

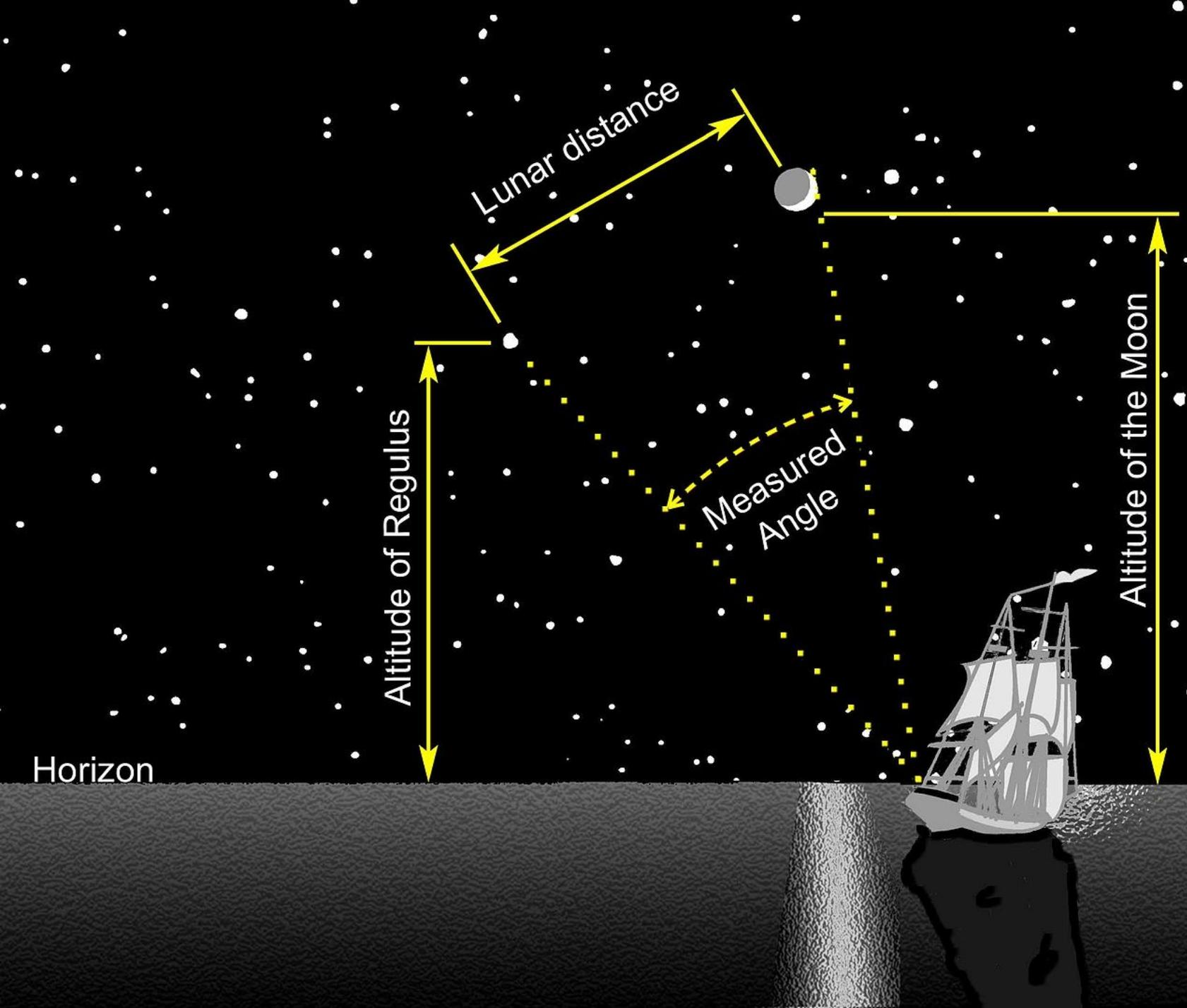


Is Now Part of Keysight

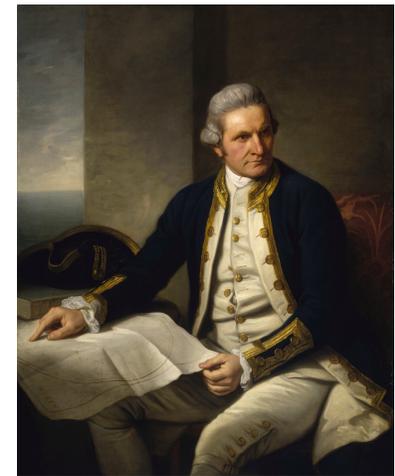
End-to-End Simulation Framework for LunaNet and Mars GPS-Like Signals for Software Receiver Assessment

Cislunar Workshop 2026

Vienna



Johannes Werner
XV Century



James Cook
XVIII Century



Agenda

- How we approach PNT simulation?
- Lunar PNT simulation challenges
- Use case



Agenda

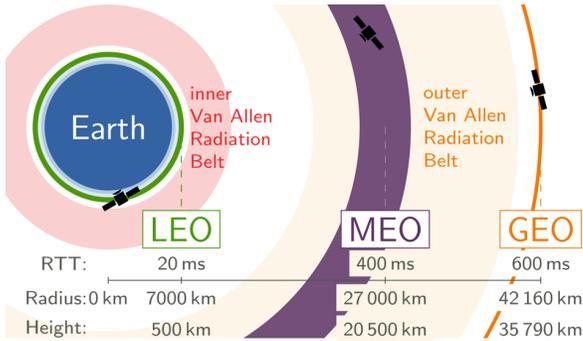
- End-to-end Mars PNT simulation
- Mars PNT simulator
- Mars PNT software receiver



Agenda

- **How we approach PNT simulation?**
- Lunar PNT simulation challenges
- Use case

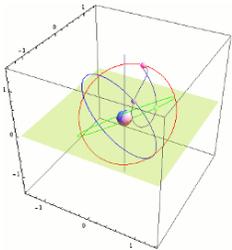
How we approach PNT simulation?



