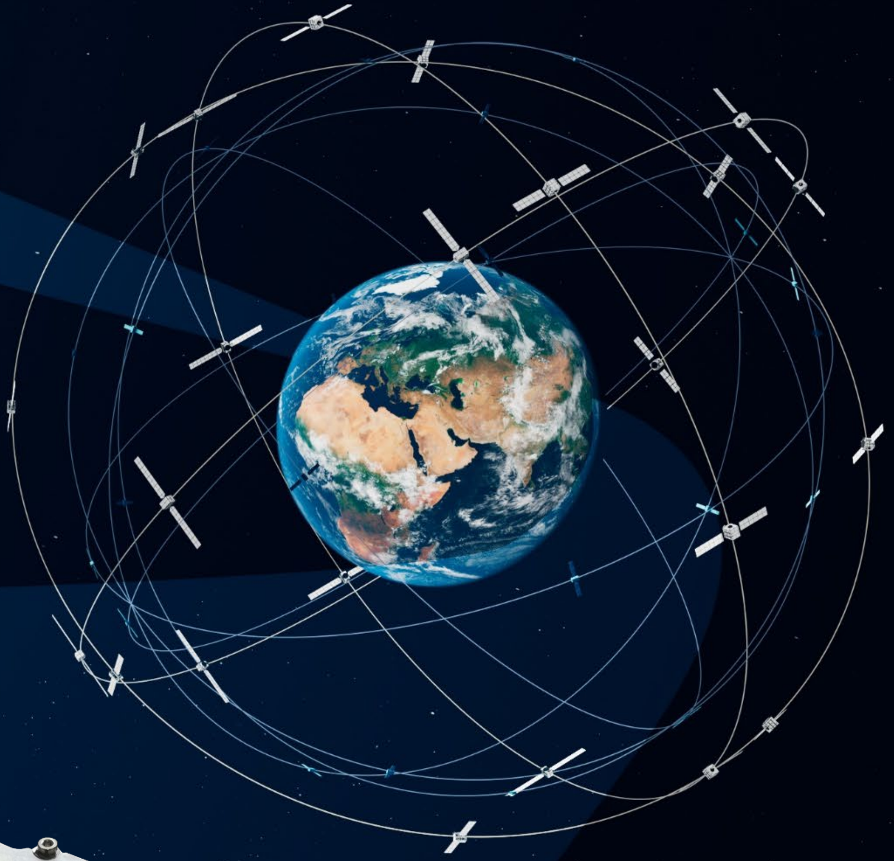
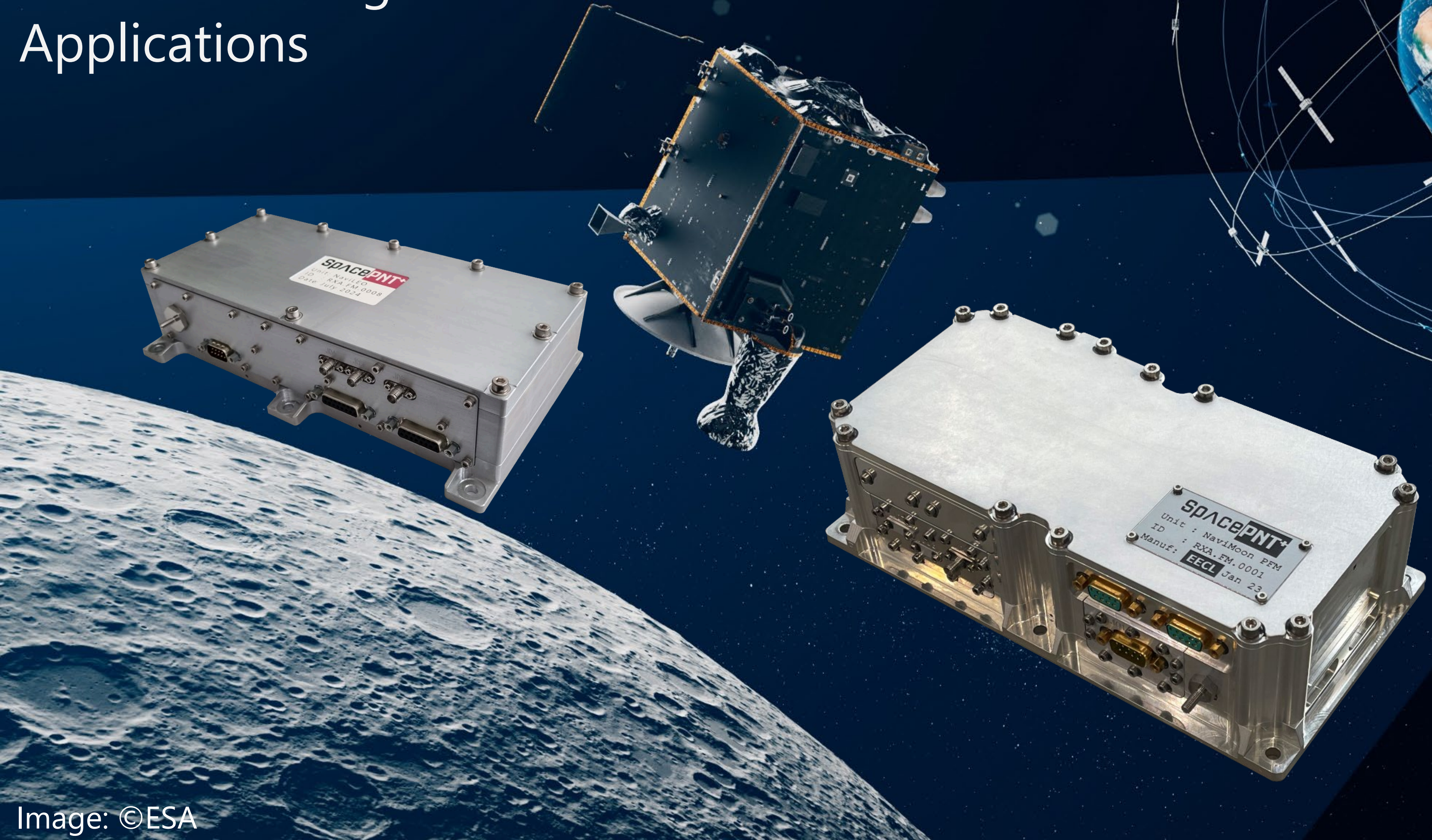
SpacePNT+

From NaviMoon to NaviLunar:
SpacePNT Roadmap from Autonomous Cis-Lunar Navigation to LunaNet Enabled Applications





Michele Scotti, Cyril Botteron, Kévin Fischer, Baptiste Marechal, Mathieu Rico, Michael Karpf, Vasili Massaras

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PART 1: NaviMoon In-Orbit Demonstration

NaviMoon IOD – Project outline (NAVISP-EL1-039)

