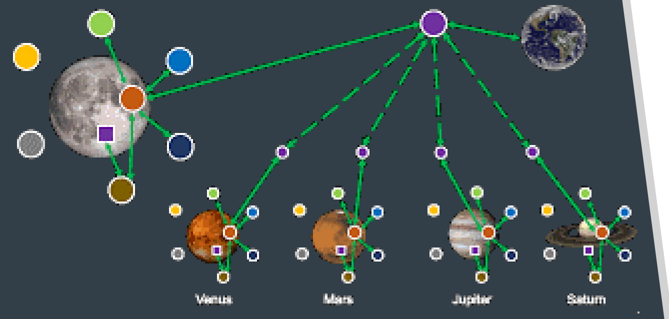
2035 - onwards

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

- Full lunar surface PNT
- Service integrity

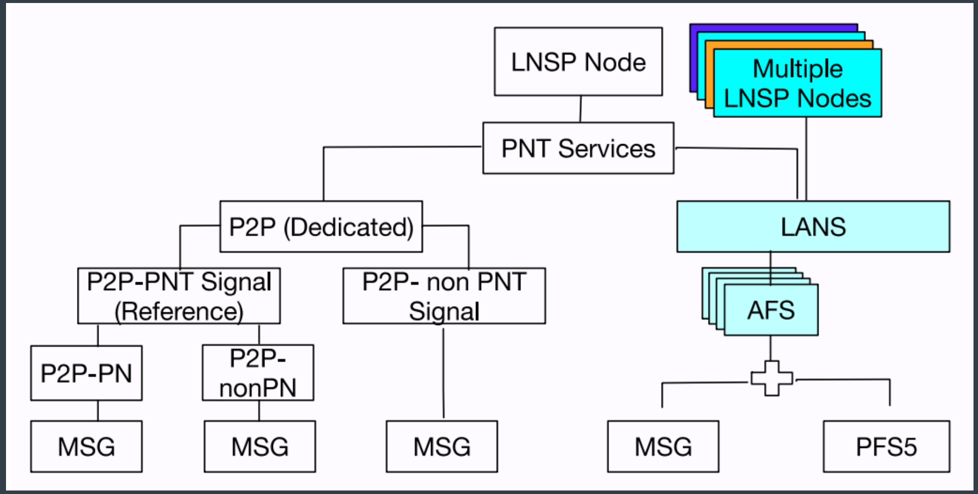
LunaNet[9,10]

- Flexible and scalable architecture for the provision of Network, PNT and science utilization services
- Infrastructure built up as mission requirements evolve
- SmallSats can be providers or users
- Combination of institutional and commercial nodes



Operations & Services

- NASA Artemis
- NASA LunaSAR within Artemis program



Agenda

1 **PNT to the Moon - Phases**

2 **Simulation Challenges**

- 2.1 Lunar Orbital Dynamics Modelling
- 2.2 Selenodetic Reference Systems
- 2.3 Realistic Tx Antenna Patterns
- 2.4 Signal Propagation
- 2.5 Multipath
- 2.6 Topography & Librations

3 **Simulation Solutions**

4 **References**

Why Simulation?

