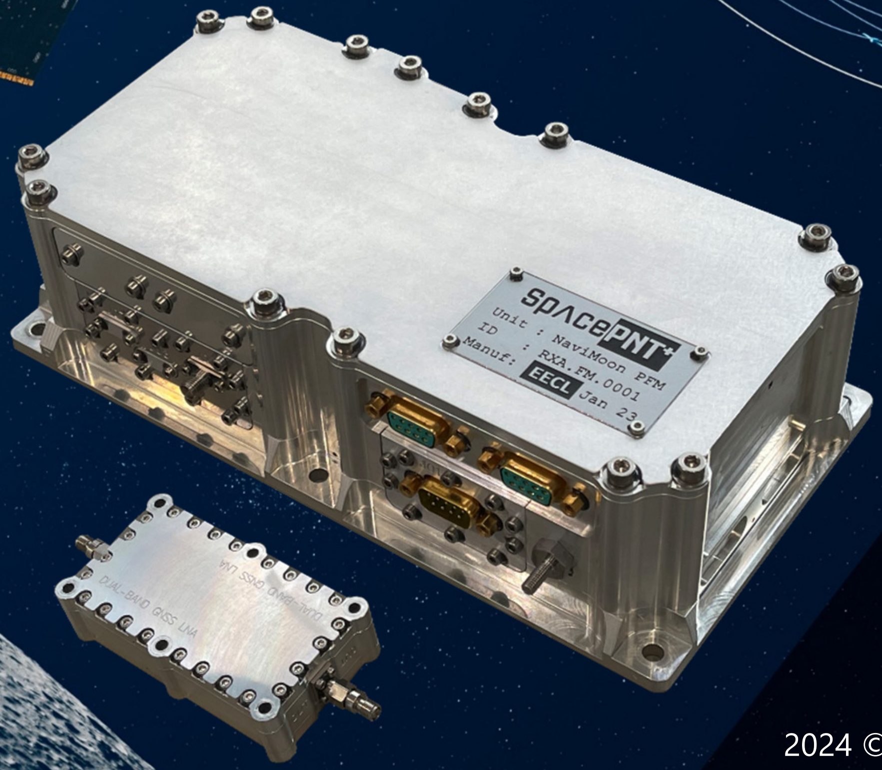
NaviMoon IOD

SpacePNT+ EECL

Earth Moon GNSS Spaceborne Receiver
For In-Orbit Demonstration
(NAVISP-EL1-039)



24 October 2024

Final Presentation

SpacePNT+

SpacePNT+

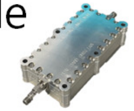
❖ Company background

- Located in Neuchâtel, Switzerland
- Key team members come with significant GNSS/space expertise from EPFL (develop. of GNSS receiver technology) & Syderal Swiss (develop. of space HW/SW technology)
- SpacePNT has developed its **own proprietary HW & SW radiation tolerant spaceborne GNSS receiver technology** with the help of two ESA NAVISP projects

❖ Key dates

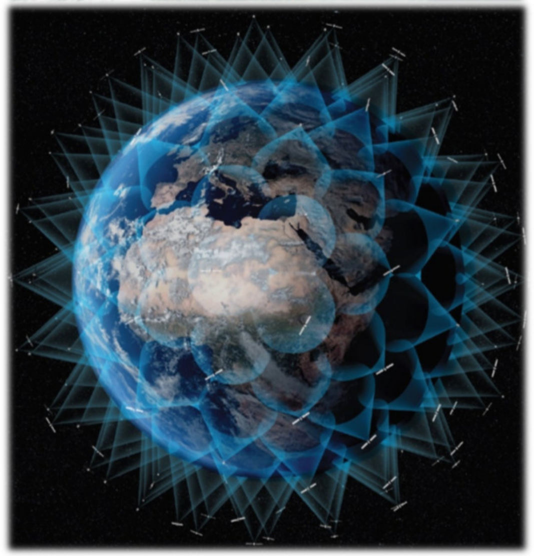
- Incorporation on Nov. 12, 2020
- Start of activities on Jan 01, 2021
- Transformation into an Anonymous Society (SA) with share capital increase on Dec. 2022
- First investment round with investors from Business Angel Switzerland (BAS) completed in Jan. 2023

SpacePNT+ Products fit to applications

Applications	Market Requirements	Product solutions
Earth observations ✓ Optical observations ✓ SAR ✓ RADAR	• Highest performance • **Real-time on-board POD** • Extended mission lifetime option	**NaviLEO™** • 100 cm pos. **NaviLEO-POD** • 10 cm position • 1 cm/s velocity • ns-level timing 
Launchers / Space transportation On-orbit servicing / Debris removal / ✓ Launchers ✓ Kick-stages ✓ GTO / GEO ✓ Moon/cislunar missions	• **Ground-based infrastructure independence** • Extended mission lifetime option	**NaviMoon** **NaviGEO**[1)] • Highest sensitivity • 100 m at Moon altitude  
Sat. com./telecom/timing ✓ LEO telecom / Sat. Internet ✓ LEO-PNT (GPS backup) ✓ Critical infrastructure ✓ SIGINT/ELINT ✓ Several 300-1000+ sat. constellations	Idem above NaviLEO plus: • **Lower SWaP-C** • **Time/frequency synch. option** (LO disciplining)	**Navi-G2** • Weight /size reduction • Optimized for large LEO constellations 
	• **Advanced simulation SW tools**	**SimORBIT** • Orbit propagation tool

[1)] *Under development, contact factory for availability*

FUGRO SPACESTAR®
REAL-TIME ACCURATE POSITIONING
SYSTEM ENABLED

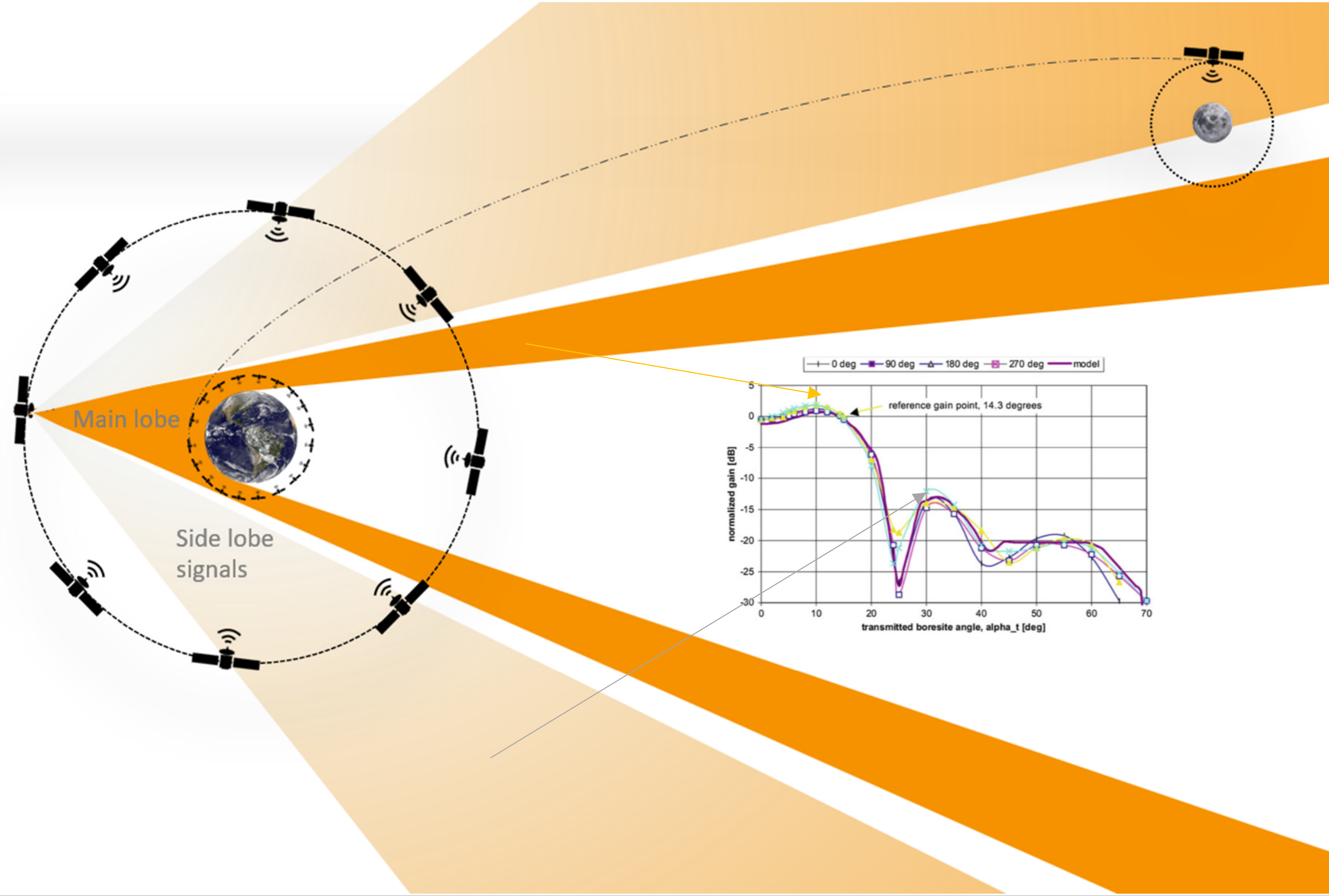


Timeline - Historical background

2004

2013 : consideration of the use of high sensitivity GNSS receiver algorithms for space exploration

Technology Readiness Level	TRL2/3
PNT & GNSS R&D	**Idea validation**
R&D	***R&D***
  	 WeakHEO PoC receiver
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE	ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
< 1 s TTFF using PCS and assistance	15 dBHz L1 C/A autonomous acquisition



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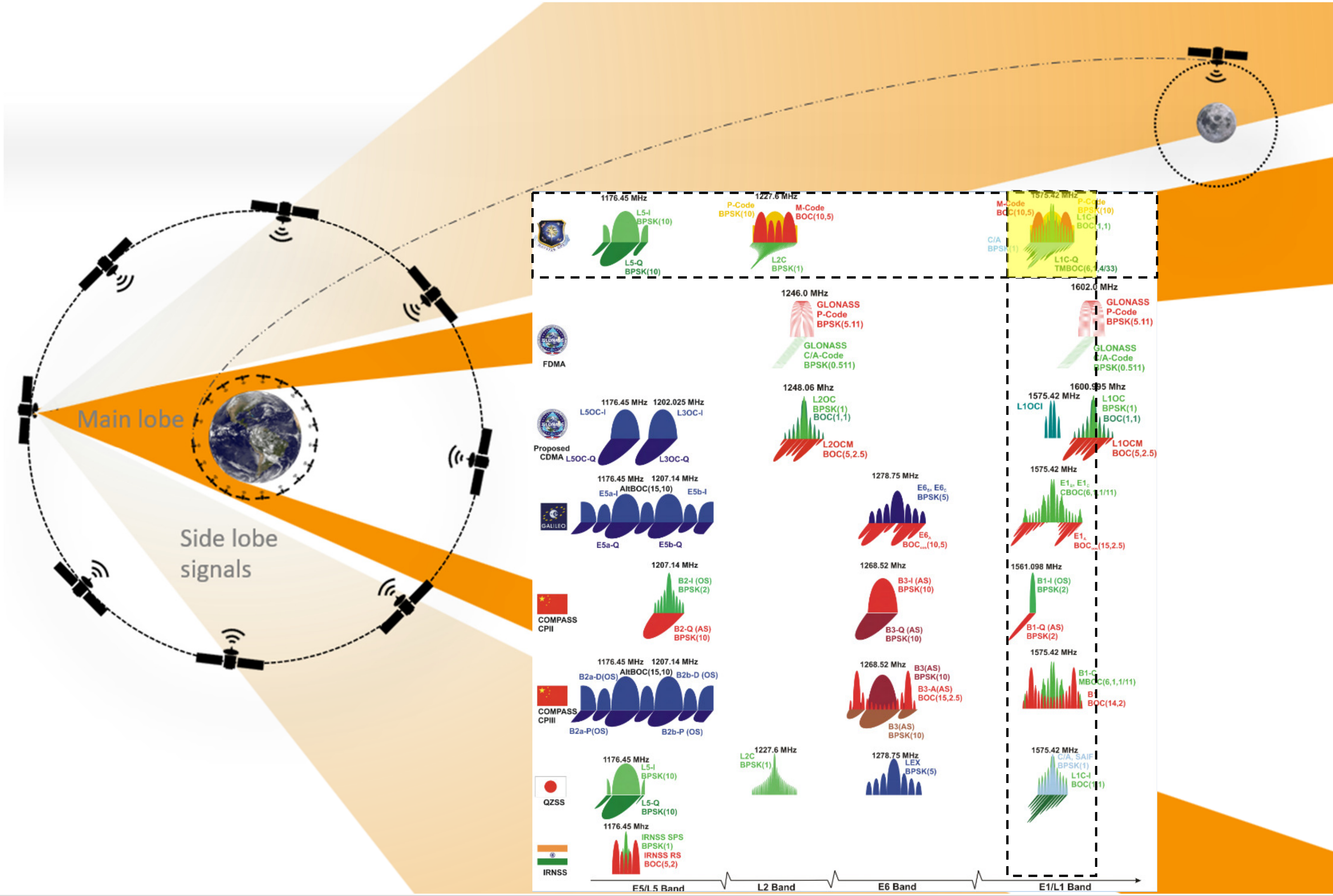