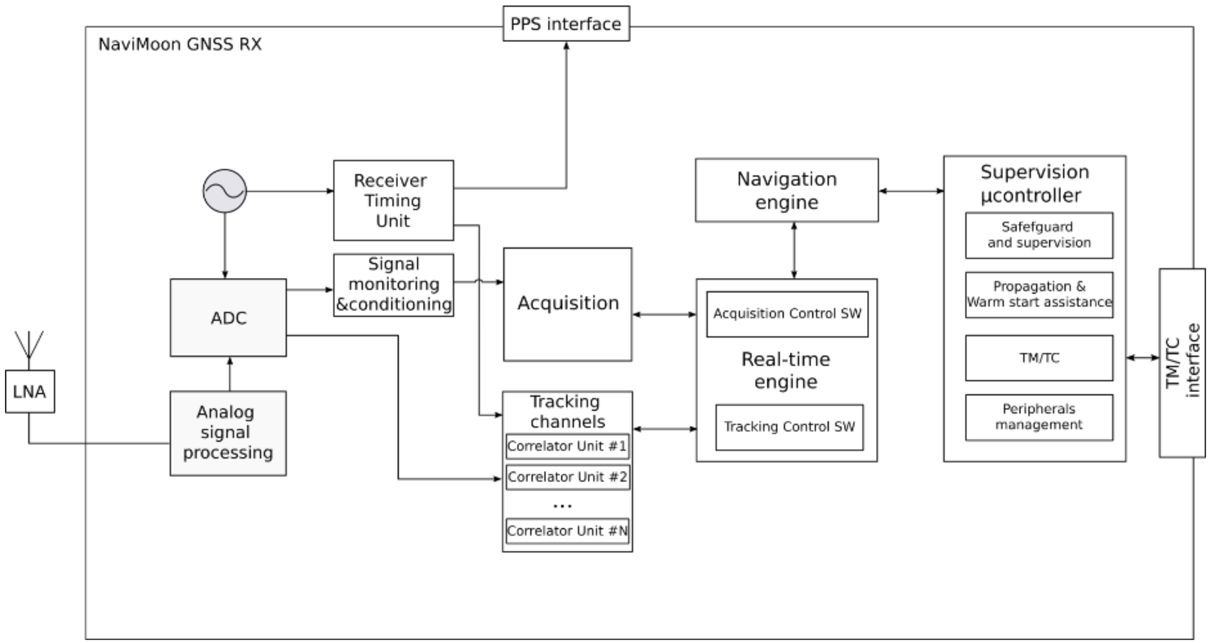
- **Main objective:** demonstrate autonomous GNSS-based navigation in cis-lunar space, exploiting the signals from Galileo and GPS

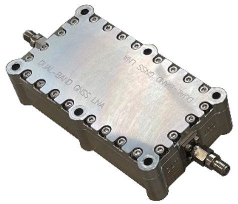
- **Implementation strategy:**
  - Develop, manufacture and test a Proto-Flight Model of the NaviMoon high-sensitivity GNSS receiver and LNA, to be embarked on SSTL's Lunar Pathfinder
  - Manufacturing 3 Engineering Models (algorithm development, satellite integration and ground twin)
  - Proto-flight qualification
  - Heavy-ions testing

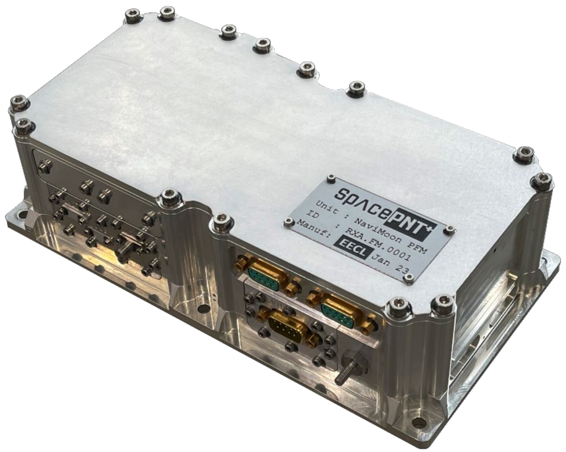
- **Performance goals:**
  - 18 dB Hz acquisition threshold, 15 dB Hz tracking threshold
  - 100 m 3D RMS positioning error, 0.1 m/s 3D RMS velocity error (on ELFO)

NaviMoon – System Overview

- NaviMoon: evolution of SpacePNT flagship spaceborne GNSS receiver NaviLEO™.
  Main features:
  - Dual constellation (GPS + Galileo)
  - Dual frequency (E1/L1 + E5a/L5)
  - COTS based + radiation mitigation
  - Fast digital signal processing in hardware
  - Acquisition/Tracking control & navigation in software
  - Dedicated microcontroller for interface management
  - **Reprogrammable in flight!**
- Improved acquisition engine: **18 dB Hz**
- High performance local oscillator
- Navigation engine (dynamics model) tailored for Lunar Pathfinder Orbit
- External LNA: gain > 25 dB, NF < 1.4 dB

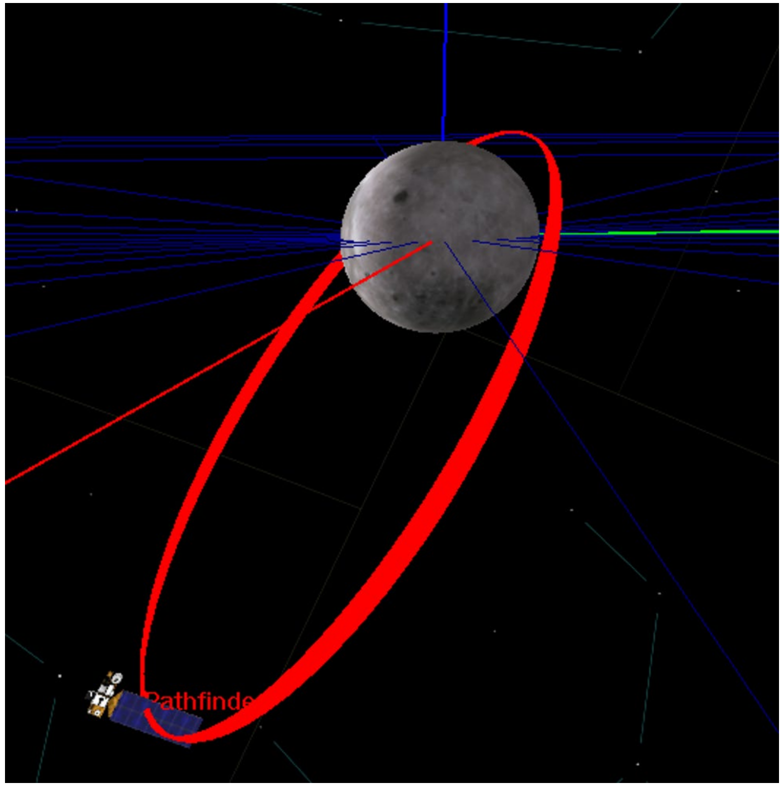






Receiver design – reference trajectory

- ❖ Design based on a potential orbit for Lunar Pathfinder
- ❖ Initial state (see table) propagated with high fidelity force model (GODOT)
  - ○ Moon gravity: GRGM1200A: order = 80; degree = 80
  - ○ Earth gravity: EGM2008: order = 100; degree = 100
  - ○ Sun as a point mass
  - ○ Solar radiation pressure (reflectivity = 1.0, SRP area = 10 m^2, mass = 1000 kg, cannonball model)
  - ○ Integrator Runge Kutta Verner 787 (GODOT default)
- ❖ Propagated for 48 hours (about 4 periods)
- ❖ Attitude: antenna boresight pointing towards Earth centre