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

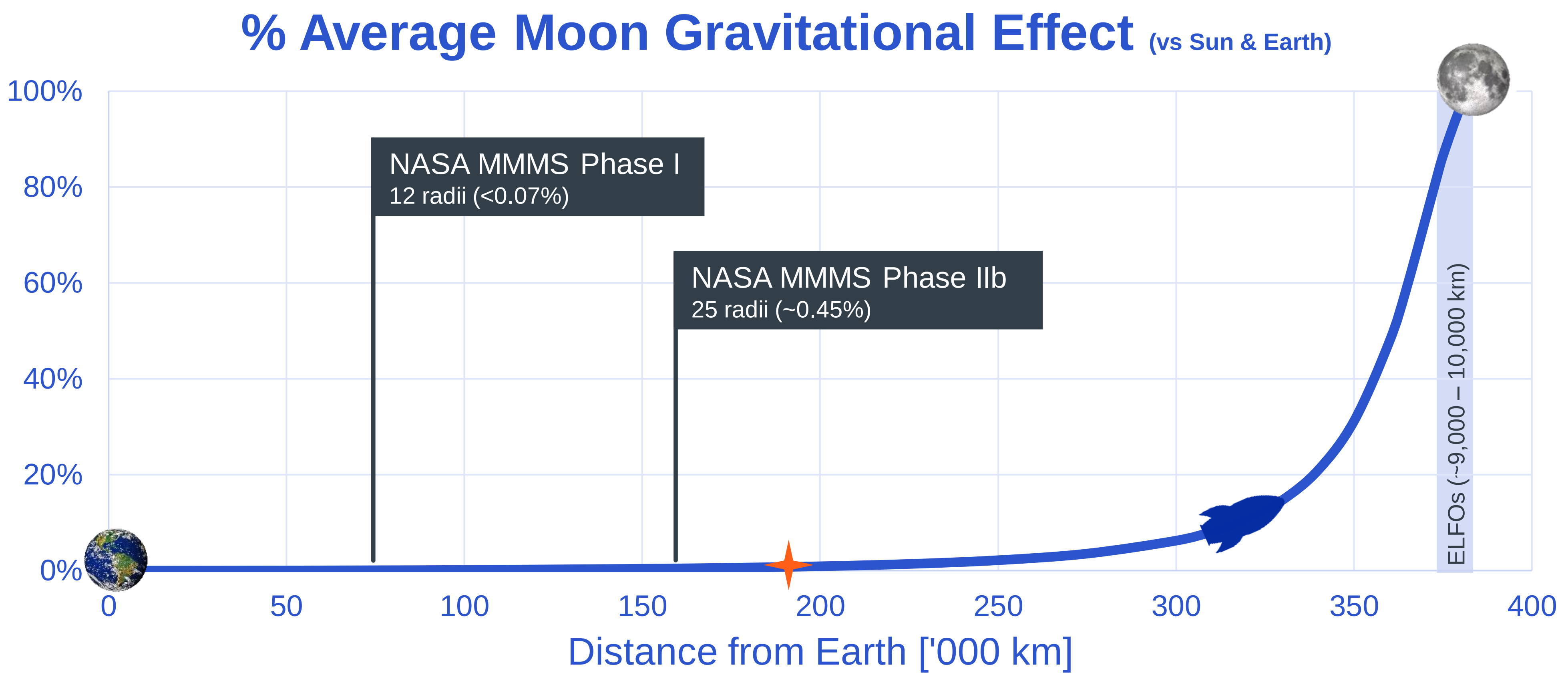
To successfully bring PNT to the Moon, the design of the various parts of the system, in particular GNSS receivers, must be of a high standard that ensures reliable performance. To enable this, it is important that the product development process is based on proper testing from concept to production.

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

Simulation Challenges

Lunar Orbital Dynamics Modelling

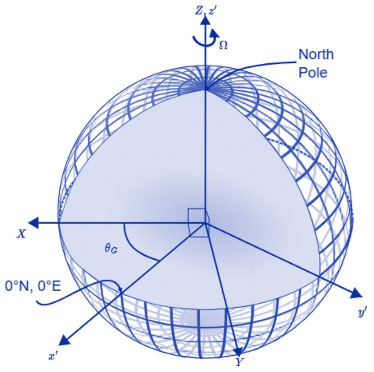


- New dynamics model required to account for the uneven gravitational pull from the Moon, perturbations from other celestial bodies, different solar radiation pressure, etc.