Timeline - Historical background

2004 — 2013 — **2016** : addition of a second constellation

Technology Readiness Level	TRL2/3
PNT & GNSS R&D	Idea validation

R&D

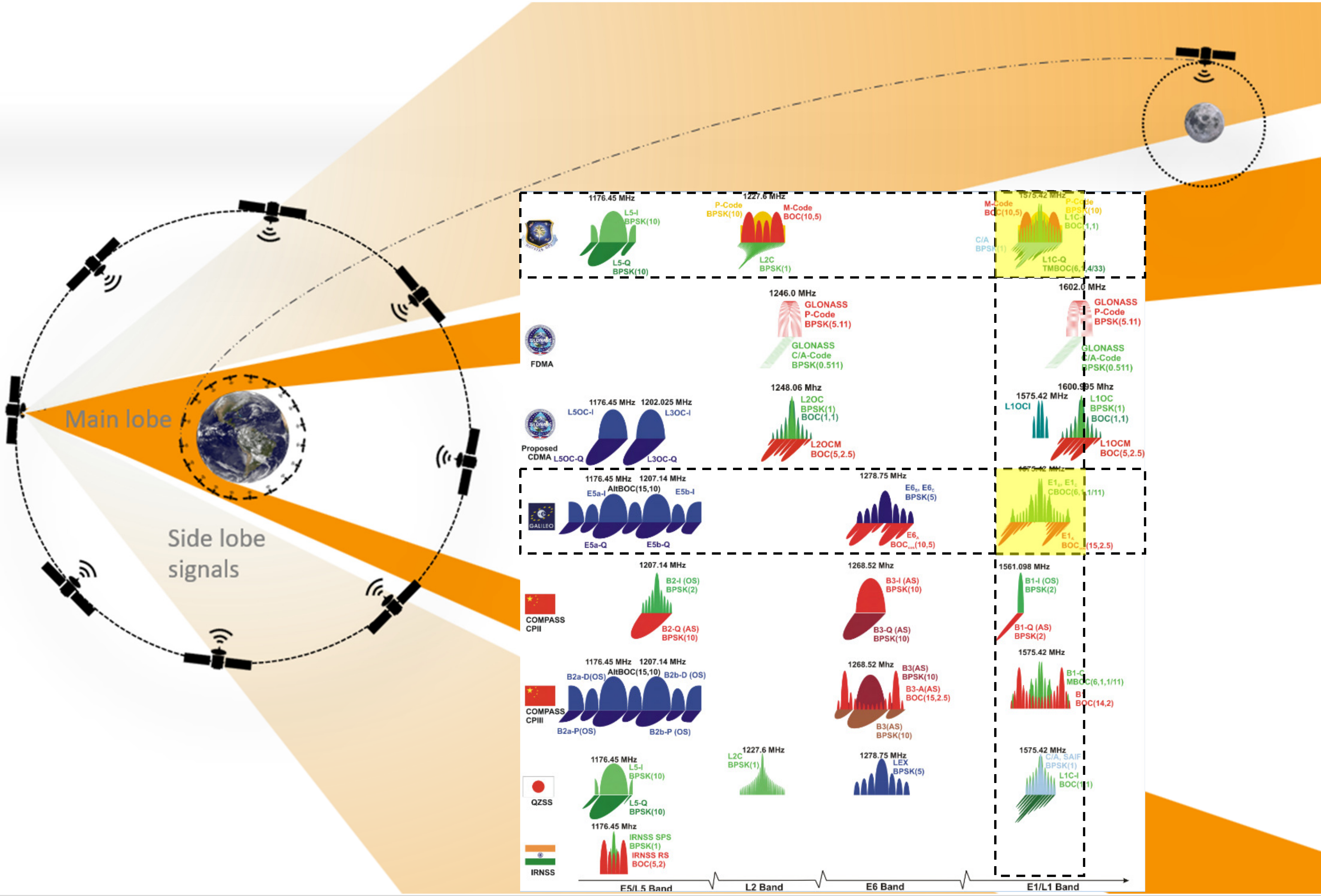
R&D

WeakHEO PoC receiver

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

< 1 s TTFF using PCS and assistance	15 dBHz L1 C/A autonomous acquisition



Timeline - Historical background

2004 | 2013 | **2016** : addition of a second constellation & second frequency & OF

Technology Readiness Level	TRL2/3
PNT & GNSS R&D	**Idea validation**
R&D	***R&D***
  	 WeakHEO PoC receiver
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE	ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
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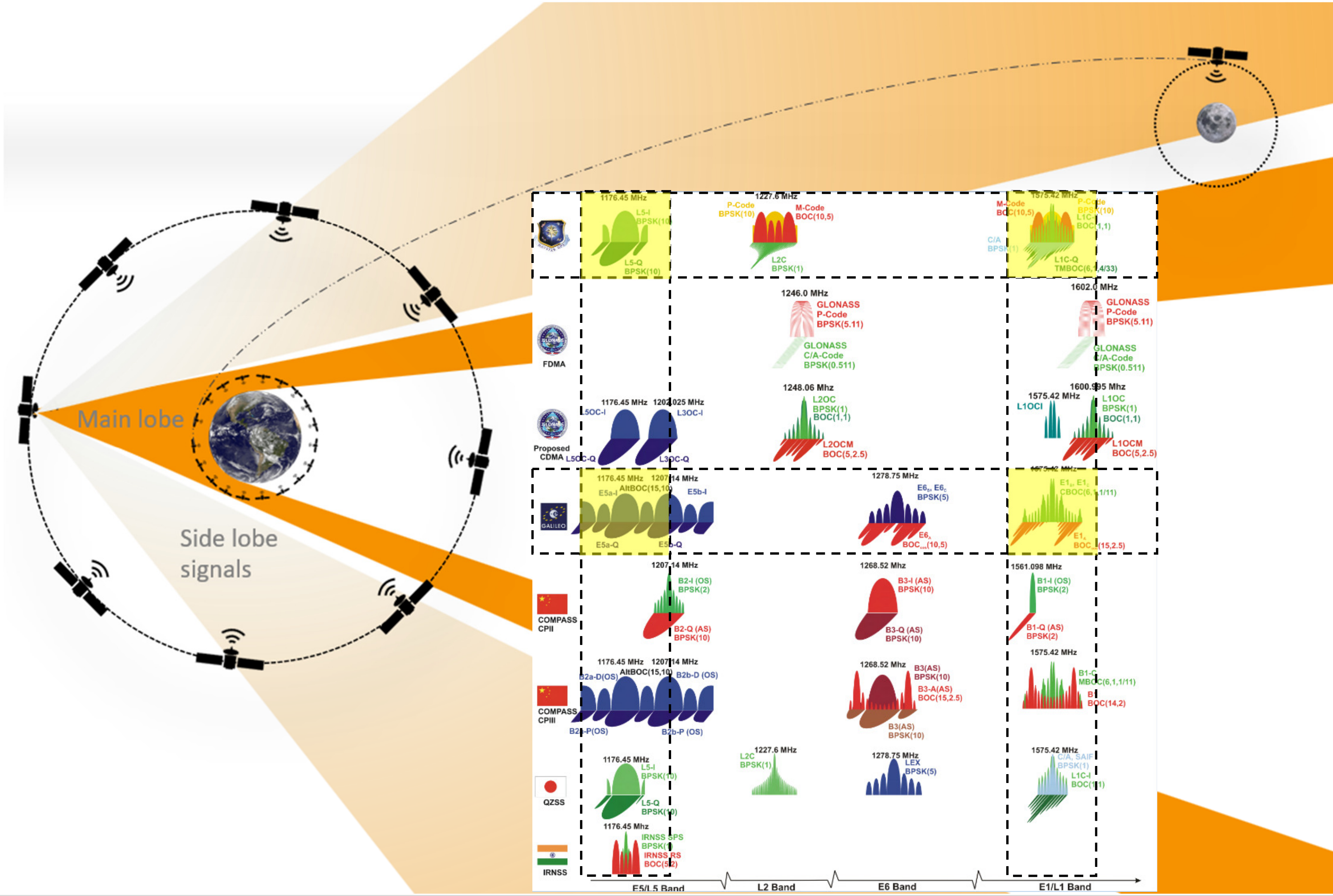


Timeline - Historical background

2004 | 2013 | 2016 | **2018** : full HIL validation

Technology Readiness Level	TRL2/3	TRL3/4
PNT & GNSS R&D	Idea validation	Proof-of-concept

R&D

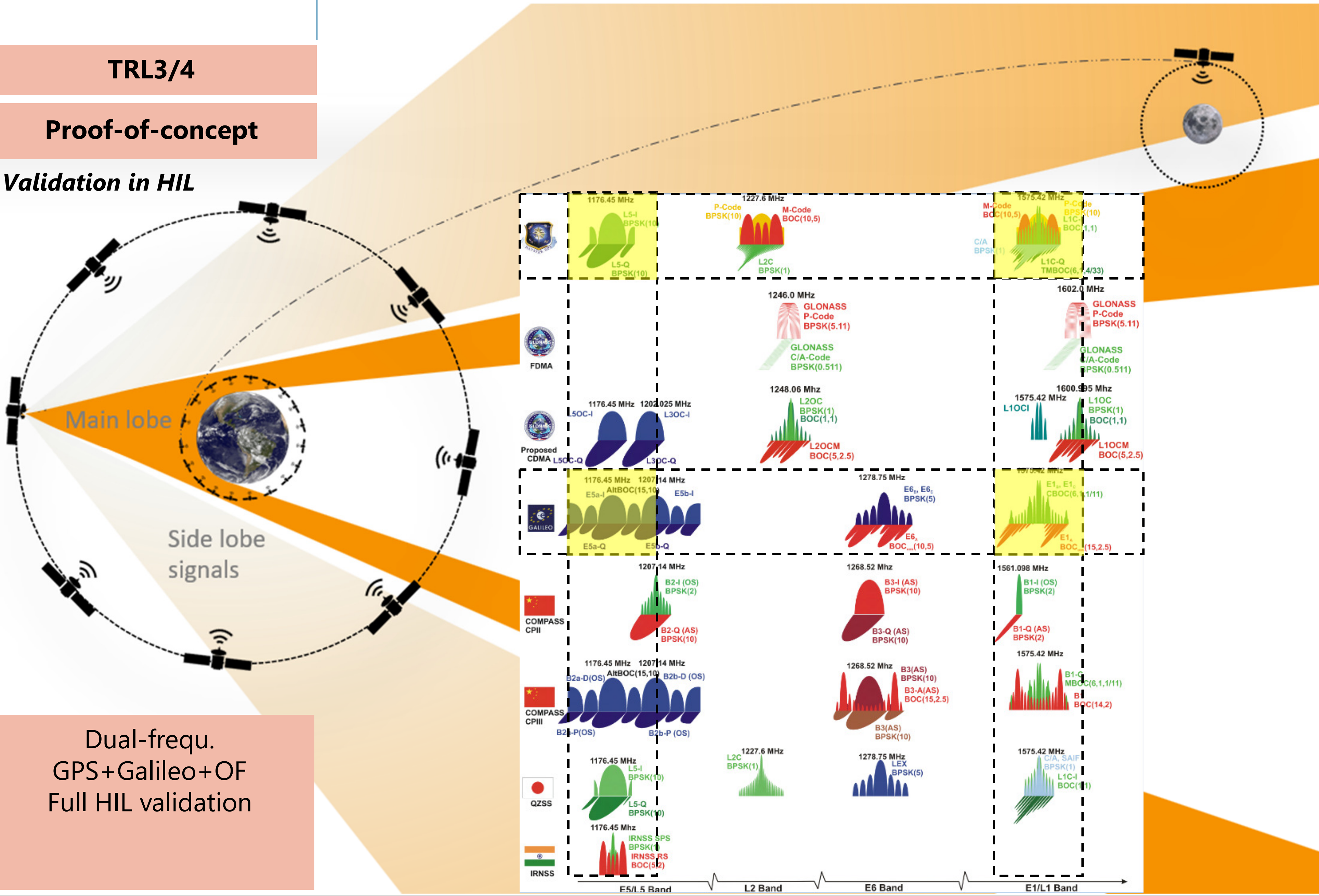
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