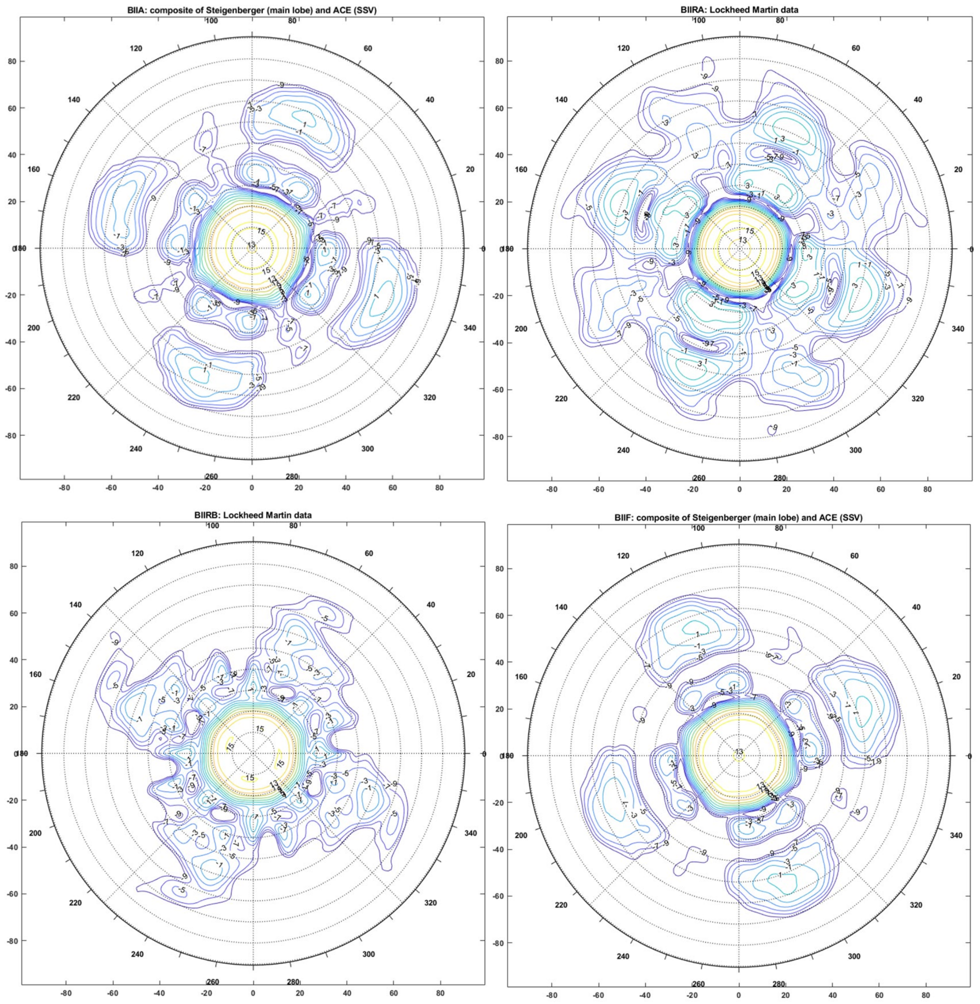


Parameter	Value
Semi major axis	5737.4 km
Periselene altitude	500 km
Aposelene altitude	7500 km
Eccentricity	0.61
Inclination	57.82 deg
RAAN	61.55 deg
Argument of periselene	90 deg
True anomaly at epoch	0 deg
Epoch	1st Dec 2022 00:00:00 UTCG

Receiver design – GNSS constellations

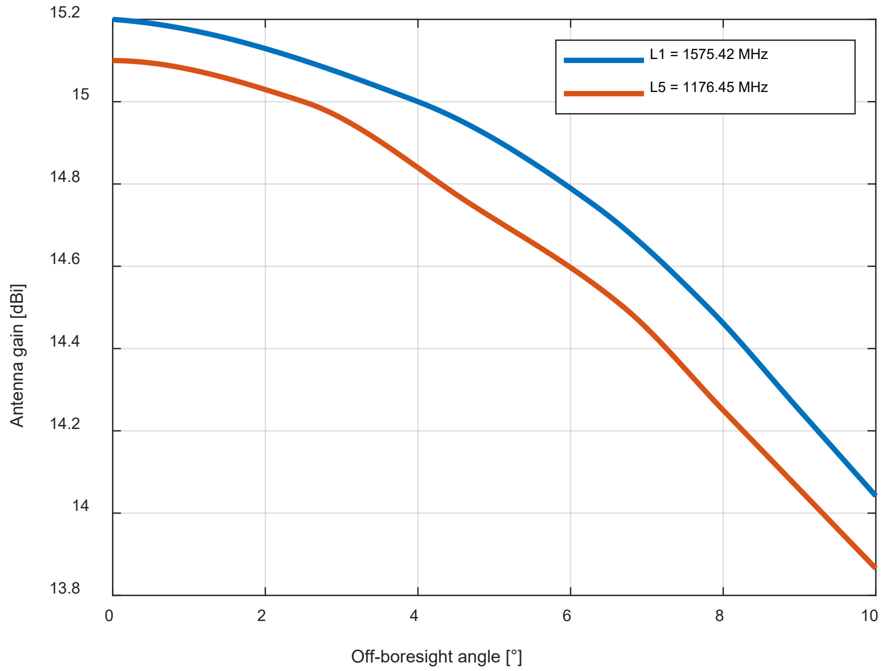
- Constellation assumptions:
  - 31 GPS satellites, of which 22 transmitting on L5
  - 27 Galileo satellites

- Very important to model the sidelobes and GNSS spacecrafts attitude
- Ideal yaw steering model
- GPS L1 patterns: IGS model (0° to 15°) + ACE (from 16° off-boresight) or Lockheed Martin Data
- GPS L5 pattern (where applicable): same pattern as L1 with power offset
- Stochastic model for Galileo patterns provided by ESA



Receiver design – receiver model

- Receiver antenna model
  - Antenna model based on MDA realised implementation
    - Axialsymmetric
    - E1/L1 peak gain = 15.2 dBi
    - E5a/L5 peak gain = 15.1 dBi
- Link budget
  - Antenna temperature: 34 K from NASA study (conservative)
  - Ambient temperature: 300 K (but likely lower for the LNA)
  - Short cable between antenna and LNA (0.2 dB loss)
  - LNA: gain = 29.5 dB, Noise Figure = 1.4 dB
  - Longer cable between LNA and receiver (1 dB loss)
  - GNSS Receiver Front End Noise Figure = 2 dB (conservative)
  - **Overall System Noise Figure = 1.6 dB**



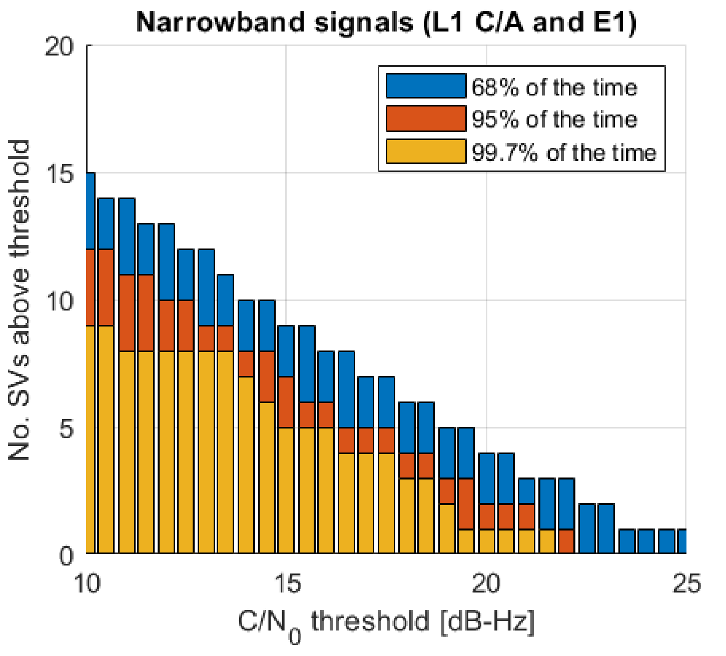
	Gain/Loss		Units	Notes
	dB	**linear**		
Boltzmann constant	-228.60	1.38E-23	J/K	
Antenna, T_A		34.0	K	Anzalone et al. 2019
Ambient Temperature, T0		300.0	K	
Cable 1 $F_1=1/G_1$	0.20	1.05		Short cable from antenna to LNA
LNA Gain, G_2	29.50	891.25		LNA performance at 1.5 GHz
LNA Noise Figure, F_2	1.40	1.38		LNA performance at 1.5 GHz
Cable 2, $F_3=1/G_3$	1.00	1.26		Longer cable from LNA to RX
Noise Figure F_4	2.00	1.58		RFM noise figure
Overall noise figure	**1.60**	**1.45**		
$\mathbf{T_{eff}}$		**167.98**	**K**	