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

Simulation Challenges

Selenodetic Reference Systems[11]



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)

Body-Fixed Lunar Reference Systems

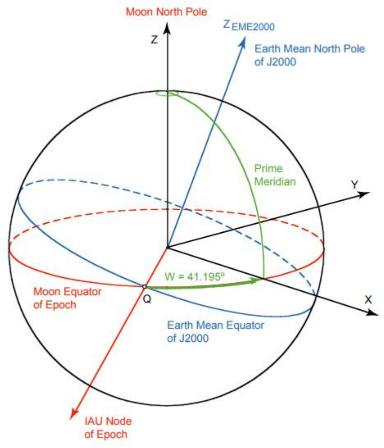
- **Mean Earth Rotation (MER)** – mean direction to Earth (X) and mean Lunar spin (Z): mainly used for cartography

$\nparallel$ 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

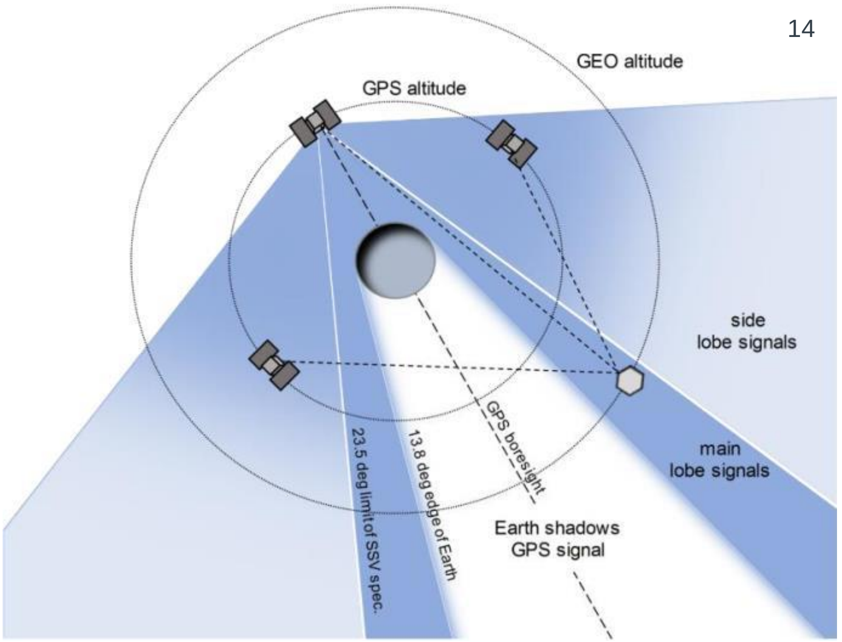
- Recommendation is to use a frame that is aligned to the Moon equator at a reference epoch to ease integration of lunar orbits
- Roncali[12] contains a complete list of Moon-Centred inertial frames



Simulation Challenges

Realistic Tx Antenna Patterns & SV Dynamics Modelling[13]

- Limited availability of Tx antenna pattern data.
- 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



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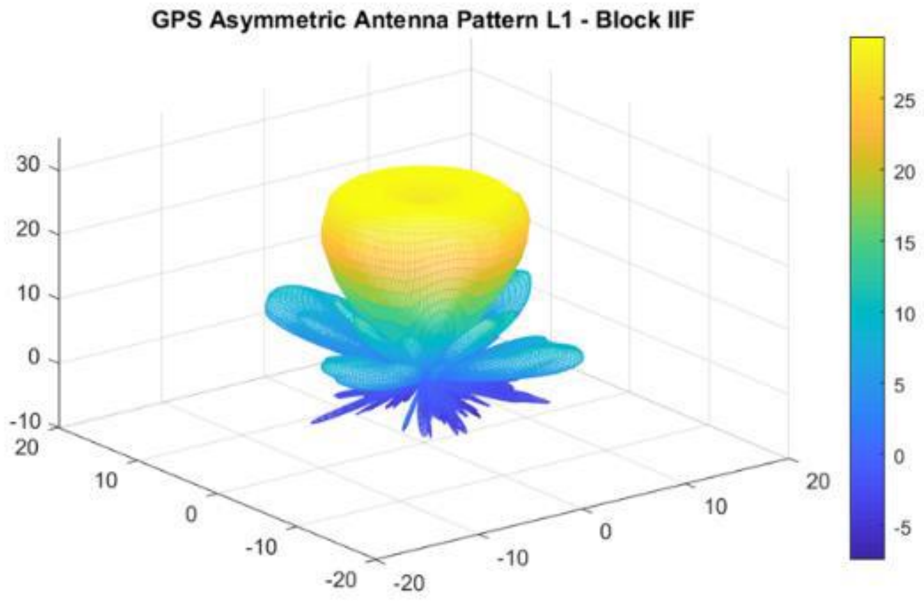

Simulation Challenges

Signal Propagation[15]

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.