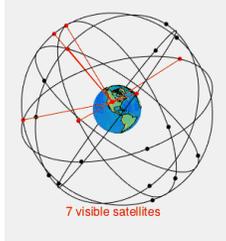
Geostationary (WAAS, EGNOS, MSAS, NavIC)

Medium Earth Orbit (GPS, GLONASS, Galileo, Beidou)

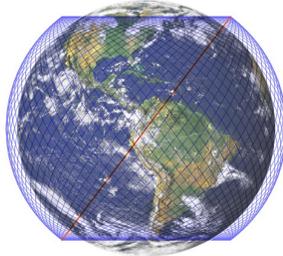
Low Earth Orbit (Starlink, Xona)



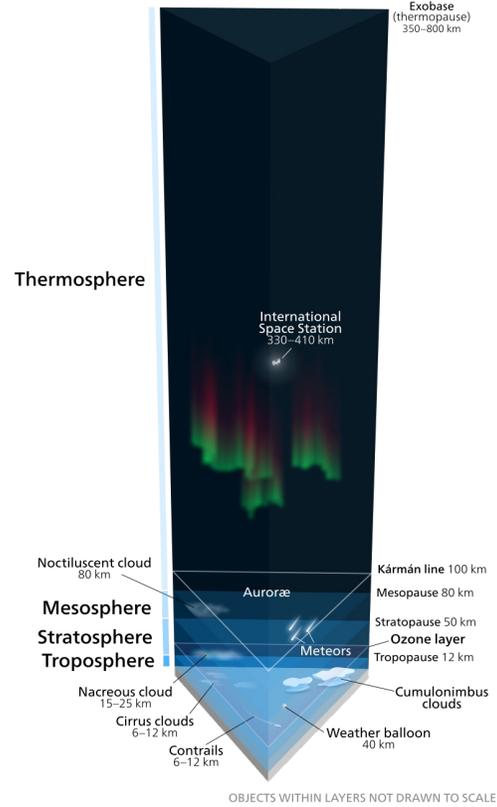
QZ



GPS



Starlink

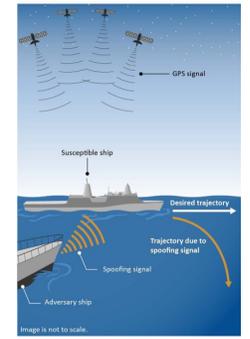


Ionosphere & Troposphere

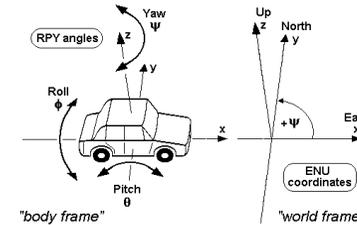


Environment

Figure 2: Potential results of a GPS spoofing attack on a naval vessel



Signal Interference



Vehicle Dynamics



Antenna Dynamics



Agenda

- How we approach PNT simulation?
- **Lunar PNT simulation challenges**
- Use case

Lunar PNT Simulation Challenges



Lunar Orbital Dynamics Modelling & DUT position

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



Selenodetic Reference Systems

Including spatial (body-fixed and inertial) and timing reference systems.



LunaNet Signal Definition

Simulating low-level signal parameters and flexible navigation data content to accommodate users' needs.



Signal Propagation

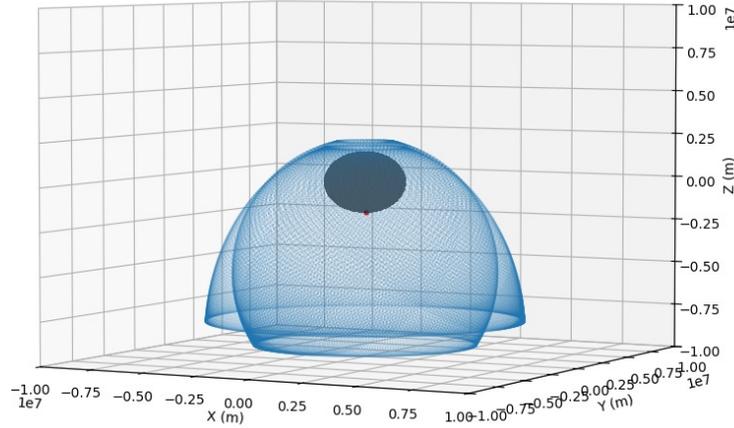
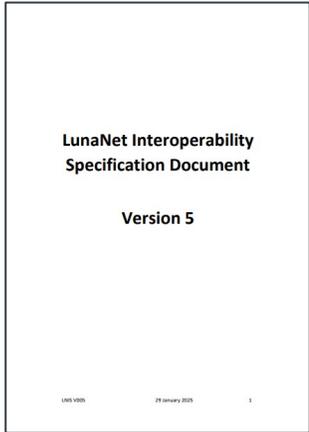
Antenna transmission, free-space loss, relativistic effects.



Moon's ephemerides & topography

Critical for obscuration and multipath calculations as well as Moon-to-Earth comms.

Lunar Orbital Dynamics



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

FLEX definition of LunaNET signals based on latest ICD available (Version 5)



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	8823314.105	-235.89	10.00	0.00

- Modelled satellite orbits as well as vehicle real-time orientation.
- Signal received includes vehicle motion, doppler shifts and power levels received as per LunaNet specification.

SimORBIT+

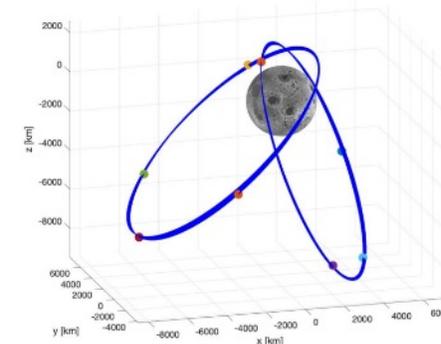
Embedded library for precise orbit generation
(LEO and Lunar)

- Accurate orbital dynamics modelling accounting for gravitational effects and drag
- Generate constellation orbits – enhanced version capable for highly precise lunar orbits
- Pre-canned vehicle types with customisable parameters



SimORBIT Lunar models include:

- **Gravitational perturbations** from the Moon, Earth, and Sun, including harmonic representations of the Moon and Earth gravity fields.
- **Celestial Body Dynamics and Ephemerides** to account for the dynamic positions and motions of all major celestial bodies relevant to lunar orbit propagation.
- **Solar Radiation Pressure (SRP)** based on a spacecraft cross-section and material properties.
- **Reference Frames and Transformations:** The core propagation operates in a Moon-centered inertial frame.
- **Defined Operational Envelope:** Valid for the complete Moon's sphere of influence (approximately 64,000 km).