R&D

WeakHEO PoC receiver

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Validation in HIL



< 1 s TTFF using PCS and assistance	15 dBHz L1 C/A autonomous acquisition	Dual-frequ. GPS+Galileo+OF Full HIL validation

Timeline - Historical background

2004 | 2013 | 2016 | **2019** : Development of NaviLEO™ EM

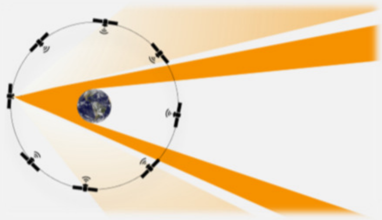
Technology Readiness Level	TRL2/3	TRL3/4	TRL5/6
PNT & GNSS R&D	**Idea validation**	**Proof-of-concept**	**Prototype**

R&D

R&D

WeakHEO PoC receiver

Validation in HIL



EM Prototypes

Navisp-EL2-006 : Development of a Spaceborne GNSS Receiver (NaviLEO™)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | SYDERAL SWISS SpacePNT

< 1 s TTFF using PCS and assistance	15 dBHz L1 C/A autonomous acquisition	Dual-frequ. GPS+Galileo+OF Full HIL validation	NaviLEO/NaviMoon product line development

Timeline - Historical background

2004 | 2013 | 2016 | 2019 | **2020** : Development of NaviMoon EM

Technology Readiness Level	TRL2/3	TRL3/4	TRL5/6
PNT & GNSS R&D	**Idea validation**	**Proof-of-concept**	**Prototype**

R&D

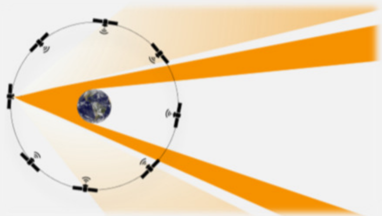
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

R&D

WeakHEO PoC receiver

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Validation in HIL



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

EM Prototypes

Navisp-EL2-006 : Development of a Spaceborne GNSS Receiver (NaviLEO™)

esa navisp

Navisp-EL1-023 : Earth-Moon Navigation / System Study and Development of Highly-Sensitive Spaceborne Receiver Prototype

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esa navisp

SYDERAL SWISS

SpacePNT

< 1 s TTFF using PCS and assistance	15 dBHz L1 C/A autonomous acquisition	Dual-frequ. GPS+Galileo+OF Full HIL validation	NaviLEO/NaviMoon product line development

Timeline - Historical background

2004 | 2013 | 2016 | 2019 | 2020 | **2021** : Development of NaviMoon PFM

Technology Readiness Level	TRL2/3	TRL3/4	TRL5/6	TRL7
PNT & GNSS R&D	**Idea validation**	**Proof-of-concept**	**Prototype**	**Qualification**

R&D

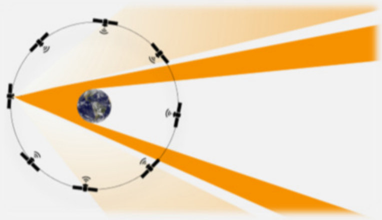
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

R&D

WeakHEO PoC receiver

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Validation in HIL



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

EM Prototypes

Navisp-EL2-006 : Development of a Spaceborne GNSS Receiver (NaviLEO™)

csem

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Navisp-EL1-023 : Earth-Moon Navigation / System Study and Development of Highly-Sensitive Spaceborne Receiver Prototype

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SpacePNT+

Navisp-EL1-039 : NaviMoon Earth-Moon GNSS spaceborne receiver for In-Orbit Demonstration

EECL European Engineering & Consultancy Ltd

< 1 s TTFF using PCS and assistance	15 dBHz L1 C/A autonomous acquisition	Dual-frequ. GPS+Galileo+OF Full HIL validation	NaviLEO/NaviMoon product line development	NaviLEO/NaviMoon qualification

Timeline - Historical background

2004	2013	2016	2019	2020	2021	2023

Technology Readiness Level	TRL2/3	TRL3/4	TRL5/6	TRL7	TRL8
PNT & GNSS R&D	**Idea validation**	**Proof-of-concept**	**Prototype**	**Qualification**	**Flight ready**

R&D

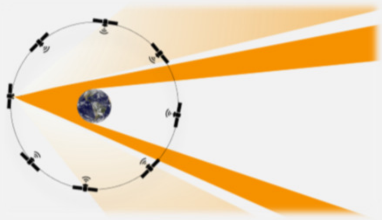
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

R&D

WeakHEO PoC receiver

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Validation in HIL



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

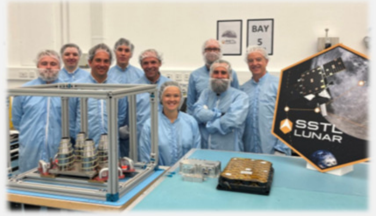
EM Prototypes

Navisp-EL2-006 : Development of a Spaceborne GNSS Receiver (NaviLEO™)

Navisp-EL1-023 : Earth-Moon Navigation / System Study and Development of Highly-Sensitive Spaceborne Receiver Prototype

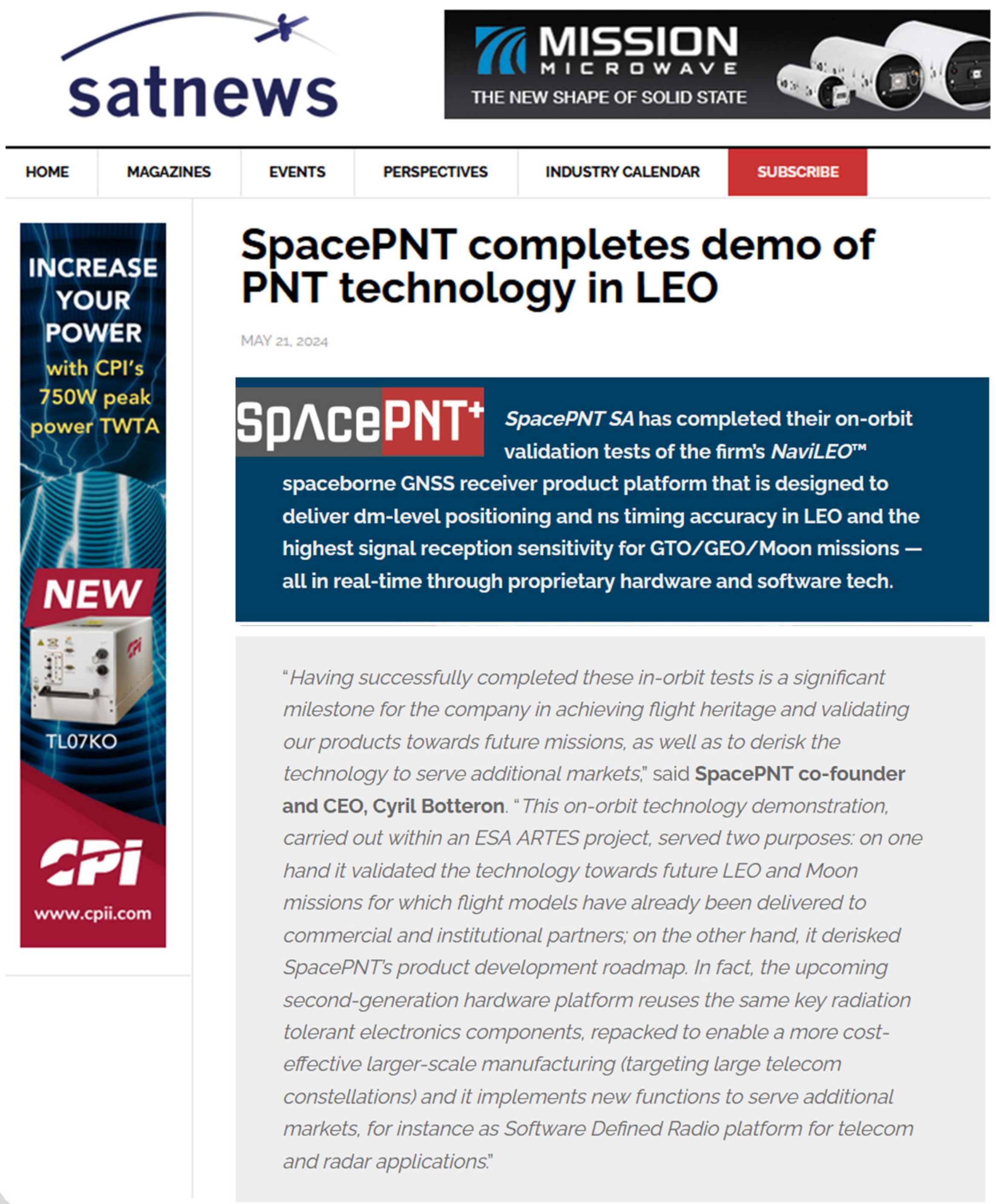
Navisp-EL1-039 : MaviMoon Earth-Moon GNSS spaceborne receiver for In-Orbit Demonstration

EECL European Engineering & Consultancy Ltd



< 1 s TTFF using PCS and assistance	15 dBHz L1 C/A autonomous acquisition	Dual-frequ. GPS+Galileo+OF Full HIL validation	NaviLEO/NaviMoon product line development	NaviLEO/NaviMoon qualification	NaviMoon FPM DRB