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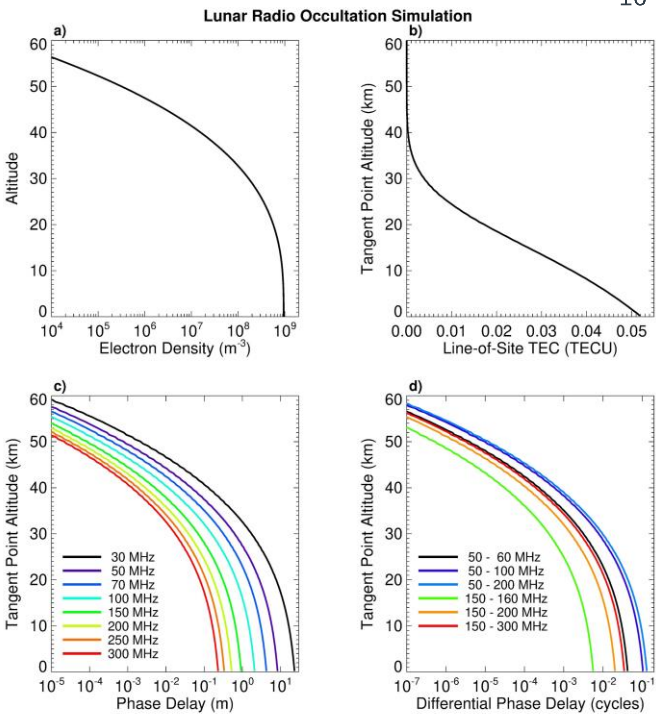


LANS

- 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.

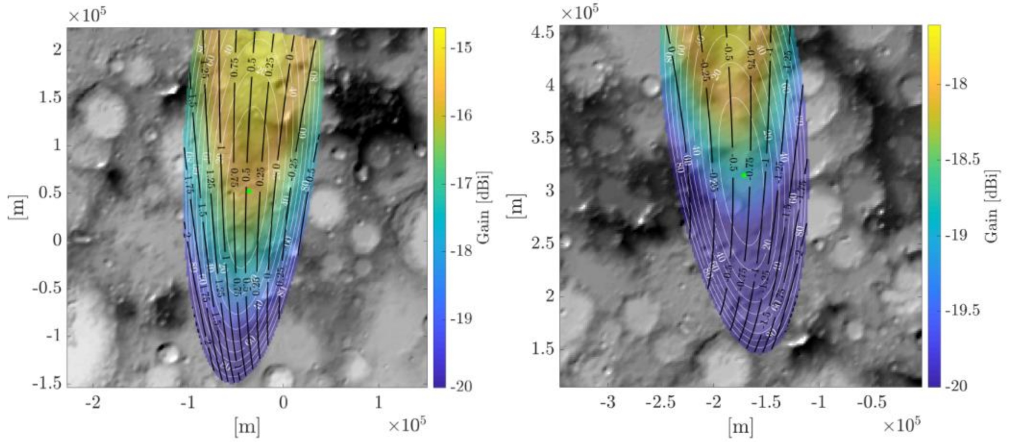
Simulation Challenges

Multipath[17]

- 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.