Lunar Orbital Dynamics



Now Part of Keysight

The screenshot displays the SimGEN software interface for configuring Lunar Orbital Dynamics. The main window shows a 3D simulation environment with various gauges (Speed, Vertical Speed, Heading, Altitude) and a map. A 'GPS signal sources - test.gps' dialog is open, showing satellite selection and orbital parameters. A 'Default' dropdown menu is open, listing orbital plane types: ECEF, ECI, ECI_B1950, MOON_PA, MOON_ME, EARTH_ORBITAL_PLANE, LME2000, and MOON_J2000. A red arrow points from this menu to the 'Orbital planes' dialog, which is also open. The 'Orbital planes' dialog shows the following configuration:

Parameter	Value	Unit	Option
Enabled satellites	8		
Orbital planes	2		
Inclination angle	55	degrees	
Semi-major axis	6540000	metres	
Orbital altitude	161863	metres	
First longitude of ascending node	0	degrees	
Longitude of ascending node spacing	60	degrees	<input checked="" type="checkbox"/> Auto
First mean anomaly (M0)	0	degrees	
In-plane M0 spacing	90	degrees	<input checked="" type="checkbox"/> Auto
Between-planes M0 offset	5	degrees	<input checked="" type="checkbox"/> Auto

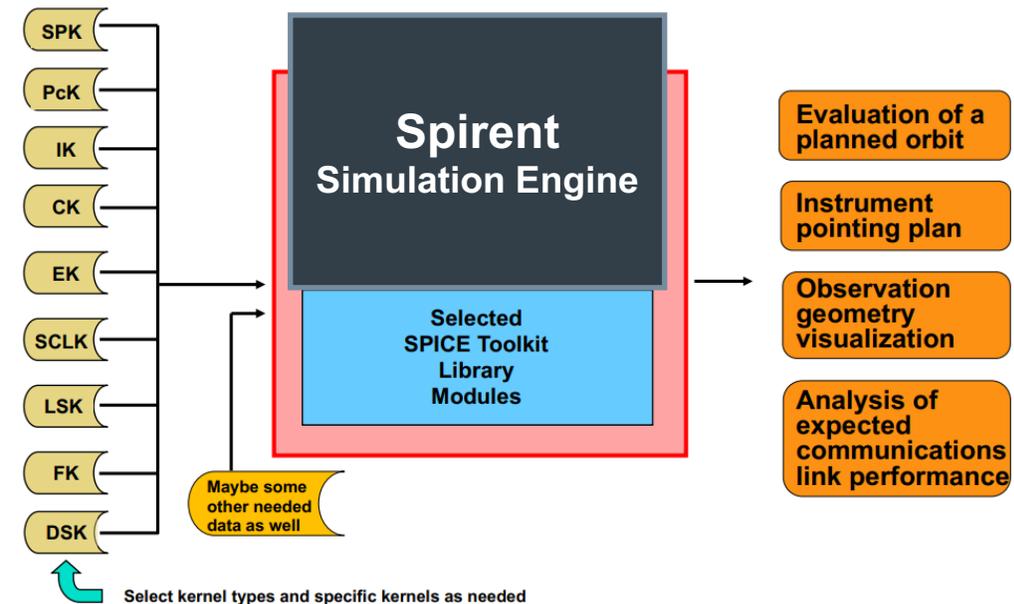
The background interface includes a 'Vehicle Dynamics' panel with gauges for Speed (0-120), Vertical Speed (0-15), Heading (0-360), and Altitude (0-10000ft). A 'Position Details' window shows coordinates and altitude. The bottom status bar indicates 'GPS best set = 2, 3, 4, 5, GDOP = 23154 (All = 23154)' and system status like 'H/W: Dual-output secure 9000', 'Compatible H/W', and 'Ready to run'.

Reference Systems – NASA SPICE

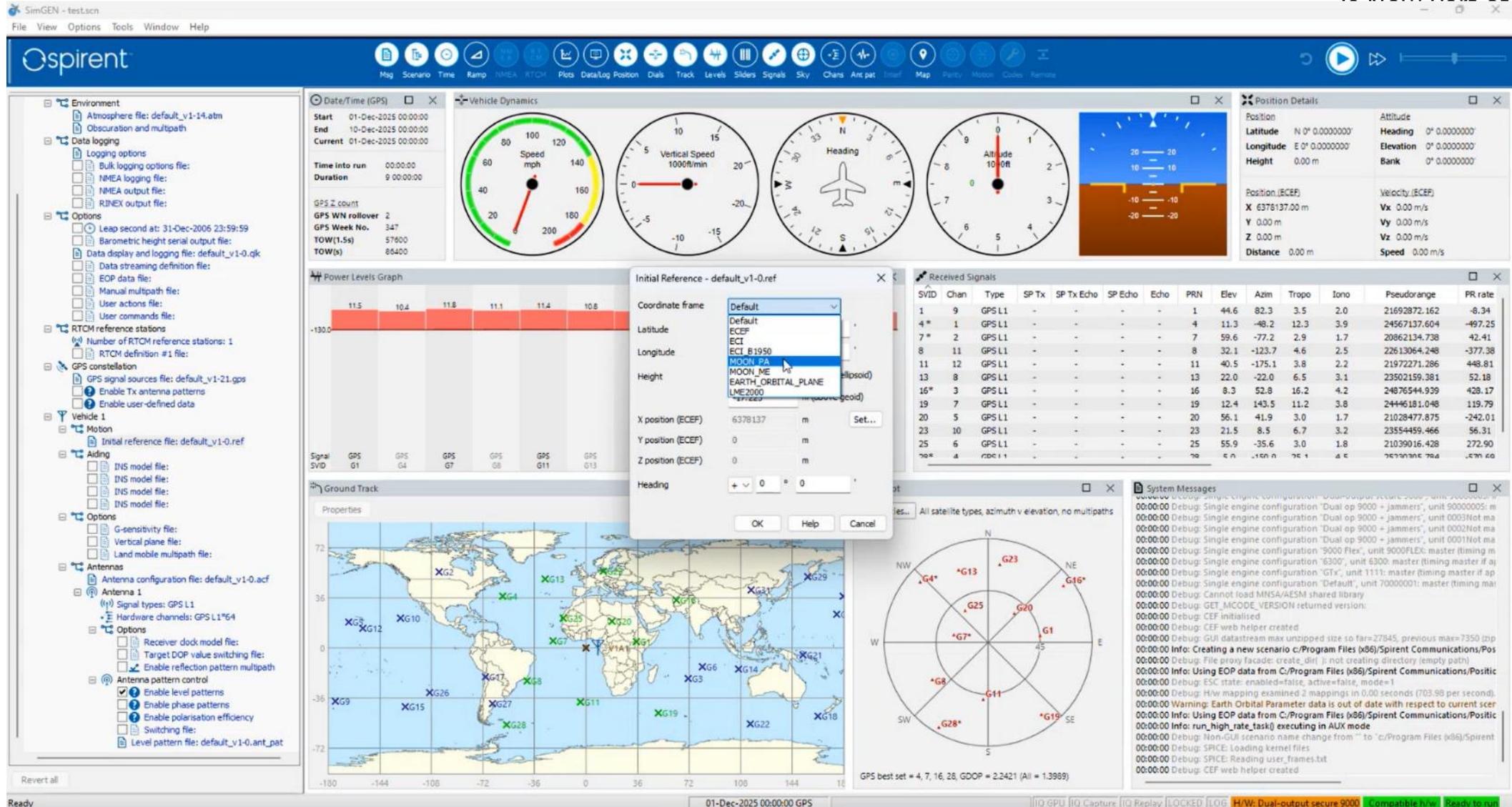
Implementation of selected SPICE kernels to define and manage reference systems.