SpacePNT+ Highlights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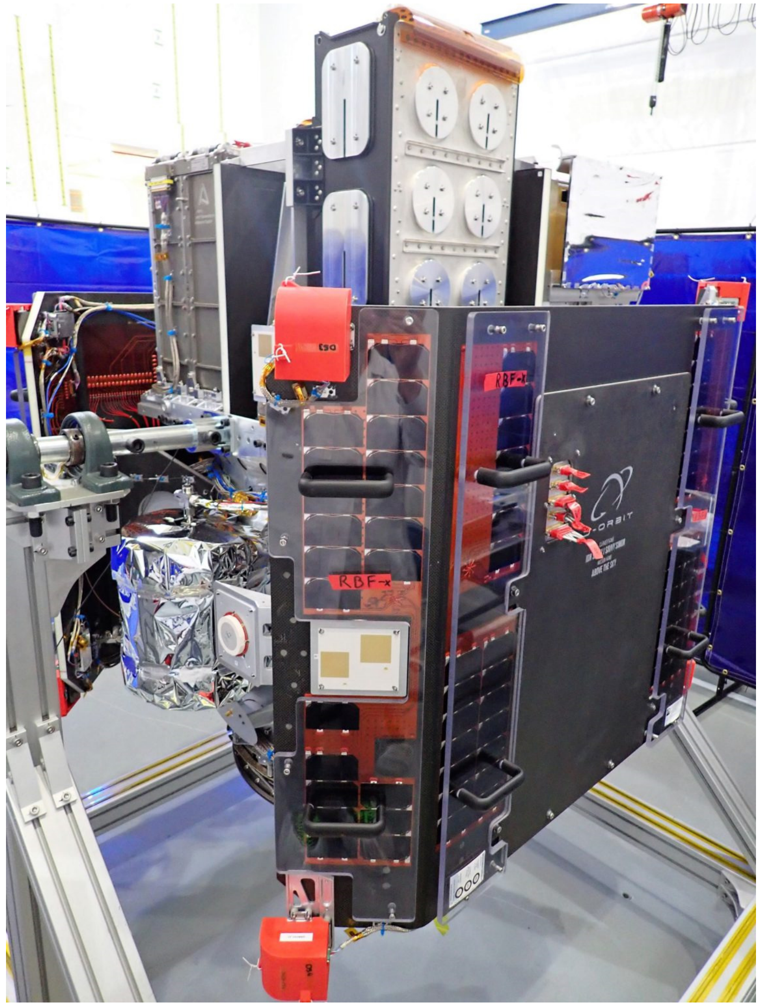
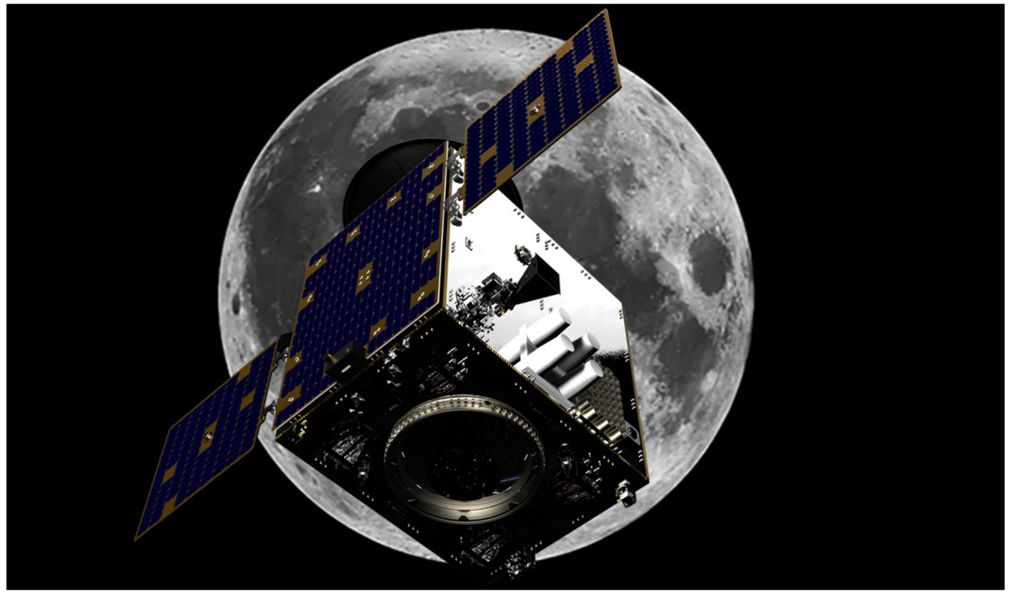
SpacePNT completes demo of PNT technology in LEO

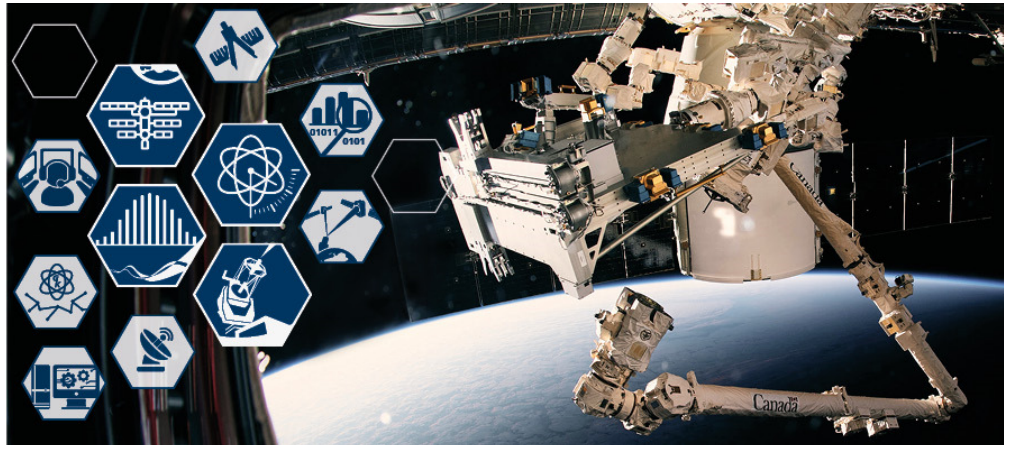
MAY 21, 2024

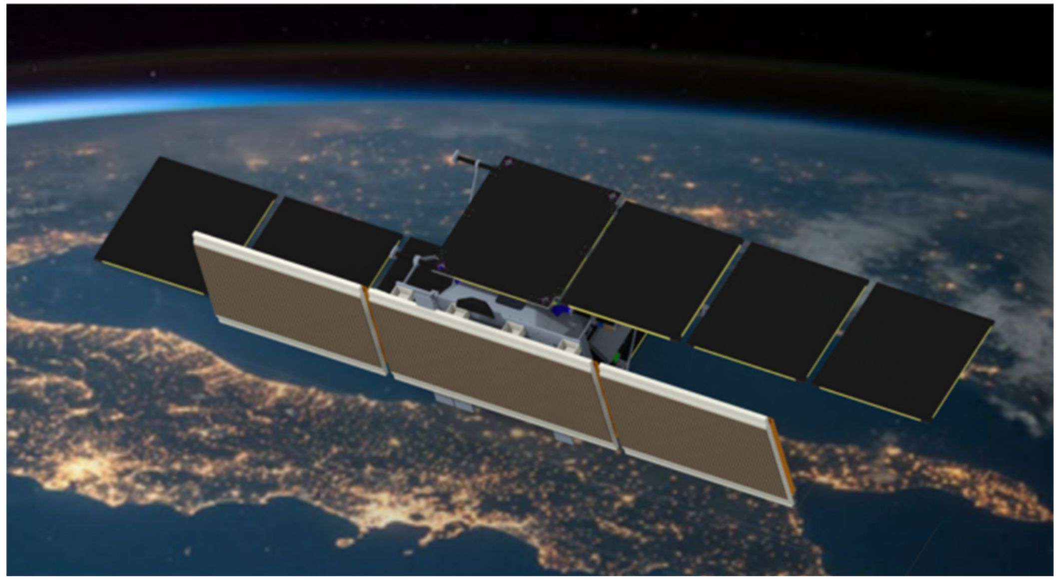
SpacePNT+ *SpacePNT SA* has completed their on-orbit validation tests of the firm's *NaviLEO*™ spaceborne GNSS receiver product platform that is designed to deliver dm-level positioning and ns timing accuracy in LEO and the highest signal reception sensitivity for GTO/GEO/Moon missions — all in real-time through proprietary hardware and software tech.

"Having successfully completed these in-orbit tests is a significant milestone for the company in achieving flight heritage and validating our products towards future missions, as well as to derisk the technology to serve additional markets," said **SpacePNT co-founder and CEO, Cyril Botteron**. *"This on-orbit technology demonstration, carried out within an ESA ARTES project, served two purposes: on one hand it validated the technology towards future LEO and Moon missions for which flight models have already been delivered to commercial and institutional partners; on the other hand, it derisked SpacePNT's product development roadmap. In fact, the upcoming second-generation hardware platform reuses the same key radiation tolerant electronics components, repacked to enable a more cost-effective larger-scale manufacturing (targeting large telecom constellations) and it implements new functions to serve additional markets, for instance as Software Defined Radio platform for telecom and radar applications."*





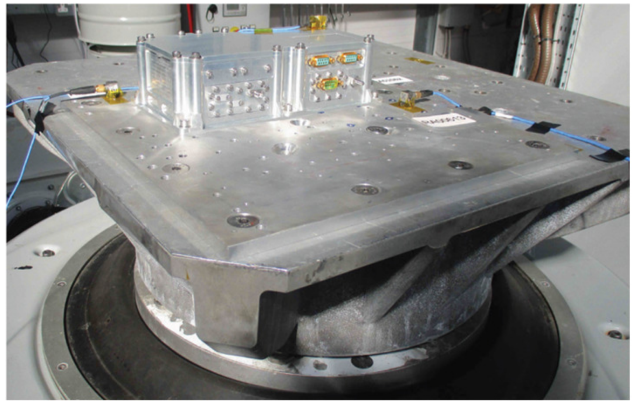
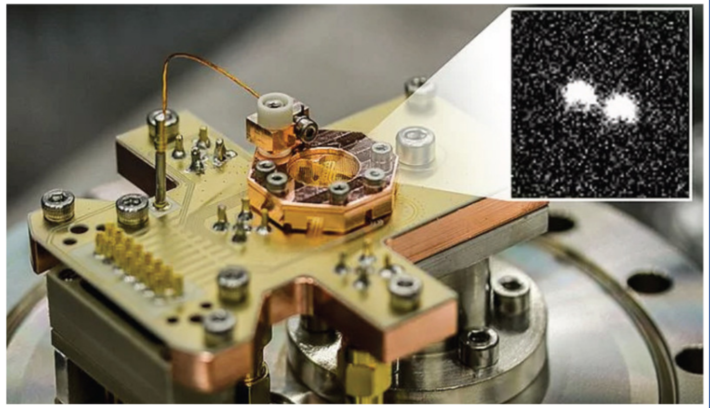




EECL European Engineering & Consultancy Ltd

Specialist Engineering Company providing world leading electronic and mechanical solutions to Space, Defence, High Technology Science and Industrial Markets.

- RF & Microwave products for Space, Defence, Commercial and Quantum Computing.
- We provide bespoke advanced electronic solutions through concept, design, development and manufacturing.
- Supplier of Product: Automated Test Solutions for the RF Industry
- ISO-Class 7 Cleanroom and Class 8 Test & Measurement lab. Fully loaded with Equipment and Instrumentation.
- Space Product Assurance: EMC, Mechanical, Thermal, Radiation, Qualification.
- Previous projects include design consultancy for Airbus OneWeb Payloads (1200+).
- Solving Difficult RF Problems in short time scales.
- We are a growing Team of Capable RF expertise and consistently taking on more complex projects. Completed 20+ projects in 8 years ranging from £10k to £1million.