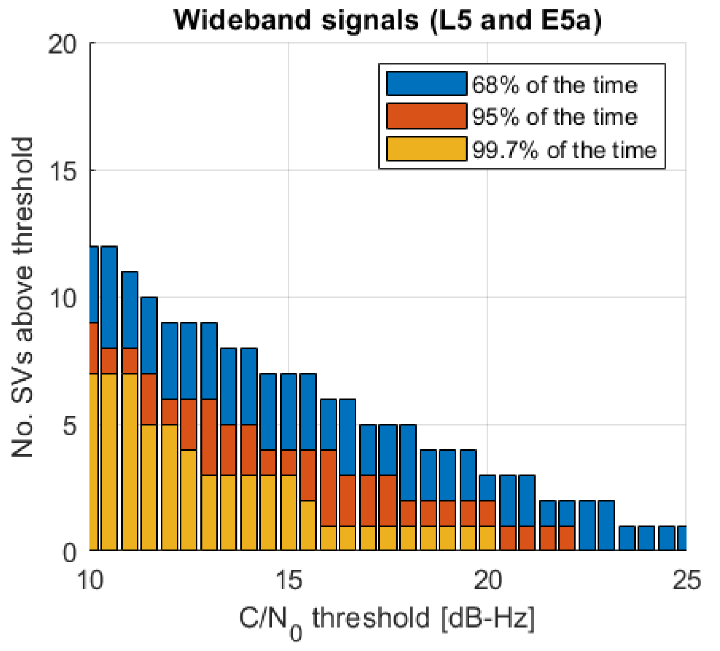
Receiver design – C/N_0 analysis

- Simulation of the C/N_0 expected after the ADC (0.6 dB loss)
- Earth and Moon occultation are accounted for

$$C/N_0 = P_{TX} + G_{ant,TX}(\theta_{TX},\phi_{TX}) - L_{FS} + G_{ant,RX}(\theta_{RX}) - L_{\mathrm{ADC}} - 10\log_{10}(k_{\mathrm{Boltz}}\, T_{\mathrm{eff}})$$

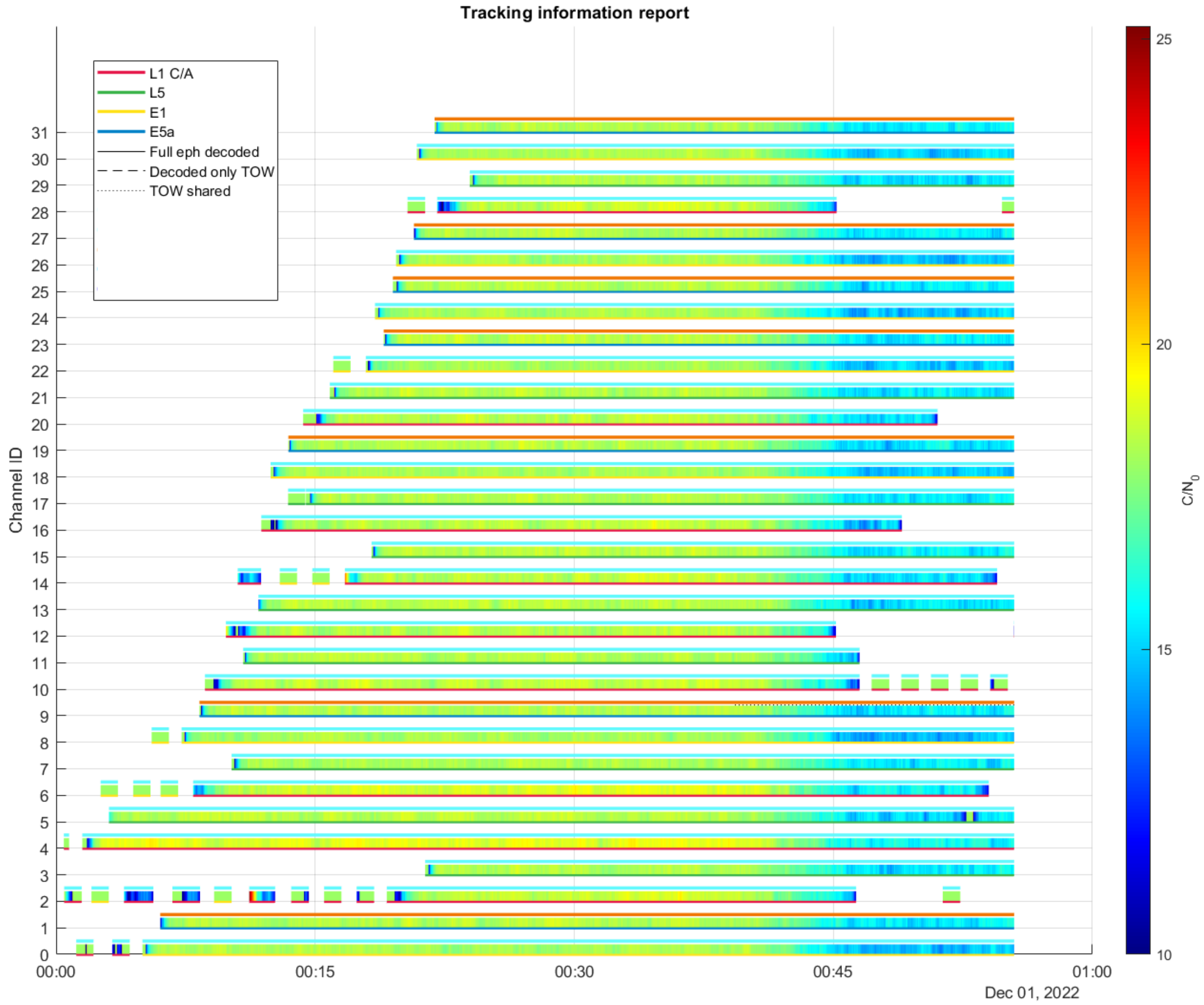
- Setting the acquisition to C/N_0 18 dB Hz ensures that at least 5 satellites are visible and within acquisition threshold for 99.7% of the time
- Less availability for the wideband components (E5a and L5), mostly because several GPS do not transmit L5
- Even in these conditions, 5 satellites are in view 68% of the time





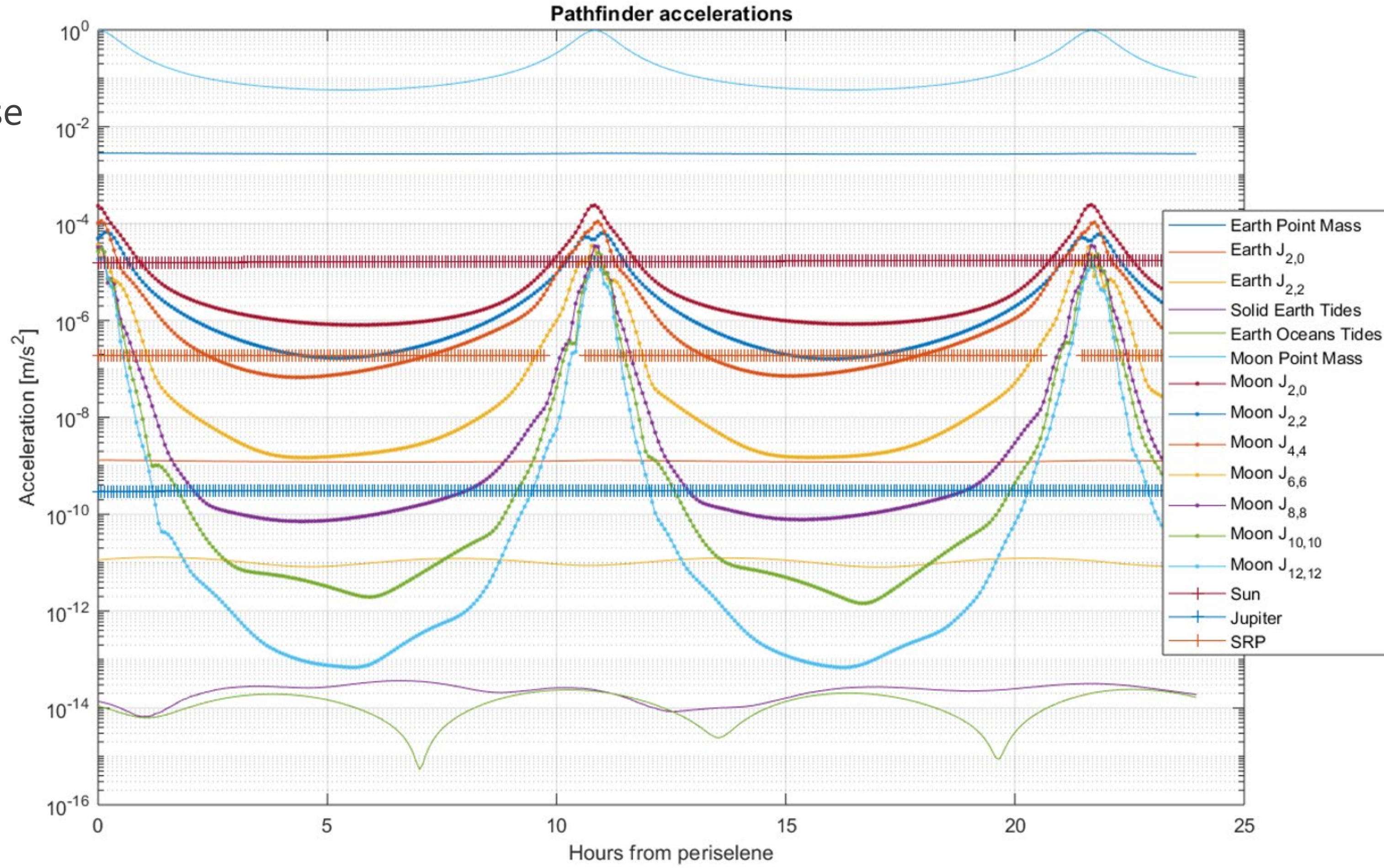
Receiver design – DSP for high-sensitivity