Modular integration that ensures:

- **Dynamic Frame Resolution:** Accurate transformations between inertial and rotating reference frames (e.g., ICRF to Moon-fixed or ITRF).
- **User-Defined Frame Flexibility:** Full support for custom frame definitions without requiring modifications to the simulator core.
- **Future-Proofing:** Ephemeris and frame data can be updated by users via kernel files without code changes.



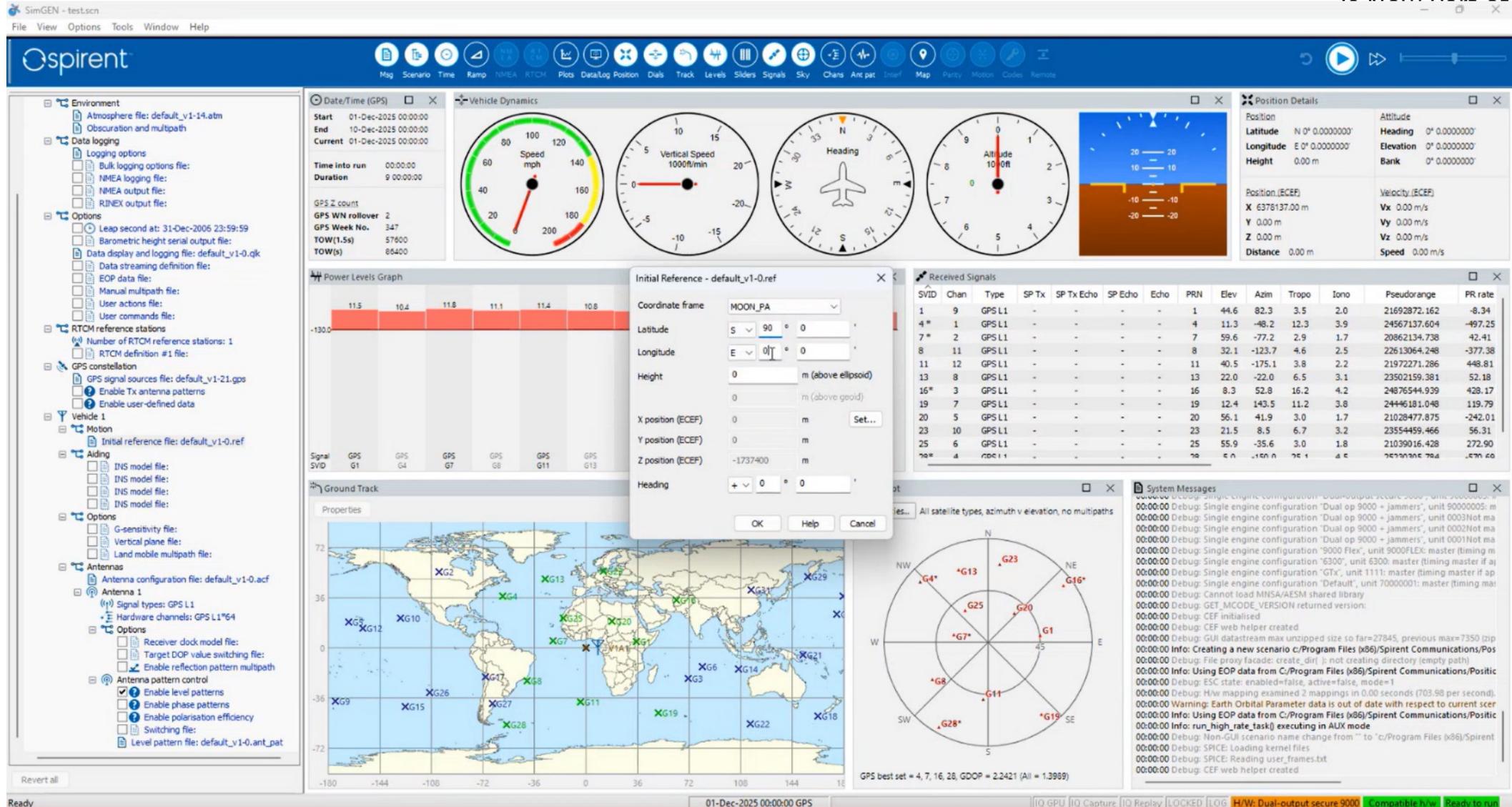
Lunar DUT Position



The screenshot displays the Spirent SimGEN software interface for a simulation titled "test.scn". The interface is divided into several panels:

- Environment:** Shows simulation settings such as "Atmosphere file: default_v1-14.atm" and "Data logging" options.
- Date/Time (GPS):** Displays simulation time: Start 01-Dec-2025 00:00:00, End 10-Dec-2025 00:00:00, Current 01-Dec-2025 00:00:00.
- Vehicle Dynamics:** Features four circular gauges for Speed (0-200 mph), Vertical Speed (0-20 1000ft/min), Heading (0-360 degrees), and Altitude (0-10000 ft).
- Position Details:** Shows Position (Latitude: N 0° 0.0000000', Longitude: E 0° 0.0000000', Height: 0.00 m) and Velocity (Vx: 0.00 m/s, Vy: 0.00 m/s, Vz: 0.00 m/s, Speed: 0.00 m/s).
- Power Levels Graph:** A bar chart showing power levels for various signals.
- Initial Reference - default_v1-0.ref:** A dialog box for setting the coordinate frame. The "MOON_PA" option is selected in the dropdown menu.
- Received Signals:** A table listing received signals with columns for SVID, Chan, Type, SP Tx, SP Tx Echo, SP Echo, Echo, PRN, Elev, Azim, Tropo, Iono, Pseudorange, and PR rate.
- Ground Track:** A world map showing the ground track of the vehicle, with various signal sources labeled (e.g., XG1, XG2, XG3, XG4, XG5, XG6, XG7, XG8, XG9, XG10, XG11, XG12, XG13, XG14, XG15, XG16, XG17, XG18, XG19, XG20, XG21, XG22, XG23, XG24, XG25, XG26, XG27, XG28).
- System Messages:** A log window showing system messages and debug information.