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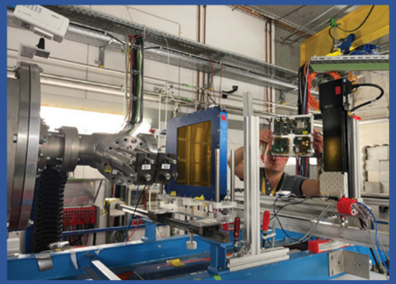
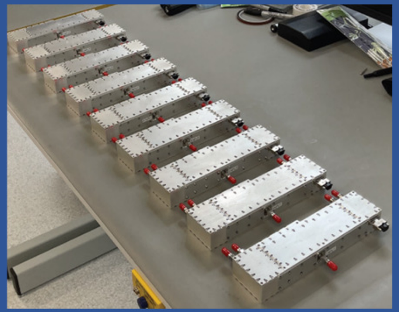
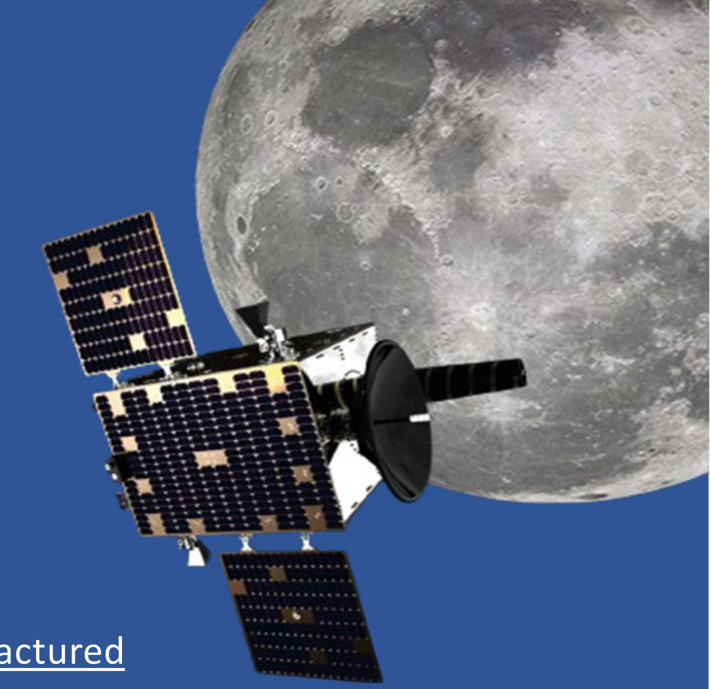
+44 203 6677196, www.euroecl.com

23 Flight Modules Manufactured

- SpacePNT World First GPS Hardware to Navigate on the Moon, ESA Lunar Pathfinder
- 9 Payloads for Remote sensing, ESA HydroGNSS
- 3 Payload Modules Remote Sensing – Amazonia-1B
- High-Spec Frequency Converters for Space Data Centers US Gov funded project

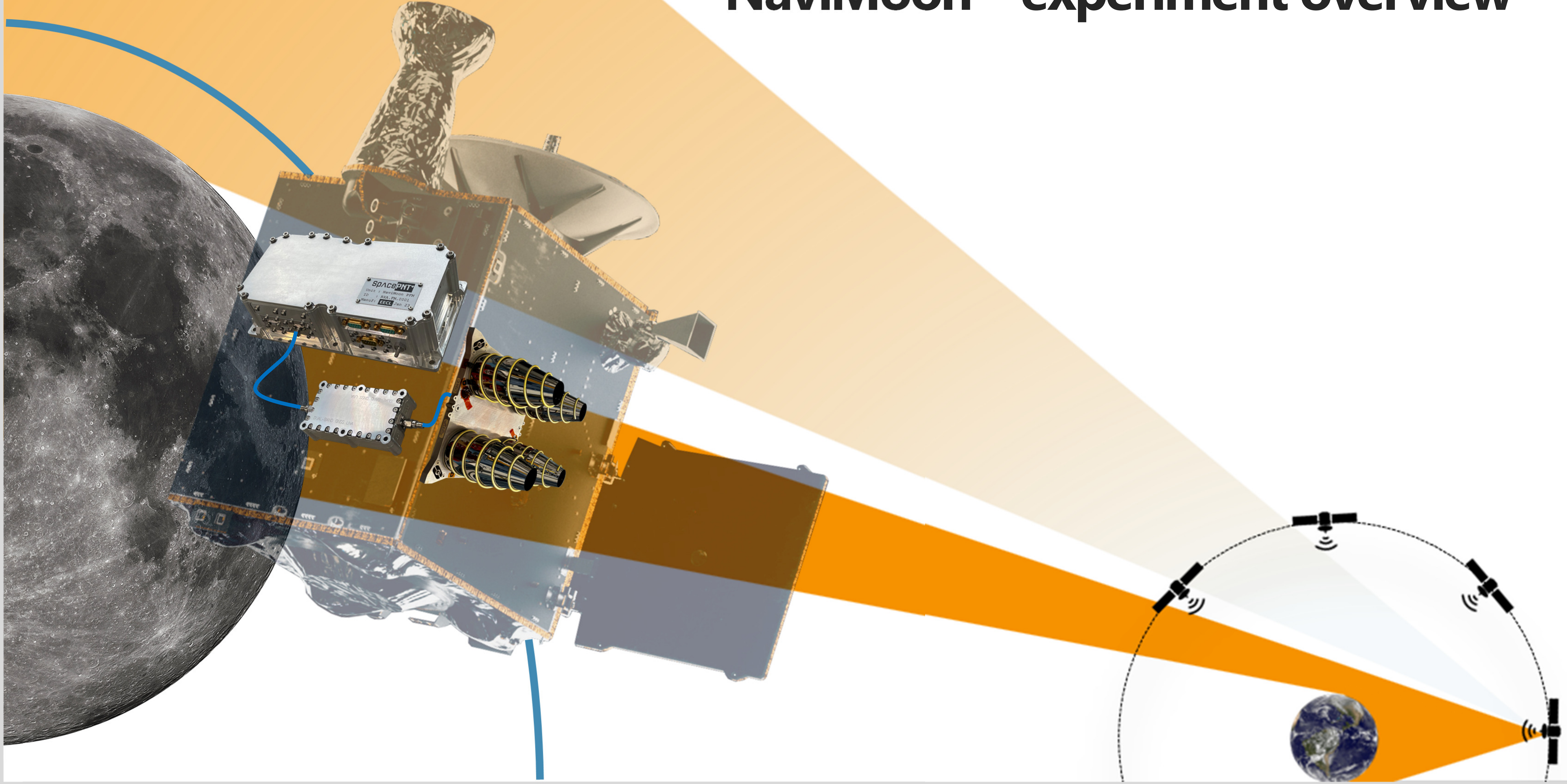
NAVISP-EL1-039 – Project outline

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

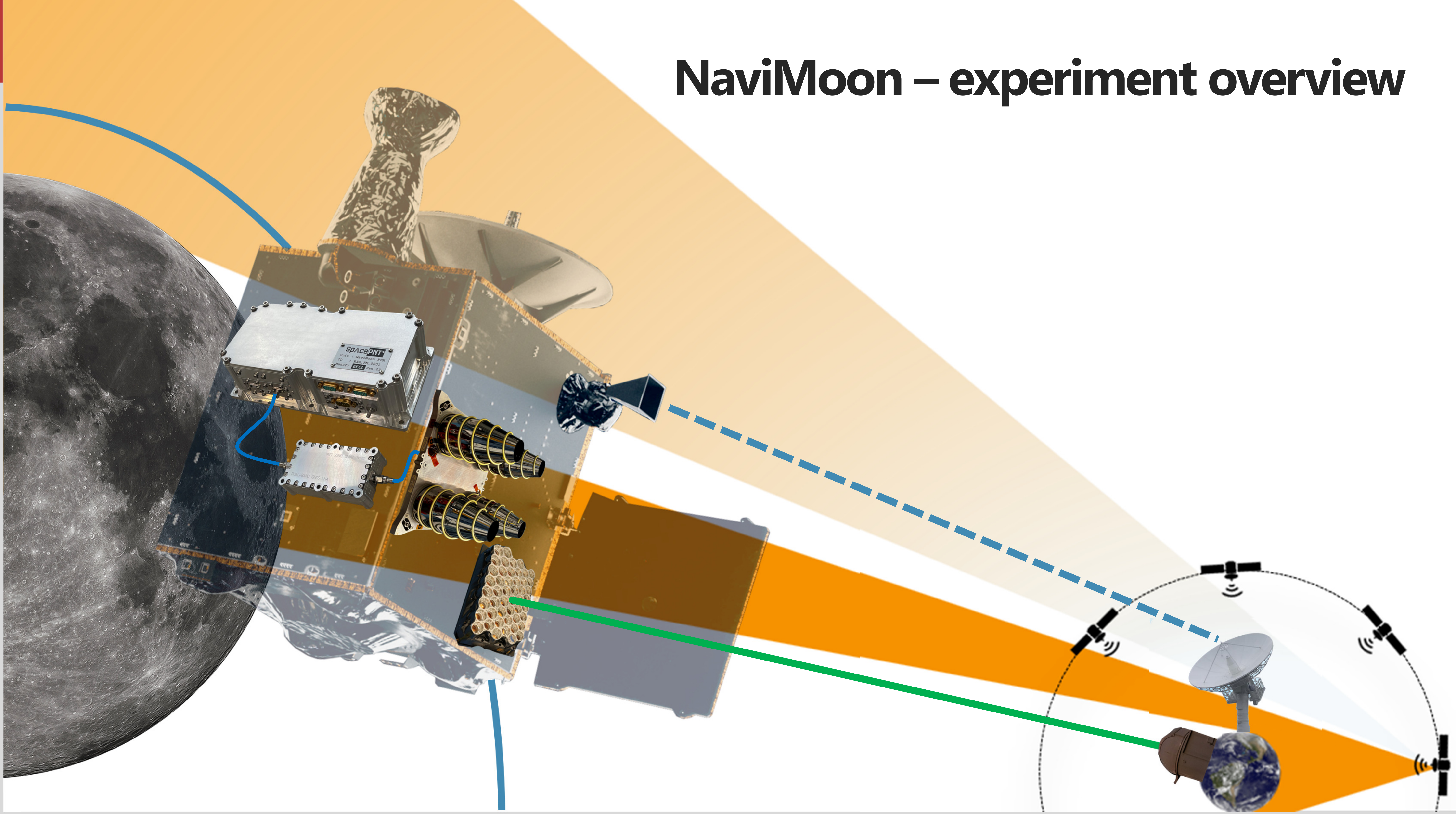
- **Implementation strategy:**
  - Develop, manufacture and test a Proto-Flight Model of the NaviMoon high-sensitivity GNSS receiver and LNA, to be embarked on SSTL's Lunar Pathfinder
  - Manufacturing 3 Engineering Models (algorithm development, satellite integration and ground twin)
  - Proto-flight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