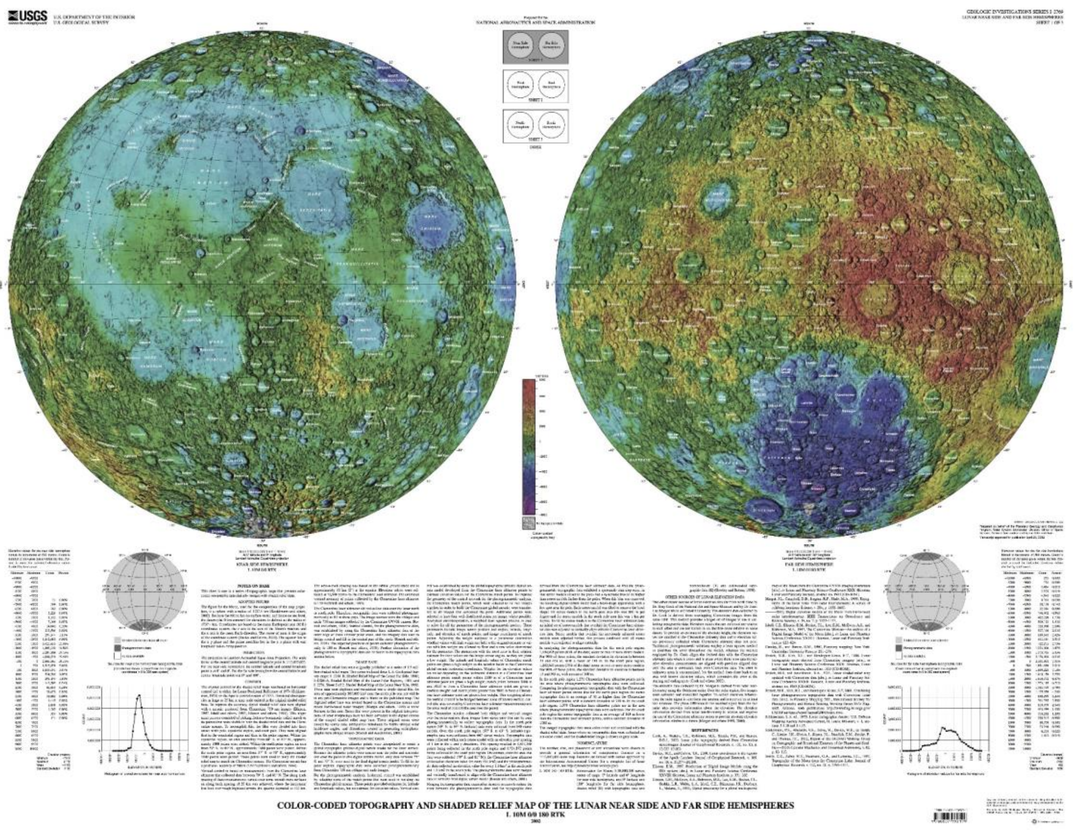
	Permittivity	Conductivity
Core	$\varepsilon_1 = 5$	$\sigma_1 = 5 * 10^{-4}$ mhos/m
Regolith	$\varepsilon_2 = 3$	$\sigma_2 = 5 * 10^{-6}$ mhos/m

- 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 Challenges

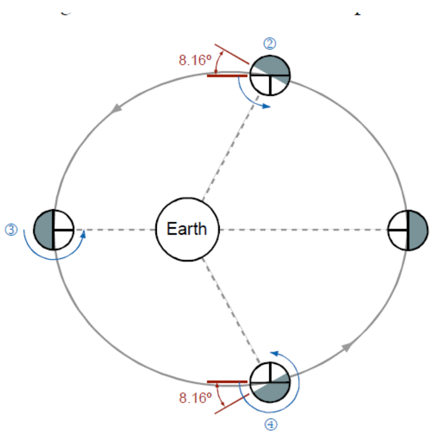
Topography[18]



- 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[12]

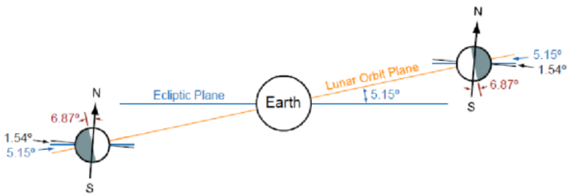
- Earth and Moon motion that allows observers to see slightly different parts of the Moon's surface at different times