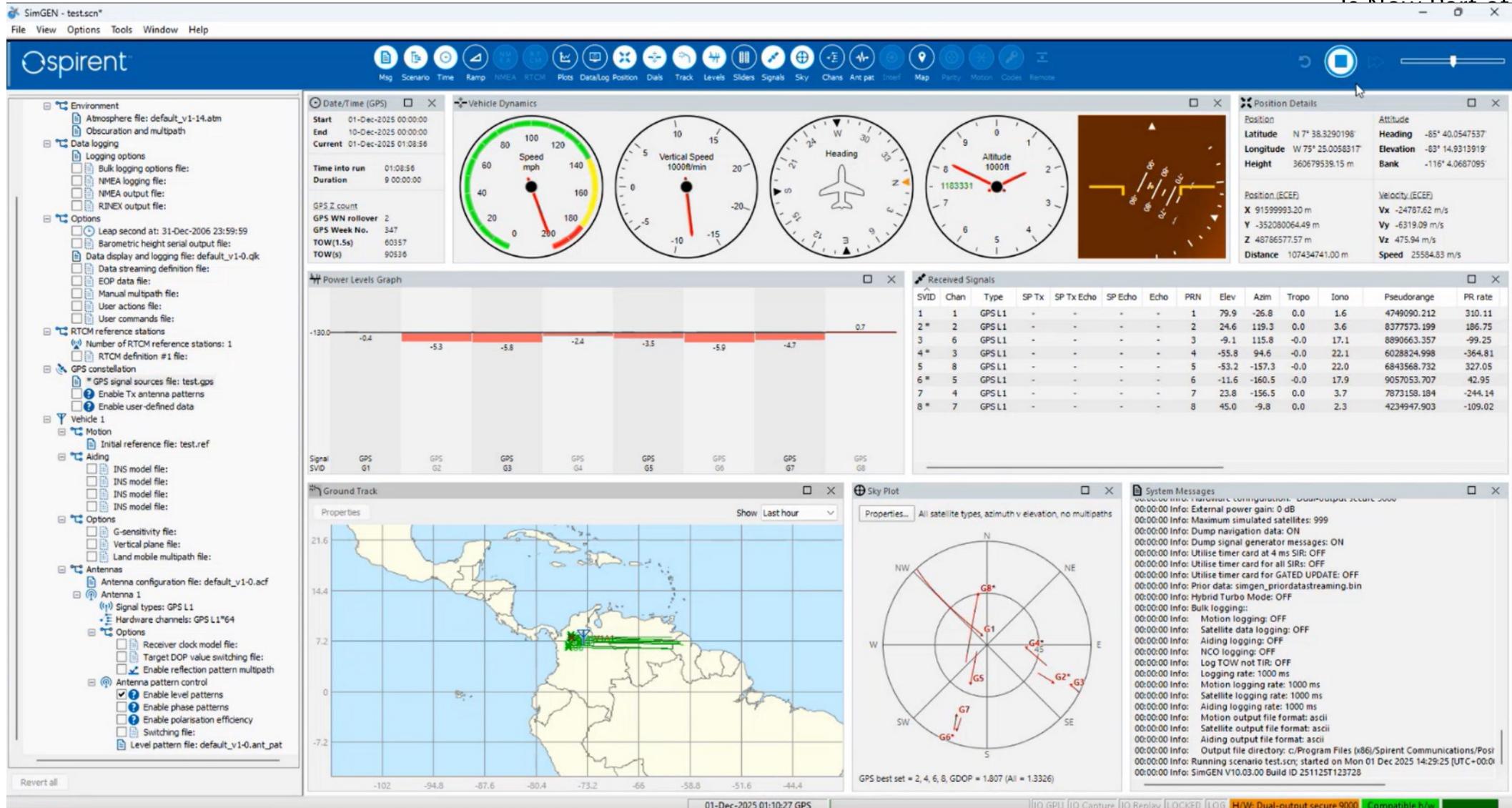
Lunar DUT Position



The screenshot displays the SimGEN software interface for a Lunar DUT Position simulation. The interface is divided into several panels:

- Environment:** Shows simulation parameters such as Atmosphere file (default_v1-14.atm), Logging options, and Options.
- Date/Time (GPS):** Displays the start and end times (01-Dec-2025 00:00:00 to 10-Dec-2025 00:00:00) and current time (01-Dec-2025 00:00:00).
- Vehicle Dynamics:** Features four circular gauges for Speed (0-200 mph), Vertical Speed (0-20 1000ft/min), Heading (0-360 degrees), and Altitude (0-10000 ft).
- Position Details:** Shows current position (Latitude: N 0° 0.000000', Longitude: E 0° 0.000000', Height: 0.00 m) and velocity (Vx: 0.00 m/s, Vy: 0.00 m/s, Vz: 0.00 m/s).
- Power Levels Graph:** A bar chart showing power levels for various signals (G1, G4, G7, G8, G11, G13).
- Initial Reference - default_v1-0.ref:** A dialog box for setting the coordinate frame (MOON_PA) and position (X, Y, Z in ECEF) and heading.
- Received Signals:** A table listing received signals with columns for SVID, Chan, Type, SP Tx, SP Tx Echo, SP Echo, Echo, PRN, Elev, Azim, Tropo, Iono, Pseudorange, and PR rate.
- Ground Track:** A world map showing the ground track of the satellite constellation, with various satellite positions labeled (e.g., XG1, XG2, XG3, XG4, XG5, XG6, XG7, XG8, XG9, XG10, XG11, XG12, XG13, XG14, XG15, XG16, XG17, XG18, XG19, XG20, XG21, XG22, XG23, XG24, XG25, XG26, XG27, XG28).
- System Messages:** A log of system messages, including debug and info messages related to engine configuration, data stream, and file operations.