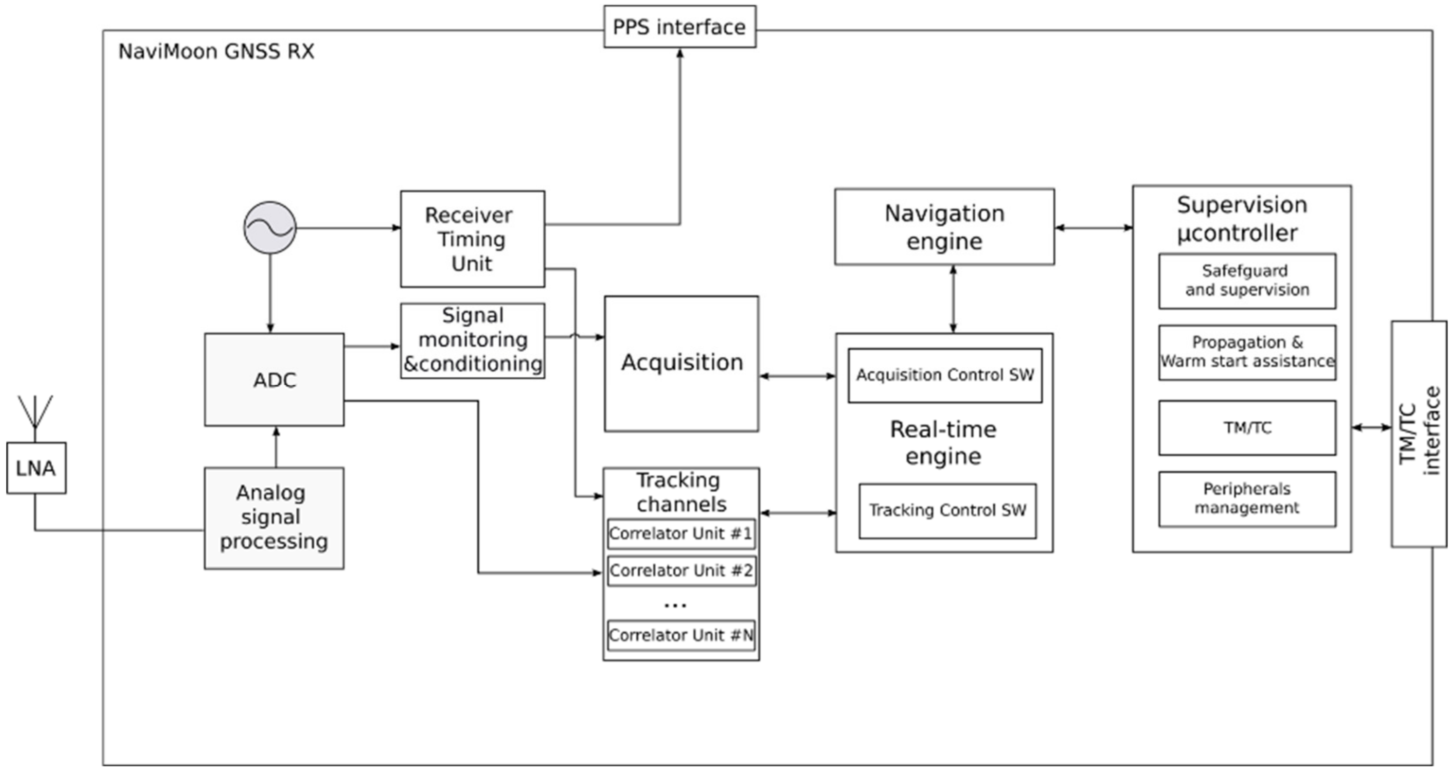


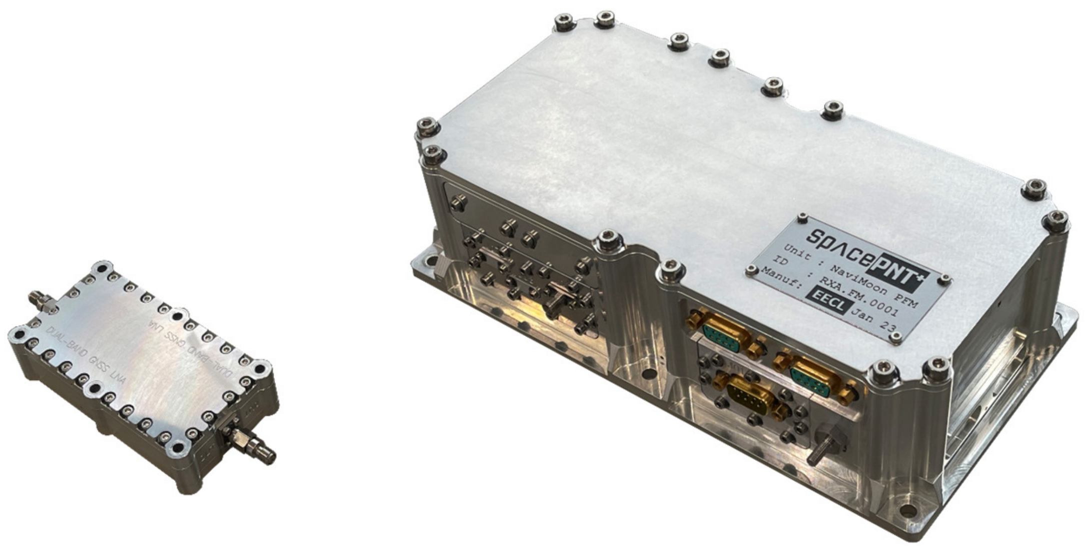
NaviMoon – experiment overview



NaviMoon – System Overview

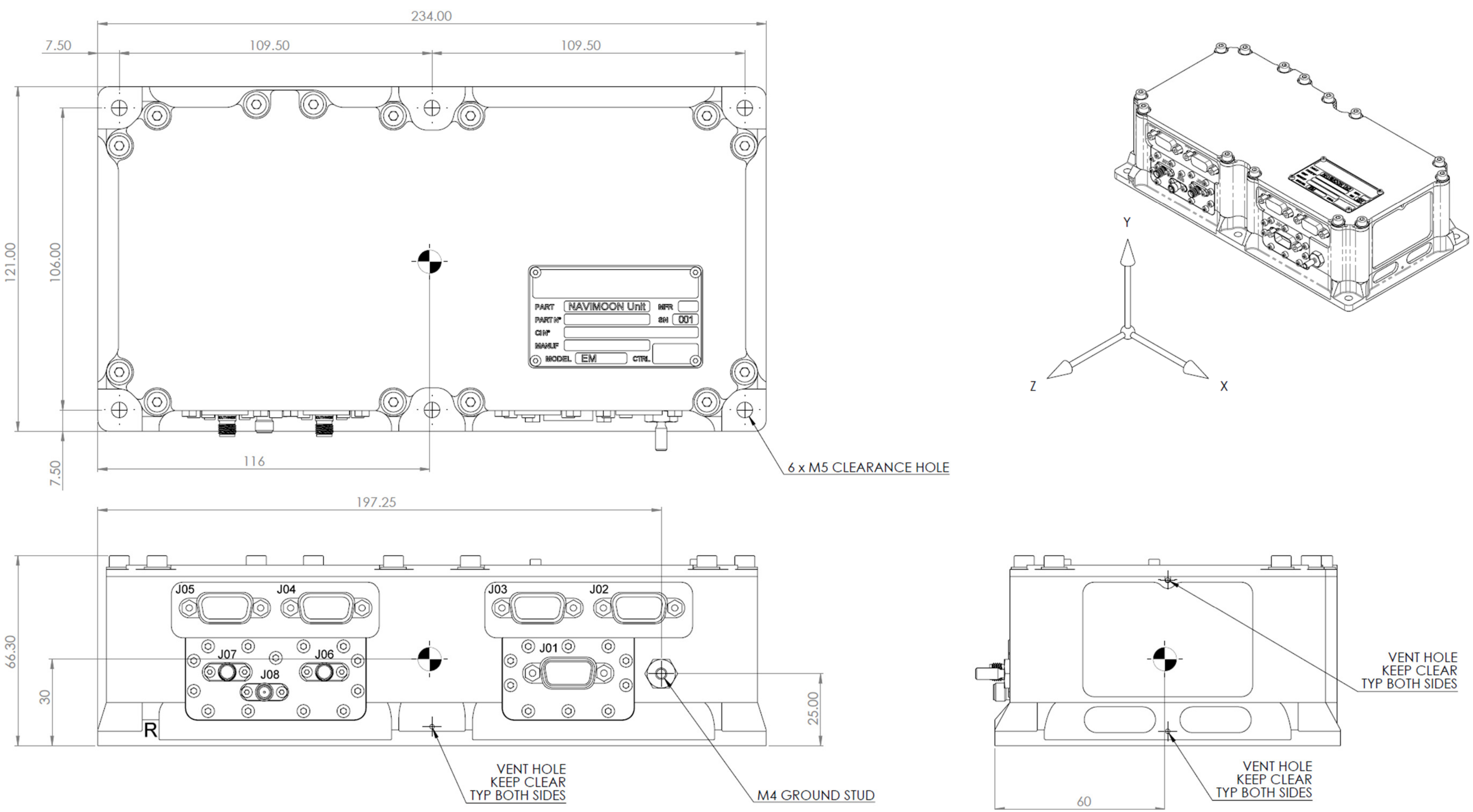
- NaviMoon: evolution of SpacePNT flagship spaceborne GNSS receiver NaviLEO™.
  Main features:
  - Dual constellation (GPS + Galileo)
  - Dual frequency (E1/L1 + E5a/L5)
  - COTS based + radiation mitigation (ECC, watchdogs, memory scrubbing…)
  - Fast digital signal processing in hardware
  - Acquisition/Tracking 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



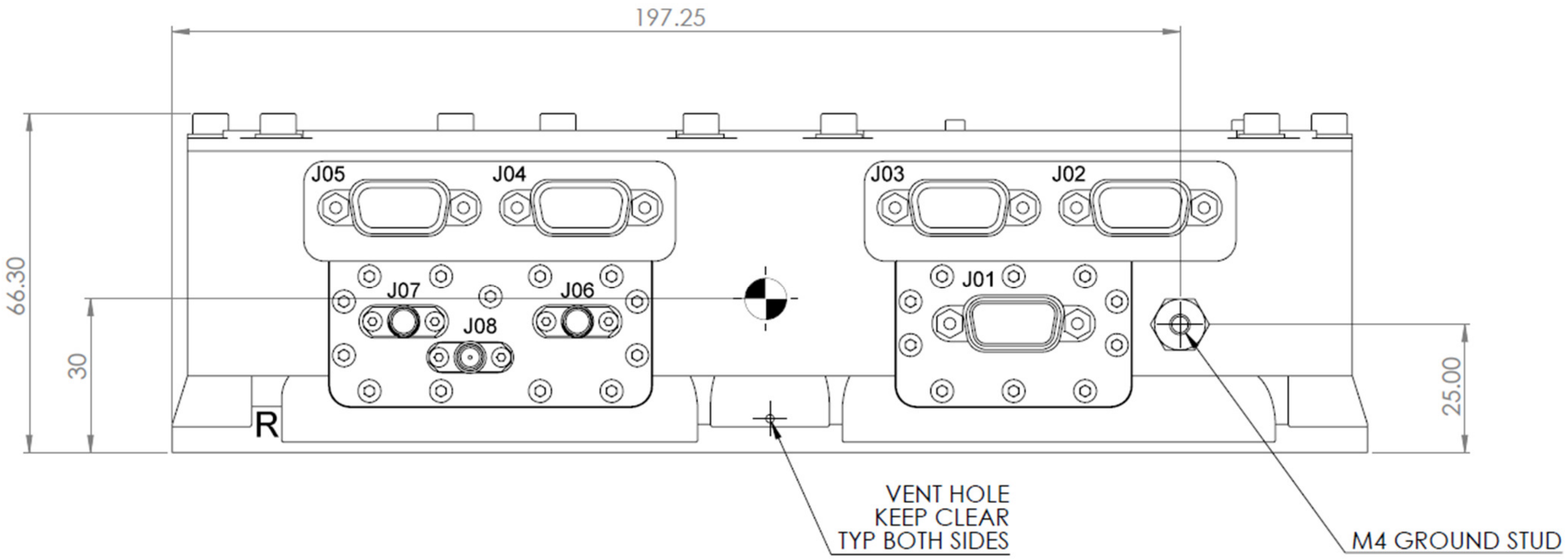


NaviMoon – MICD (generic)

Mass = 1.5 kg
Power = 8 W (12 W peak)