- **Signal baseline**
  - GPS L1 C/A + L5
  - Galileo E1 + E5a
- **Fast acquisition accelerator**
  - Coherent + non-coherent integration
  - Multi-step acquisition, takes up to ~1.5 minutes per satellite (aided start, 600 Hz Doppler search space)
  - Secondary code/bit edge search
  - Acquisition sensitivity: better than 18 dB Hz
- **High-sensitivity tracking channels**
  - C/N_0 indicator designed for faint signals, adaptive averaging time
  - Tracking sensitivity ~15 dB Hz for all processed signals
  - Adaptive loop bandwidth to handle strong dynamic and various C/N_0 conditions
  - Initialisation on long coherent integration time
  - Bit synchronization monitoring and correction
  - False-frequency lock detection and recovery



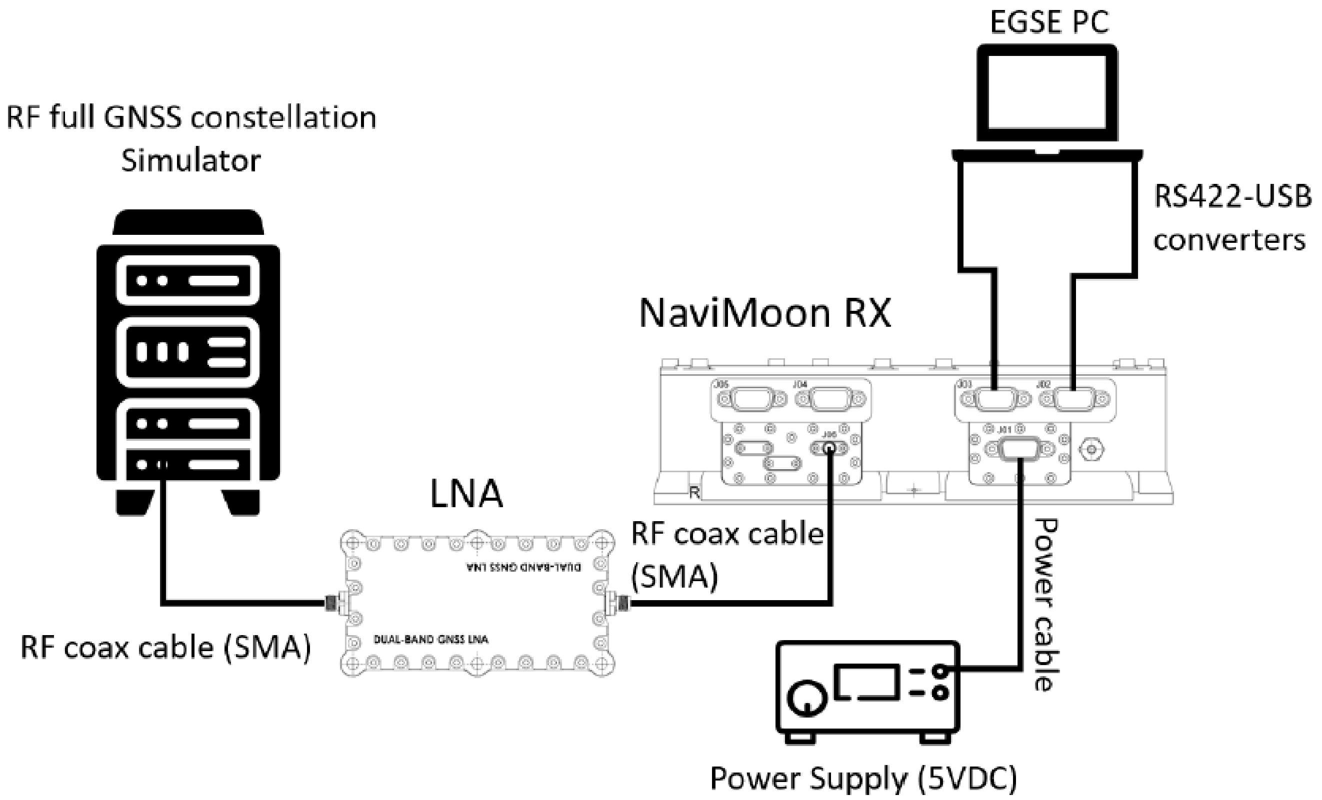
Receiver design – Navigation engine

- Tightly coupled Extended Kalman Filter
  - Initialised with Least Squares Solution (if enough observables are available) or coarse PVT solution
- Dynamics model sized to warrant propagation error < 1 km after 24 hours
  - 12 x 12 Moon gravity field (GRGM1200A)
  - Earth and Sun point masses
  - Solar Radiation Pressure
- Reference frames models:
  - ITRF ↔ GCRF: IAU 2000/2006 precession-nutation, EOP
  - DE440 for Moon position and PA
  - Simplified model for Sun position