Lunar DUT Position



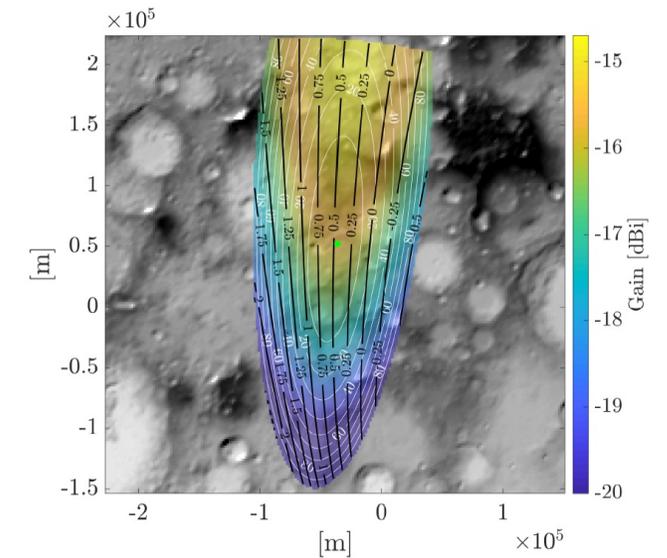
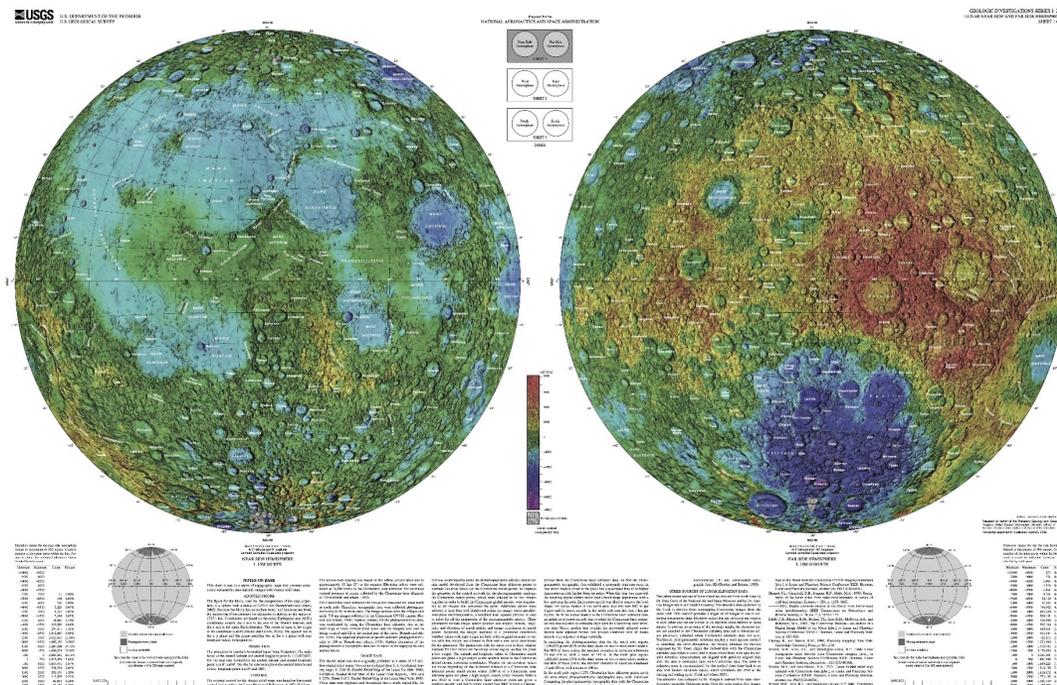
Environment

- Atmosphere file: default_v1-14.atm
- Obscuration and multipath
- Data logging
 - Logging options
 - Bulk logging options file:
 - NMEA logging file:
 - NMEA output file:
 - RINEX output file:
- Options
 - Leap second at: 31-Dec-2006 23:59:59
 - Barometric height serial output file:
 - Data display and logging file: default_v1-0.qk
 - Data streaming definition file:
 - EOP data file:
 - Manual multipath file:
 - User actions file:
 - User commands file:
- RTCM reference stations
 - Number of RTCM reference stations: 1
 - RTCM definition #1 file:
- GPS constellation
 - GPS signal sources file: test.gps
 - Enable Tx antenna patterns
 - Enable user-defined data
- Vehicle 1
 - Motion
 - Initial reference file: test.ref
 - Aiding
 - INS model file:
 - INS model file:
 - INS model file:
 - INS model file:
 - Options
 - G-sensitivity file:
 - Vertical plane file:
 - Land mobile multipath file:
 - Antennas
 - Antenna configuration file: default_v1-0.acf
 - Antenna 1
 - Signal types: GPS L1
 - Hardware channels: GPS L1*64
 - Options
 - Receiver clock model file:
 - Target DOP value switching file:
 - Enable reflection pattern multipath
 - Antenna pattern control
 - Enable level patterns
 - Enable phase patterns
 - Enable polarisation efficiency
 - Switching file:
 - Level pattern file: default_v1-0.ant_pat

DEM (Obscuration & Multipath)

- Research values indicate that core and regolith permittivity and conductivity are similar to some ceramic materials.

	Permittivity	Conductivity
Core	$\epsilon_1 = 5$	$\sigma_1 = 5 * 10^{-4}$ mhos/m
Regolith	$\epsilon_2 = 3$	$\sigma_2 = 5 * 10^{-6}$ mhos/m



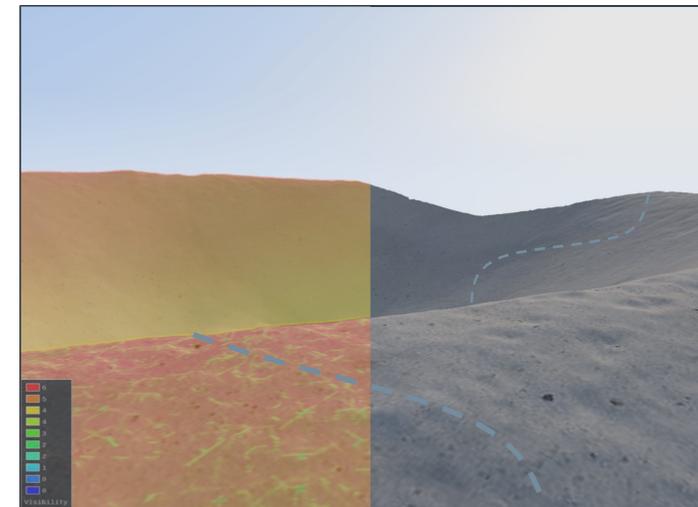
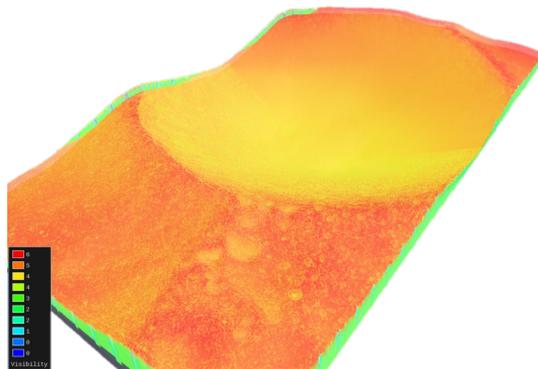
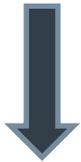


Agenda

- How we approach PNT simulation?
- Lunar PNT simulation challenges
- **Use case**