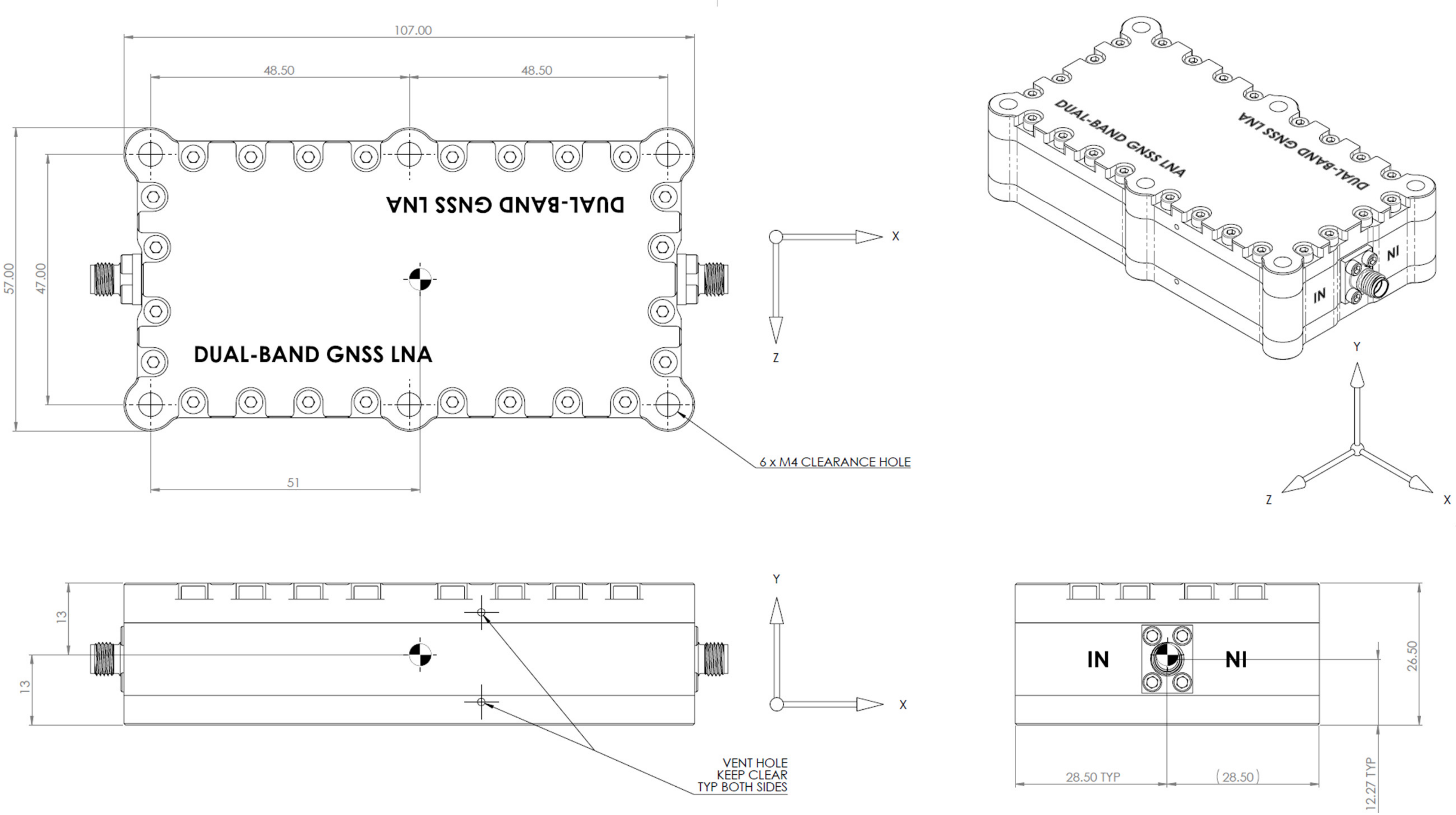
NaviMoon – EICD (generic)



IF ID	Connector type	Description
J01	D-sub 9 pin (male)	POWER SUPPLY INPUT (5V)
J02	D-sub 9 pin (female)	RS422 - TELEMETRY/TELECOMMAND I/F (NOMINAL)
J03	D-sub 9 pin (female)	RS422 - TELEMETRY/TELECOMMAND I/F (REDUNDANT)
J04	D-sub 9 pin (female)	RS422 - PULSE PER SECOND I/F
J05	D-sub 9 pin (female)	RS422 - PULSE PER SECOND I/F
J06	SMA (female)	ANTENNA I/F
J07	SMA (female)	ANTENNA I/F
J08	SMA (female)	10 MHz input I/F

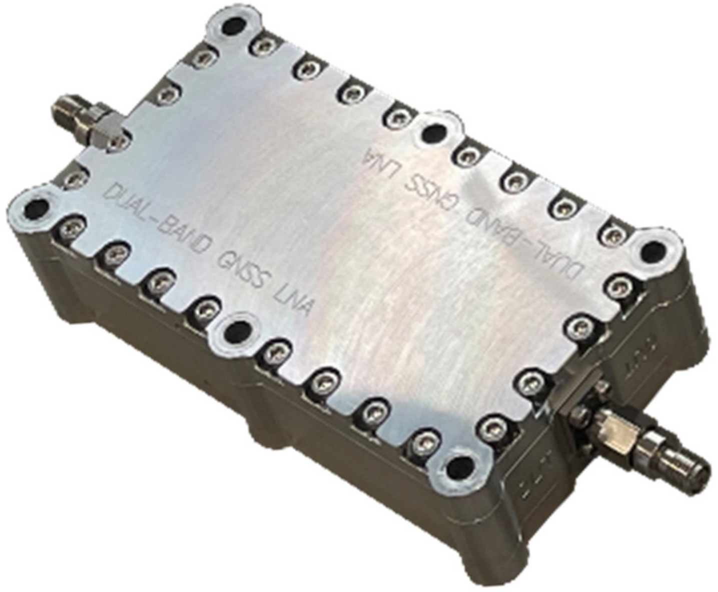
LNA – MICD, EICD

Mass = 275 g
Power = 0.5 W (phantom feed)



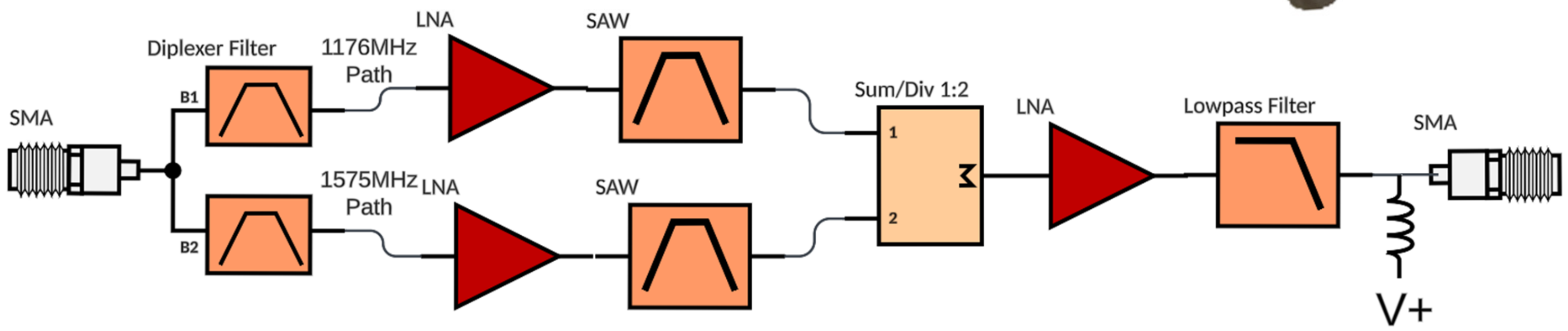
High Performance LNA Design

EECL provided the GNSS reflectometry front end for remote sensing. We have the capability to design best in class RF modules. Similar design techniques have been employed for Lunar LNA as highest possible performance is required for ultra weak signals. A separate LNA is desirable as we can amplify the signals in the coldest environment possible, as close to the antenna as possible and out of the GNSS receiver that may have a higher internal noise floor.



Requirements

- Space Qualified
- Dual Band
- Lowest in Class Noise Figure
- Gain around 30dB (to set the system noise figure up the chain)
- High rejection of out of band signals.
- Low Group Delay and High phase stability

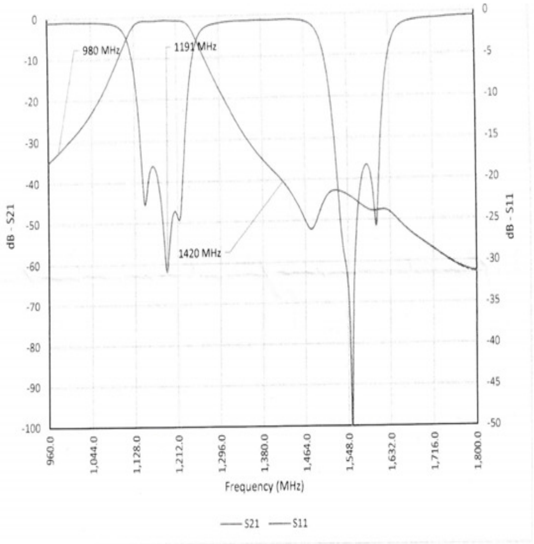


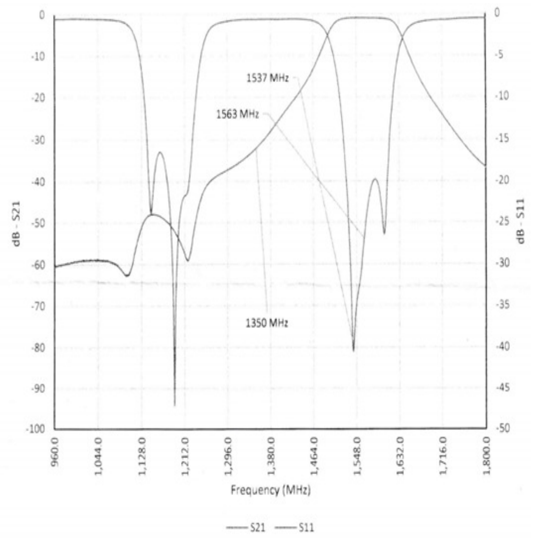
High Performance LNA Design – Input Stage

The noise figure must be minimised. Noise figure is a direct sum of any loss before amplification and the amplifier noise. After amplification subsequent loss due to Friis equation becomes less consequential.

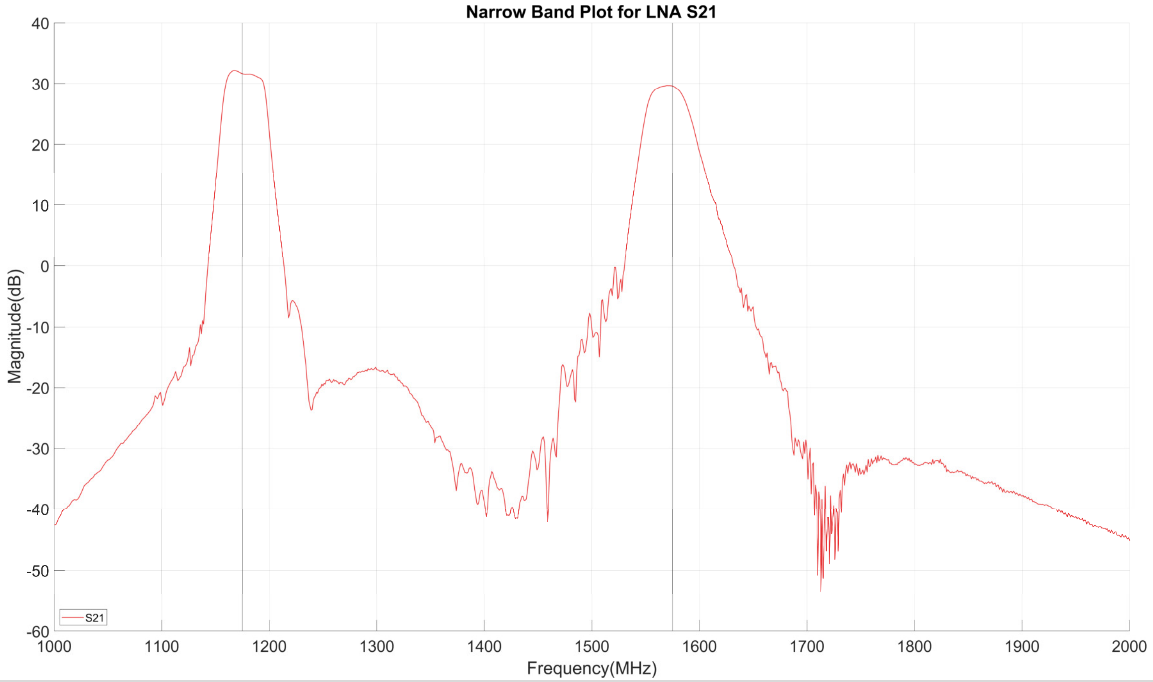
The key things in this design are: Low Loss Feed, Novel Custom Diplexer design and Ultra Low Noise Figure LNA.