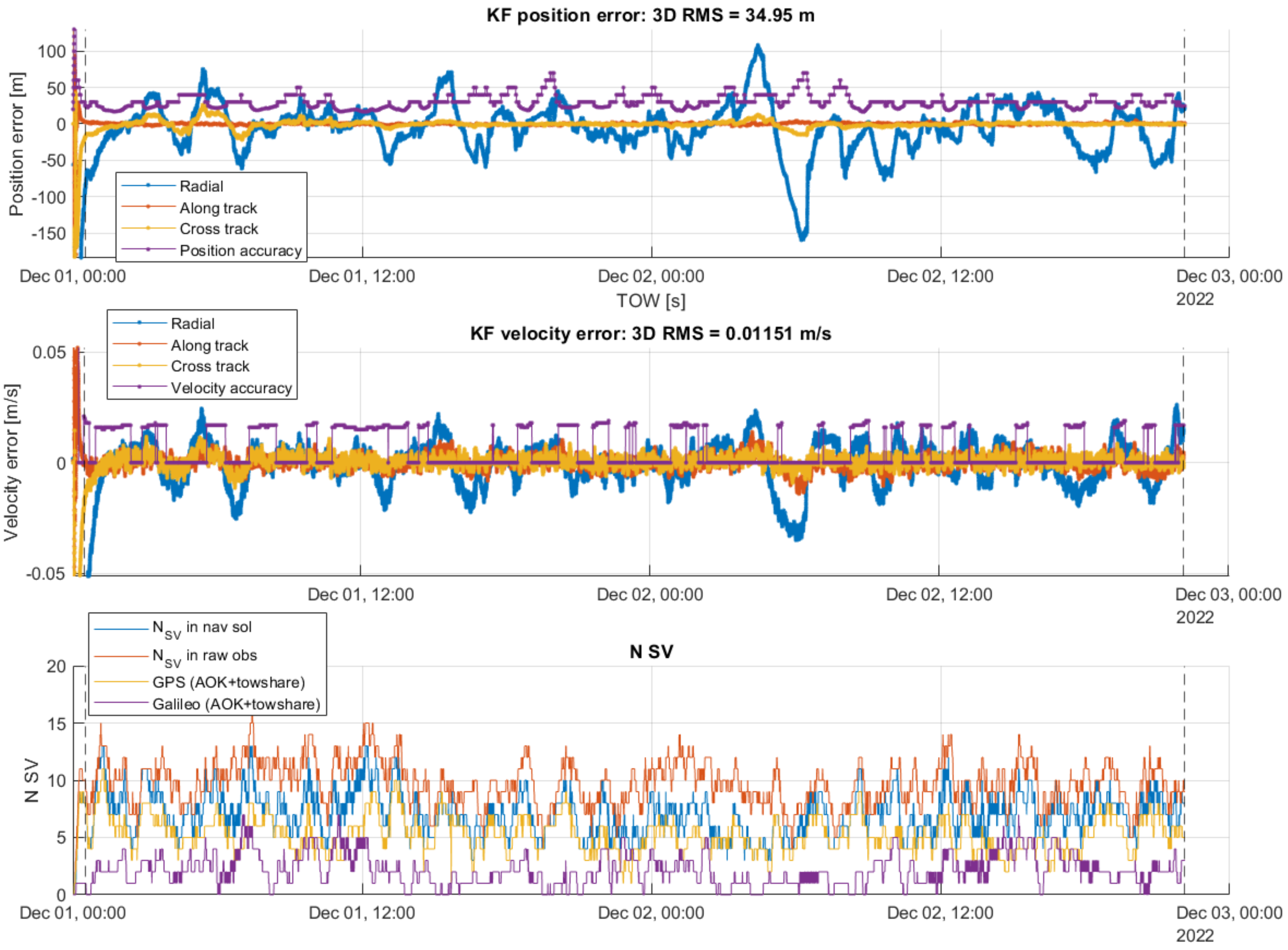


Functional and performance test campaign

- Functional and performance test campaign
  - Static analysis: SonarQube
  - Hardware-in-the-loop test configuration
- Boot Software Test campaign
  - Non-reprogrammable in flight
  - Full coverage by test
  - Stringent metrics (complexity, nesting, etc.)
- Application Software Test campaign
  - Reprogrammable in flight
  - Thorough functional and performance testing
  - ..but higher thresholds for the SW metrics
- GNSS Test campaign
  - Functional tests for standard features and for experiment-specific features
  - Performance tests on acquisition, tracking and navigation (no SISE modelled)

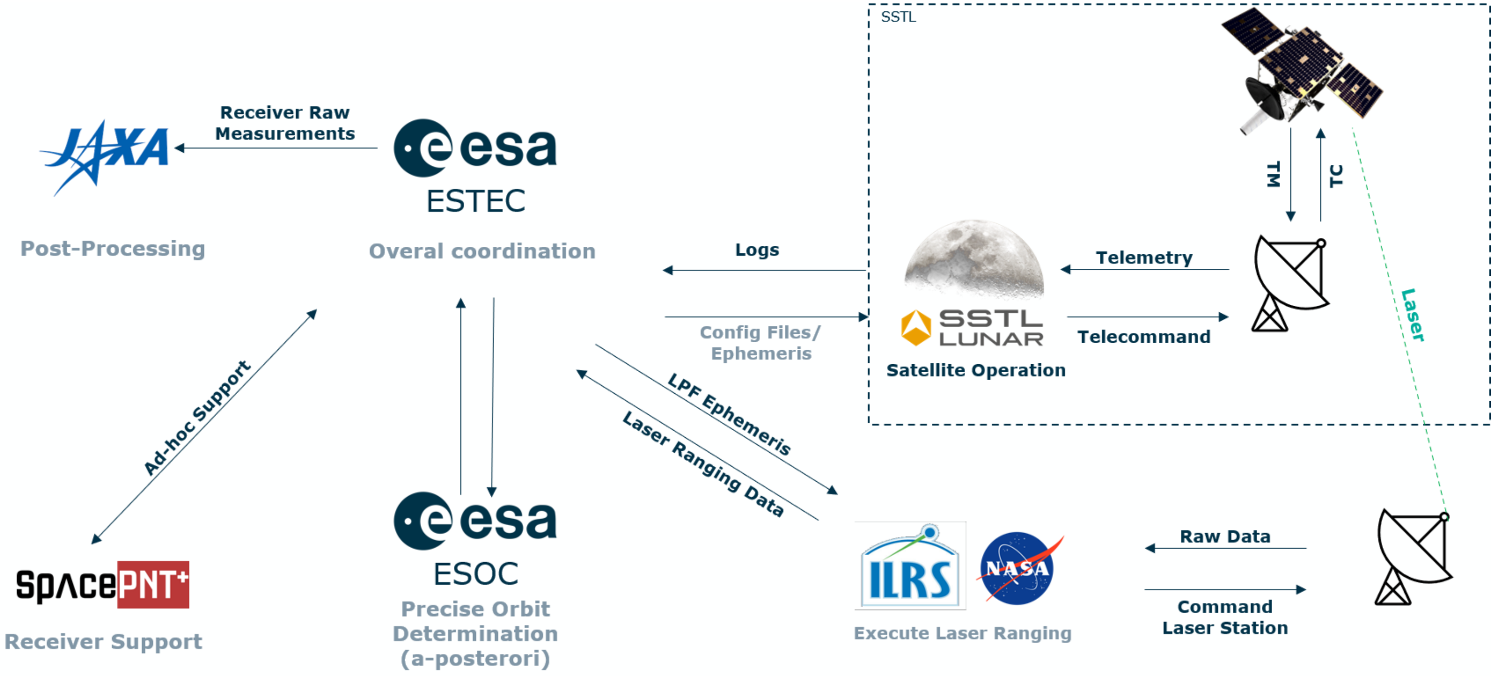


Navigation performance (no SISE modelled)



Experiment setup

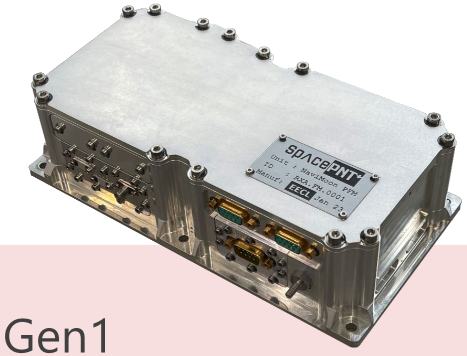
- 5 days experimentation windows
- Two months between experiments
- Attitude: GNSS antenna shall point towards Earth centre
- Warm start: provision via Telecommand of
  - predicted ephemerides and clocks ("as late as possible")
  - Coarse PVT solution + LO frequency offset (may be quite old upon first startup – configurable search space)



- Nominal operations
  - Long term ephemerides provided via Telecommand
  - Ephemeris ranking: decoded > telecommanded
- Contingency
  - Periodic provision of coarse PVT solutions (to speed up recovery in case of unexpected reboot). To be ignored during nominal operations; triggers KF reset in case of large discrepancy.
  - Large set of configurable parameters (including tracking loops BW, EL spacing, Doppler search space, process noise...)