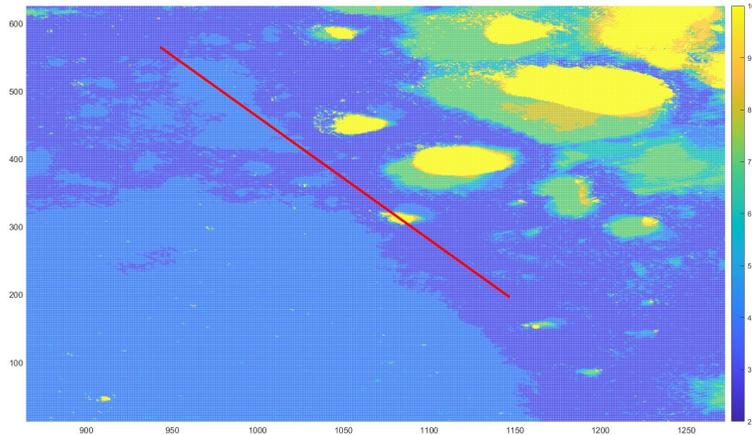
Optimal Lunar Rover Navigation with LANS

- Assess signal reception characteristics of the lunar navigation constellation on the Moon's surface. Leveraging our advanced 3D capabilities, to analyse obscuration, multipath effects, satellite visibility, and dilution of precision.
- Current lunar sites:
 - Connecting ridge: $-89.090\ 284^\circ, -136.468\ 801^\circ$
 - Shackleton rim: $-89.423\ 127^\circ, -149.036\ 243^\circ$
 - Peak near Shackleton: $-88.825\ 732^\circ, 141.842\ 773^\circ$
- Large scale non-linear interpolation methods for rover's routes on the surface of the Moon.



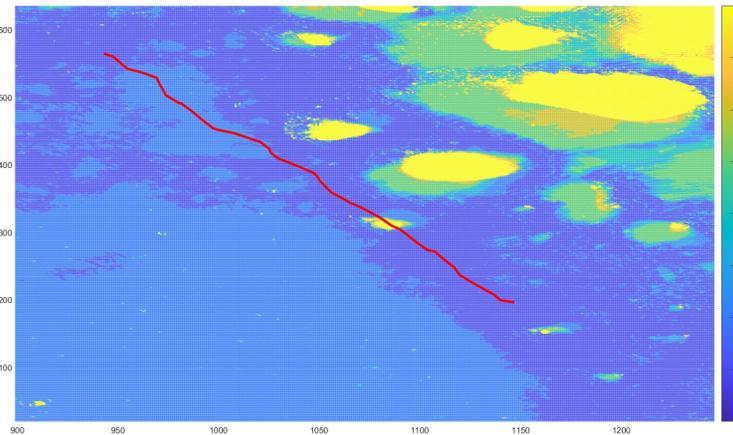
Optimal Lunar Rover Navigation with LANS

No Constraints



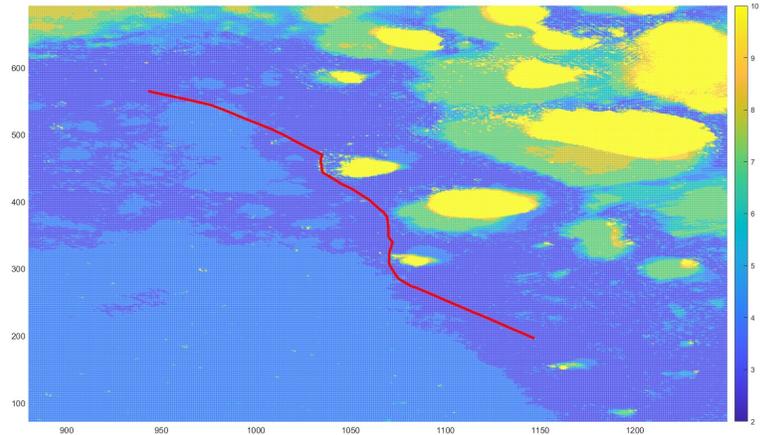
Distance: 4,216 m Time: 1,405 s

<20° Slope

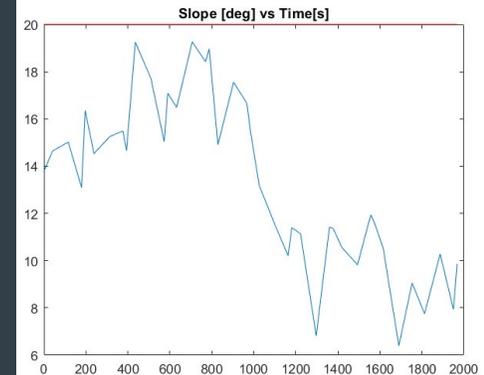
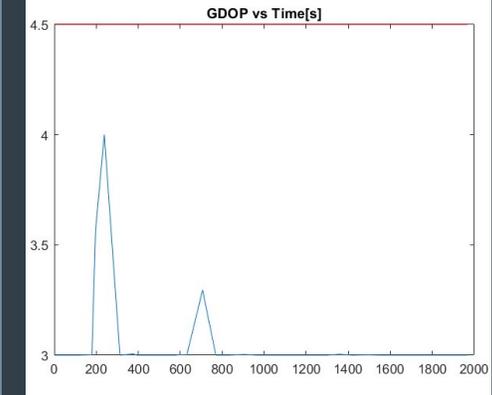
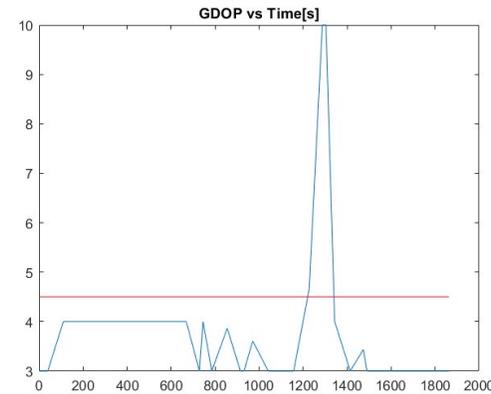
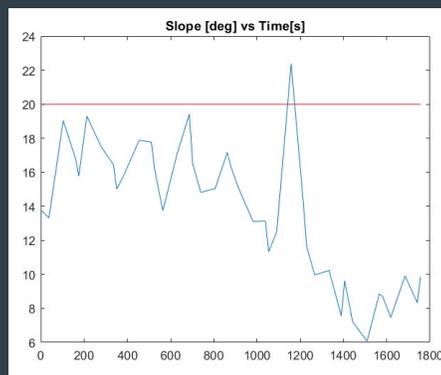
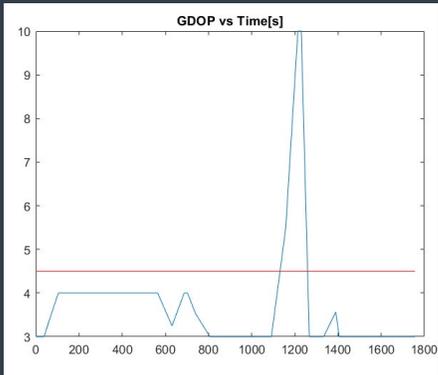