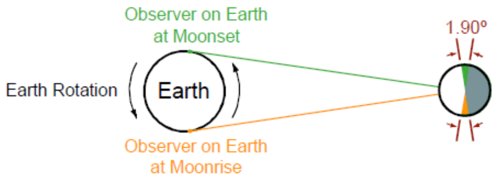


- **Longitude librations** → Relative velocity of the Moon with respect to the Earth is not constant because its orbit is elliptical

- **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





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2 **Simulation Challenges**

3 **Simulation Solutions**

3.1 System Requirements

3.2 Spirent Solutions

4 **References**

Simulation Solutions

System Requirements

- Scalable platform capable of simulating high-fidelity GNSS and LANS AFS (Augmented Forward Signal) RF.
- Embedded solar and lunar orbital dynamics for accurate trajectory and constellation orbits generation.
- Support for different lunar body-fixed and inertial reference frames.
- Accurate representation of Tx antenna patterns and satellite in-orbit rotations.
- Realistic Earth ionospheric modelling based on TEC calculations relative to the distance travelled by RF signals.
- Statistical multipath modelling for moon’s regolith and core.
- Future-proof platform that can accommodate future needs (e.g., realistic 3D environments).

Simulation Solutions

High Dynamics

Up to 2 kHz (0.5 ms) update rate

Multi-Orbit Definition

Native support for multi-constellation RF and orbital data input (e.g., via SP3 files)

Custom Antenna Patterns

User-defined Rx antenna patterns

Atmospheric Modelling

Customisable atmospheric models, including ionospheric, tropospheric and scintillation effects

Multipath

Statistical and 3D-based multipath solutions available

Spirent GSS9000[19]

Defining Non-SIS ICD Signals

RF Generation from I/Q

Generate any type of in-band RF signals from I/Q files including interference, noise and non-SIS ICD signals

Import any I/Q file from external software applications and generate high-fidelity RF to test your hardware platform

FLEX Signal Generation

Design open and secure non-SIS ICD signals controlling low level signal parameters such as chip rate, modulation, frequency, codes and navigation data

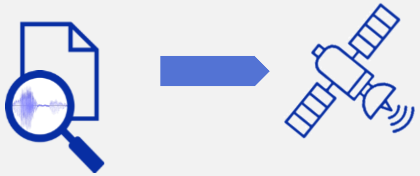
Generate synchronous RF including GNSS and custom FLEX signals

Simulation Solutions

RF GENERATION FROM I/Q

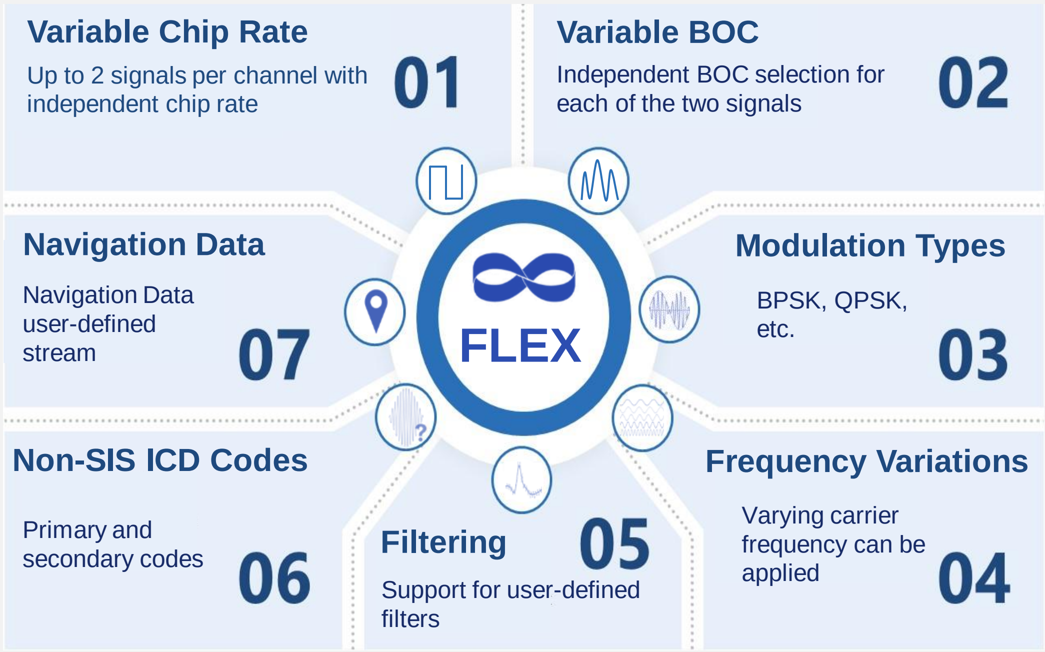
User provides I/Q file containing all satellite signal data for individual SVs or constellations