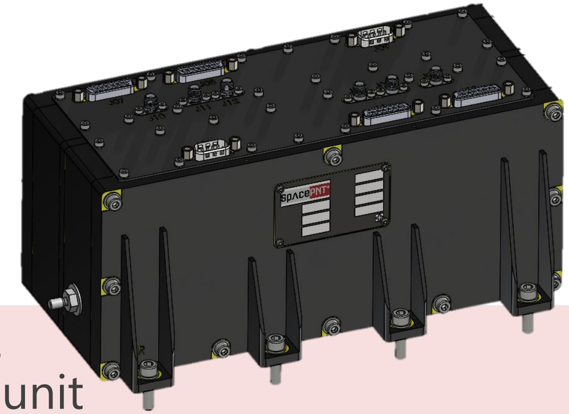
PART 2: SpacePNT Lunar Roadmap

SpacePNT Roadmap - Our Hardware Platforms

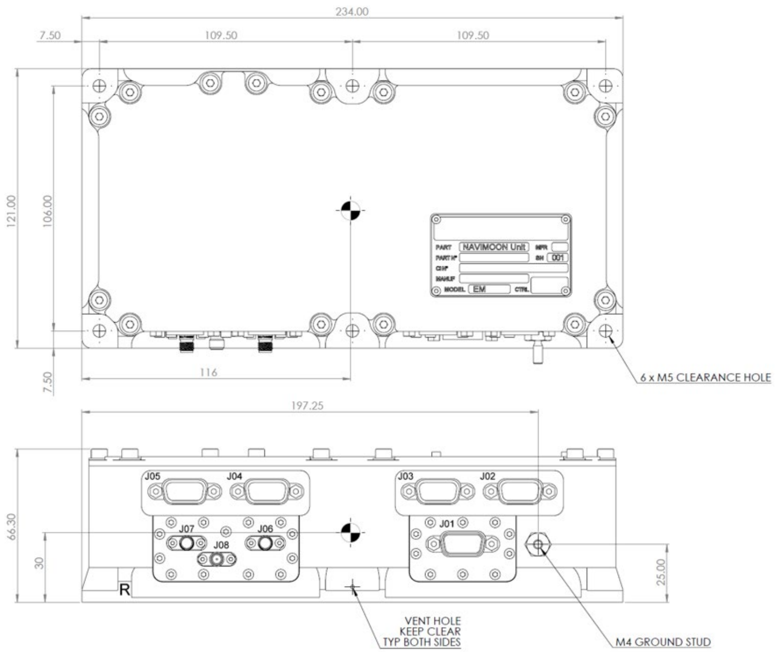


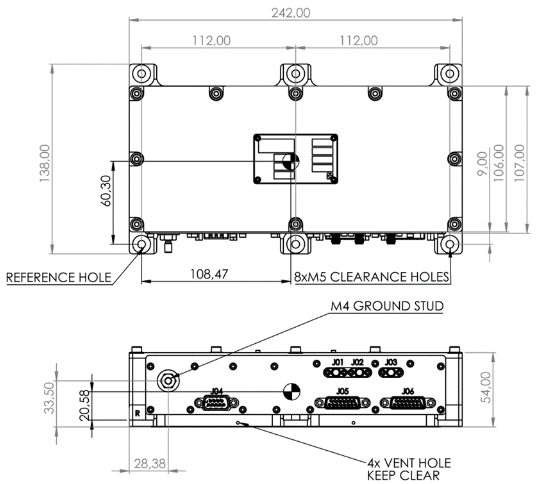
Gen1

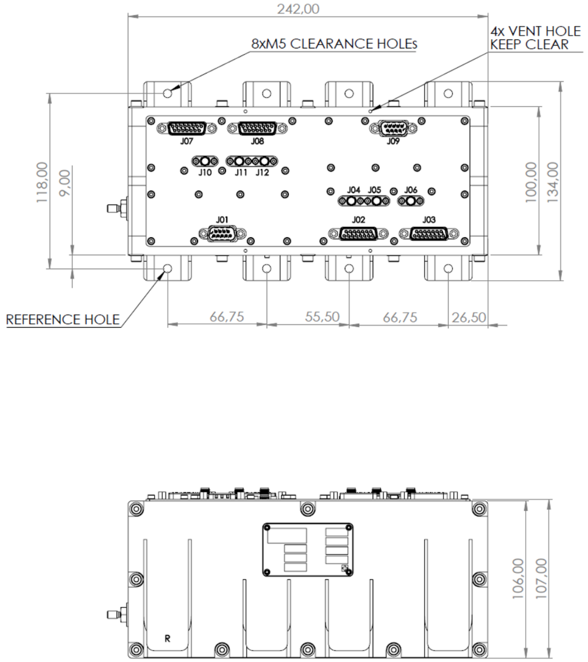
Gen2
Single unit



Gen2
Dual unit





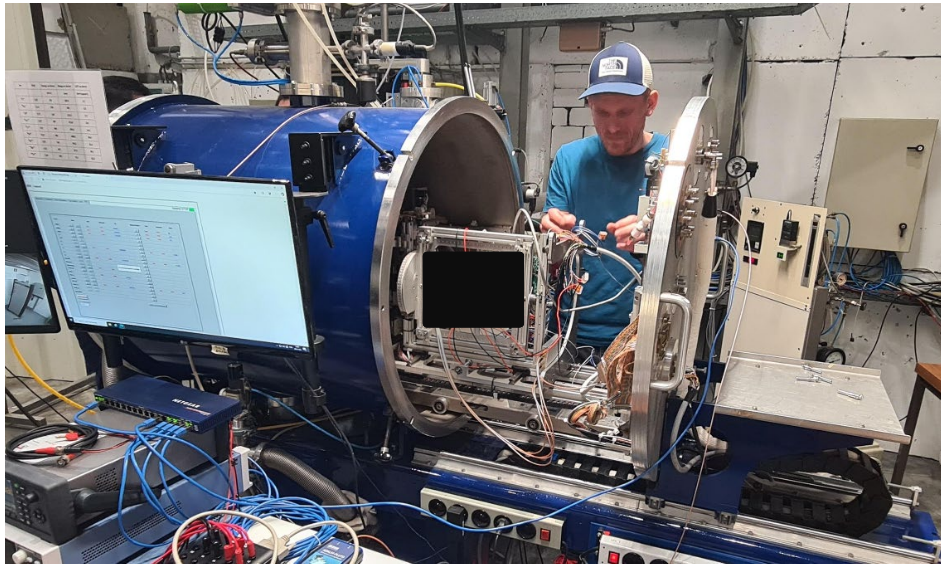


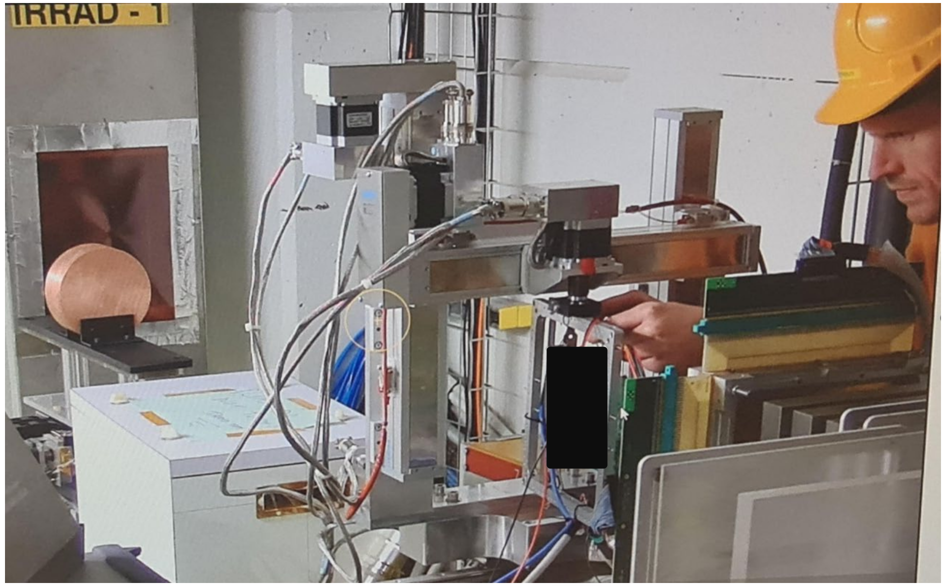
Radiation effects mitigation strategy

- In-depth characterisation of all EEE components through SEE testing, multiple campaigns:
  - UCL Heavy Ion Facility
  - GSI Synchrotron Facility
  - HEARTS@CERN