Distance: 4,320 m Time: 1,863 s

<4 GDOP



Distance: 4,433 m Time: 1,967 s



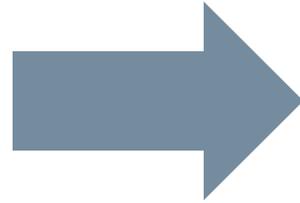


Agenda

- **End-to-end Mars PNT simulation**
- Mars PNT simulator
- Mars PNT software receiver

End-to-End Mars Simulation

**PNT Simulator
(Output: I/Q stream)**



**PNT SW Receiver
(Input: I/Q stream)**



End-to-End Mars Simulation

**PNT Simulator
(Output: I/Q stream)**



**PNT SW Receiver
(Input: I/Q stream)**



Mars PNT Simulator - Elements



DUT Position



Reference System



Constellation Definition



Signal Propagation

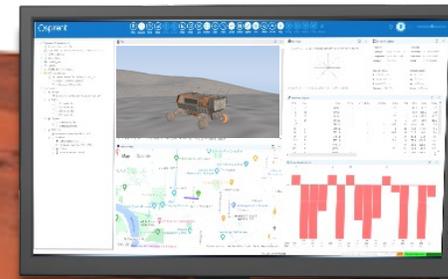
Signal Definition



Time Reference System



Already implemented
as part of LunaNet
program



Mars PNT Simulator – Assumptions

- GPS LNAV frame and sub-frame structure
- Same clock polynomial model
- Same ephemeris parametrization
- GPS-style time architecture – continuous GNSS time
- No ionosphere model
- Classical Keplerian broadcast model

Self-consistent geometric system

Field / Block (IS-GPS-200)	Earth Role	Mars Adaptation (Minimal Change)
HOW: Z-count, sub-frame ID	GPS time-of-week / 6 s tick	Keep format. Interpret Z-count as Mars GNSS time-of-week .
Week Number (Sub-frame 1)	10-bit GPS week (mod 1024)	Reuse field. Interpret as Mars week number .
Clock parameters ($a_{f0}, a_{f1}, a_{f2}, t_{oc}$)	Clock polynomial vs GPS time	Regenerate vs Mars GNSS time . Same scaling.
IODC	Issue of clock+ephemeris	Retain semantics. New issue count for Mars data.
URA / SV health / L2 flags	Quality indicators	Keep semantics. Use reasonable URA and “healthy”.
TGD	Group delay L1/L2	Set to 0 (single-frequency Mars L1).
Ephemeris (Sub-frames 2–3)	Kepler + corrections (Earth)	Regenerate all params for Mars orbits: $M_0, \Delta n, e, \sqrt{A}, \Omega_0, i_0, \omega, \dot{\Omega}, IDOT$, and $C_{uc}, C_{us}, C_{rc}, C_{rs}, C_{ic}, C_{is}, t_{oe}$, IODE.
Fit interval flag / AODO	Ephemeris fit window	Optional. Keep 4 h semantics or ignore.
Underlying constants	Earth μ, Ω_e, R_E, J_2	Conceptually replace with $\mu_{Mars}, \Omega_{Mars}, R_{Mars}, J_{2,Mars}$.
Almanac (Subframes 4–5)	Reduced-accuracy constellation	Optional. Generate Mars almanac with same format; or leave unused.
UTC parameters	GPS ↔ UTC(Earth)	Zero / ignore. No Earth UTC mapping.
Ionospheric parameters	Klobuchar (Earth iono)	Set all $\alpha_i, \beta_i = 0$.
SV health / A-S flags	Receiver config bits	Keep unchanged, planet-agnostic.
Parity / TLM / framing	Integrity / sync	No changes . Keep GPS LNAV framing.

Domain	Earth GPS Assumption	Mars GNSS Requirement
Gravity (μ)	$3.986004418 \times 10^{14} \text{ m}^3/\text{s}^2$	$\approx 4.282837 \times 10^{13} \text{ m}^3/\text{s}^2$.
Rotation (Ω)	$7.2921151467 \times 10^{-5} \text{ rad/s}$	$\approx 7.0882181 \times 10^{-5} \text{ rad/s}$.
Equatorial Radius	$\approx 6378.137 \text{ km}$	$\approx 3389.5 \text{ km}$.
J_2 (Oblateness)	1.08263×10^{-3}	$\approx 1.96045 \times 10^{-3}$.
Reference Frame	ITRF / ECEF	MCMF (Mars-centered, Mars-fixed).
Time Scale	GPS Time	“Mars GNSS Time” (Reusing GPS week modulo logic; not referenced to UTC).

Mars PNT Software Receiver

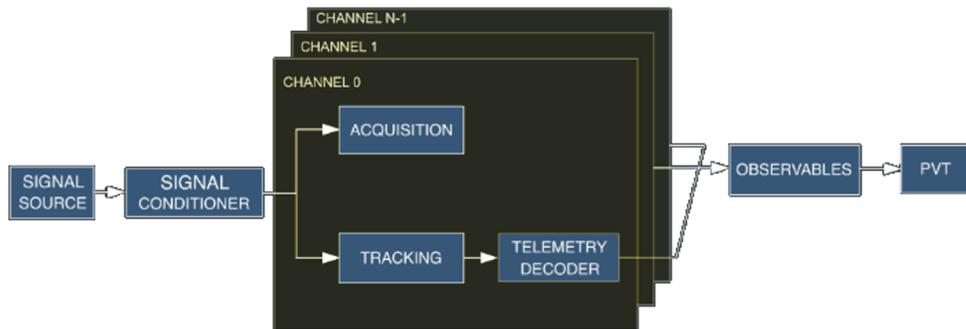
PNT Simulator
(Output: I/Q stream)



PNT SW Receiver
(Input: I/Q stream)



Mars PNT Software Receiver



- GNSS-MEO-like orbits to reduce the impact of doppler changes on **acquisition** and **tracking** modules.
- **Navigation** module redesigned:
 - Mean motion propagation
 - Planet rotation rate (Sagnac)
 - Reference frames (ECEF to Mars fixed)
 - Ephemeris parameters (subframes 2&3) regenerated for Mars orbits
 - Iono set to zero as per I/Q data.

 spirent™

Is Now Part of Keysight

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