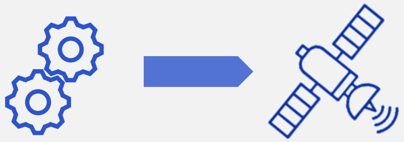
- Injection of various I/Q files per scenario run containing custom waveform, interference, noise and/or non-SIS ICD signal data
- Definition of transmitter objects associated with the I//Q files that apply the corresponding **attenuation power levels** to the signals in the I/Q files based on the distance from the transmitter to the receiver antenna
- Generation of RF from I/Q data alongside existing GNSS signals defined in SimGEN



FLEX SIGNAL GENERATION

User defines individual low-level signal parameters prior to RF generation



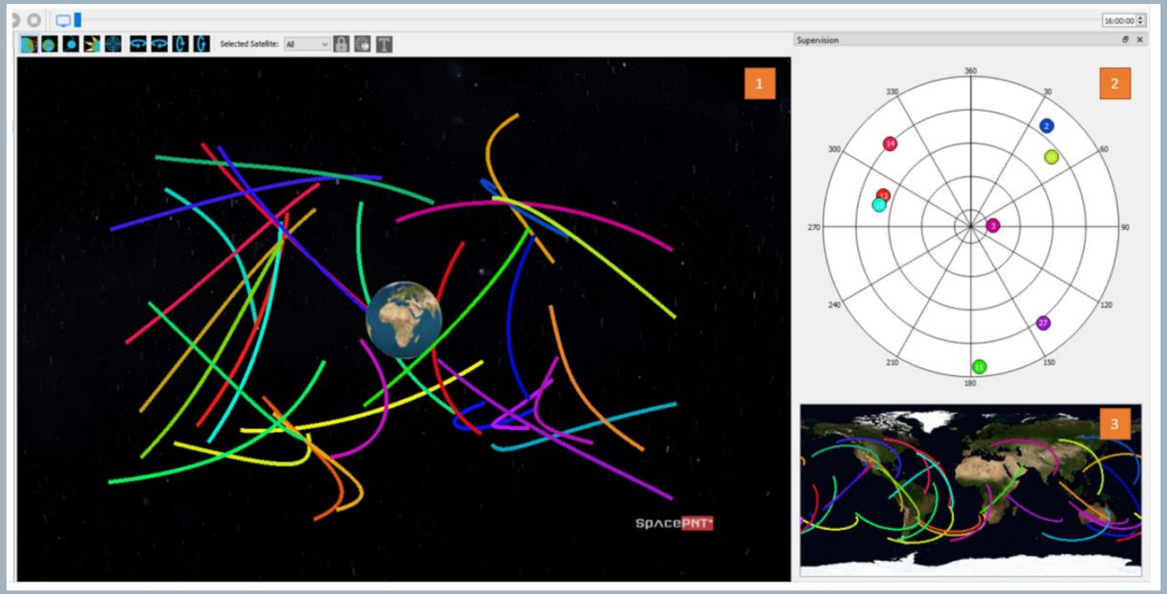


Simulation Solutions

SimOrbit

Accurate orbital modelling tool that can be used as a reference trajectory propagator

- Create vehicle trajectories based on accurate orbital dynamics modelling accounting for gravitational effects and drag
- Generate constellation orbits with up to 85 satellites
- Pre-canned vehicle types with fully customisable parameters (e.g., drag coefficient, mass, cross-section area, etc.)



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