- SEE mitigation strategy:
  - Current limiters
  - Memory scrubbing / ECC
  - Watchdogs
  - Redundant TM/TC interface

- Radiation Lot Acceptance Testing for long missions (high TID)





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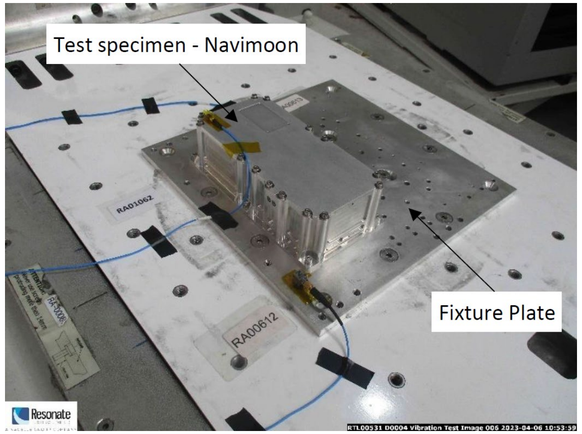
Equipment qualification

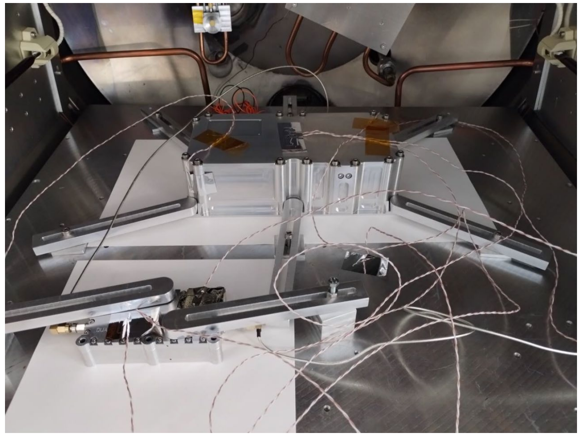
- **Mechanical**
  - Sine excitation: one sweep per axis, at 2 octaves/minute
  - Random vibration: three axes
  - Shock: three axes
- **Thermal vacuum (10^{-5} mbar)**
  - 1 cycle ranging from -40 °C to + 70 °C (non-OP temp. limits)
  - 4 cycles ranging from -25 °C to + 60°C (OP temp. limits)
- **Electro-Magnetic Compatibility test**
  - According to MIL-STD-461F

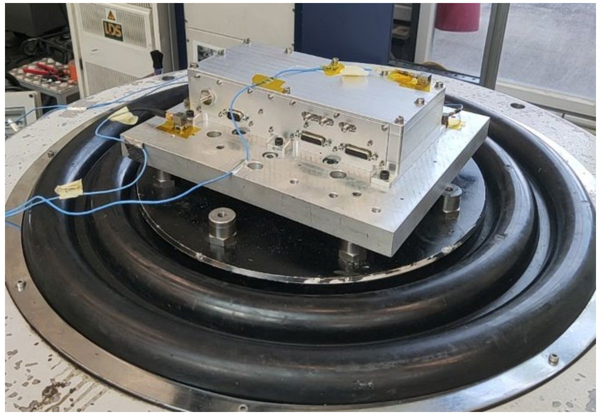
Frequency (Hz)	Amplitude
5 – 20	10 mm
20 – 100	20 g

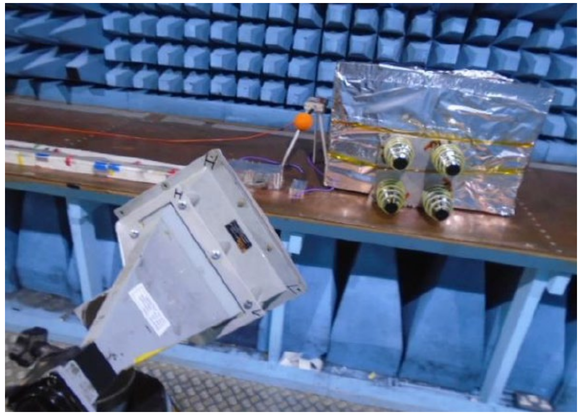
Frequency (Hz)	PSD (g2/Hz)
20	0.052
20 - 50	+ 6 dB/oct.
50 - 800	0.32
800 - 2000	- 6 dB/oct.
2000	0.052
GRMS	**20.0**

Frequency [Hz]	SRS [g]
100	40
1000	2000
10000	2000









- Gen1: qualification complete
- Gen2 (single unit): qualification in progress

SpacePNT Roadmap – Our Building Blocks

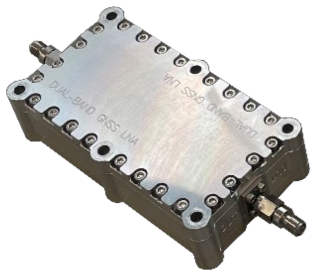
Hardware

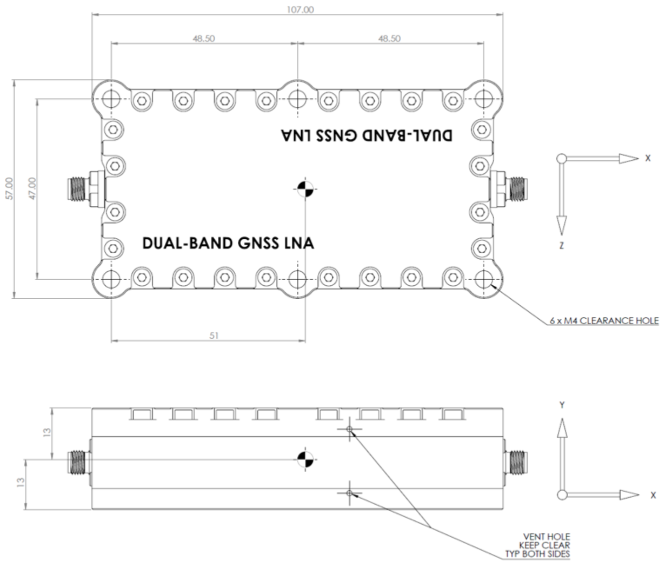
- Dual antenna input
- Cold redundancy with dual unit
- Radiation Hardness Assurance
- 28 V input (from unregulated bus)
- External LNA
- L-band front-end
- S-band front-end
- Software Defined Radio
- Internal OCXO
- Internal TCXO
- External oscillator

Software

- High sensitivity (15 dB Hz)
- Precise cis-lunar dynamics model
- LO disciplining
- Real-time POD (10 cm 3D RMS accuracy)
- Correction services (Fugro)

External LNA block



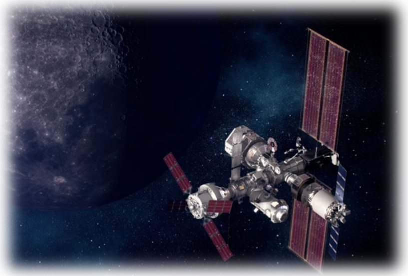


SpacePNT Roadmap – Use cases

Autonomous spacecraft in cislunar orbit

L-band front-end | Internal OCXO | External LNA | 28 V input

High sensitivity | Precise cis-lunar dynamics model



LunaNet satellite platform (AFS provider) | Lunar Gateway

L-band front-end | Radiation Hardness Assurance | External LNA | Cold redundancy

High sensitivity | Precise cis-lunar dynamics model | LO disciplining | External oscillator

NaviLunar – Moon surface NAV+COMMS integrated terminal (AFS enabled)

Dual antenna | S-band front-end | Internal TCXO

Software Defined Radio | COMMS IP

Images: ©ESA

Conclusions

Image: ©ESA

- NaviMoon has been developed as a robust HW platform, both in terms of radiation tolerance and environmental performance
- Target performance (100 m, 0.1 m/s) exceeded with large margin (35 m, 0.01 m/s)
- The technology developed at SpacePNT is highly customisable, enabling a wide range of lunar applications