Custom Diplexer design to provide the lowest possible loss when mounted on the PCB. Hand wound coils and manually tuned resonant circuits. Insertion loss of 0.5dB achieved from connector to LNA. Manufactured to withstand shock and vibration.





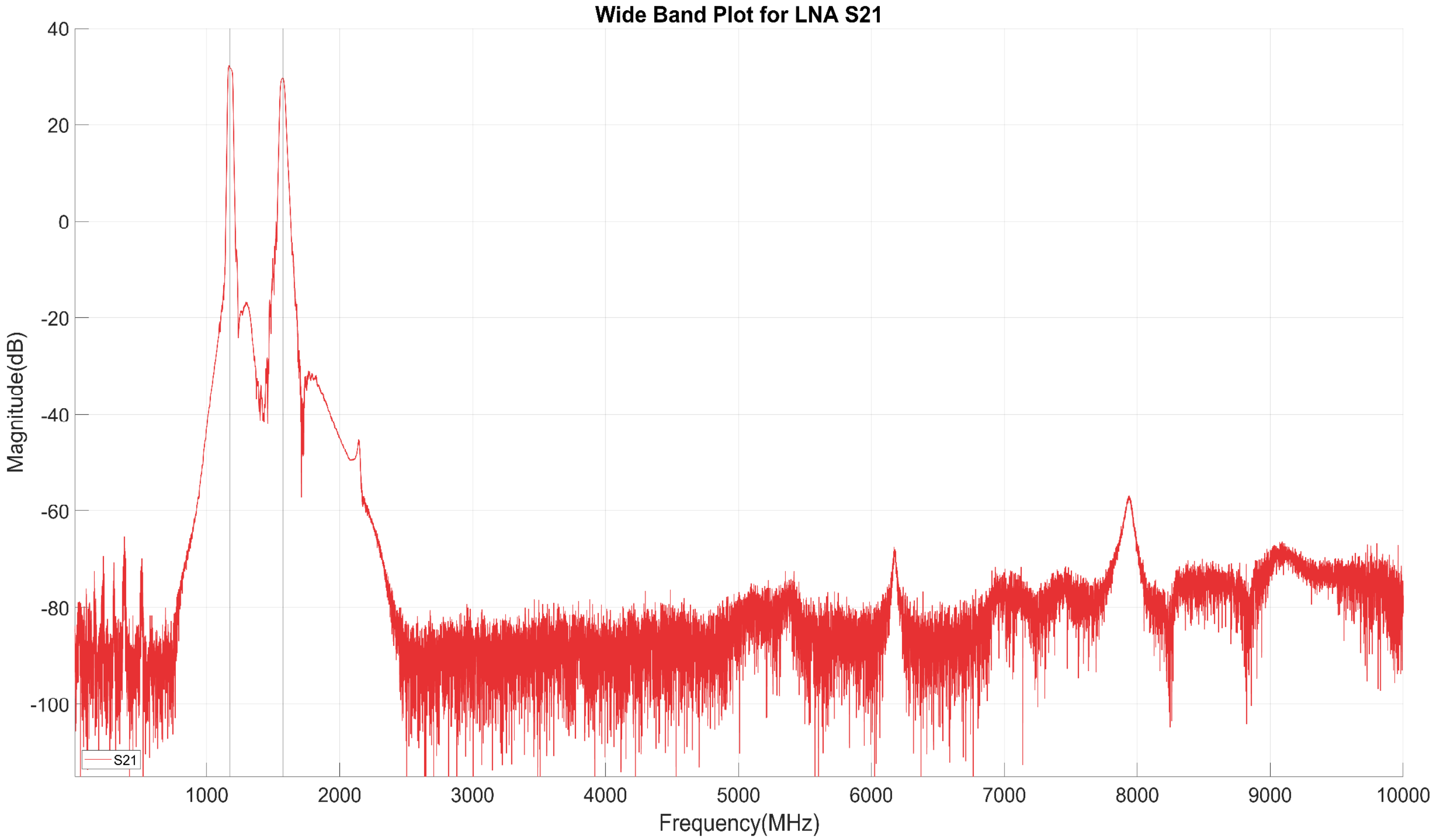
The GNSS amplifier was designed to achieve best in class noise figure and the phase mismatch from the diplexer for each band was tuned out so that mismatch loss was minimised. We achieved the following performance for the LNA.

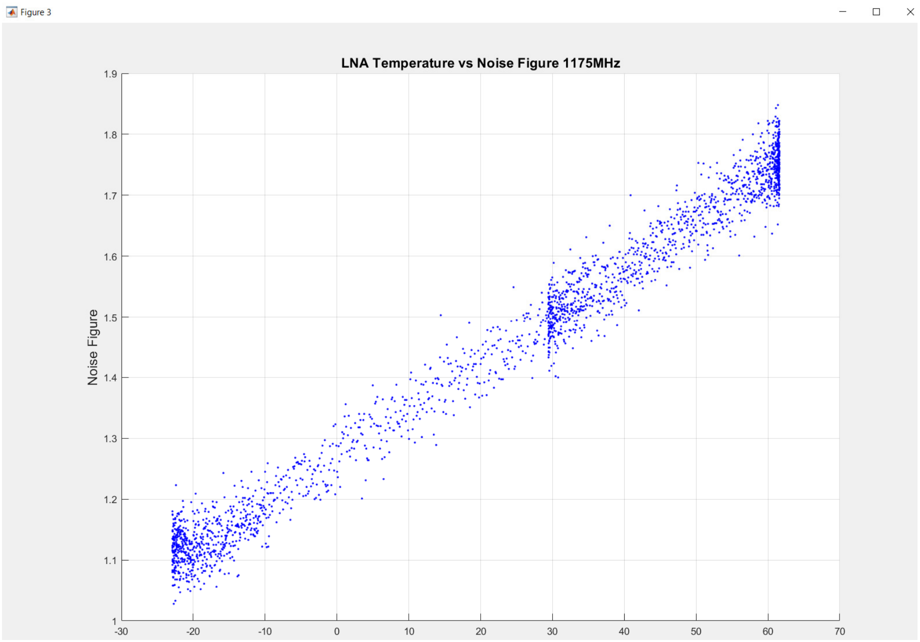


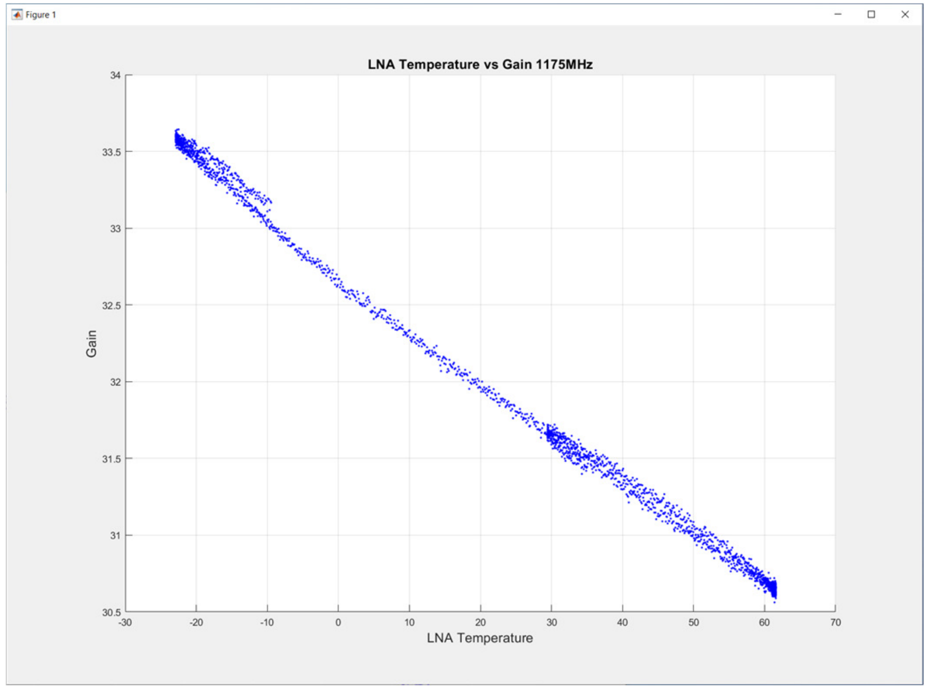
High Performance LNA Design – Results

The LNA was characterised for the noise figure and gain over temperature. We employ automated test to characterise it.

- ❖ 1.2 dB total noise figure at 25°C including all connectors, diplexer and LNA.
- ❖ Gain of 30dB per band
- ❖ Flat group delay
- ❖ Out of band filtering 70dB between bands and >100dB above 2GHz

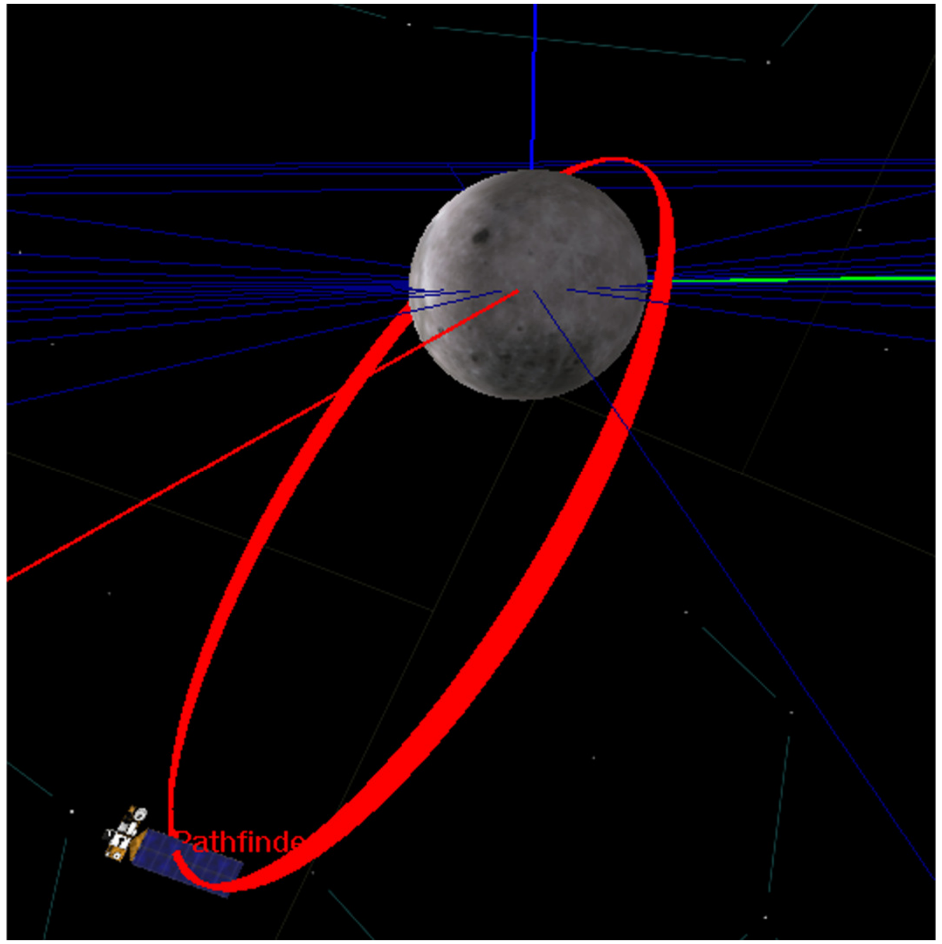






Receiver design – reference trajectory

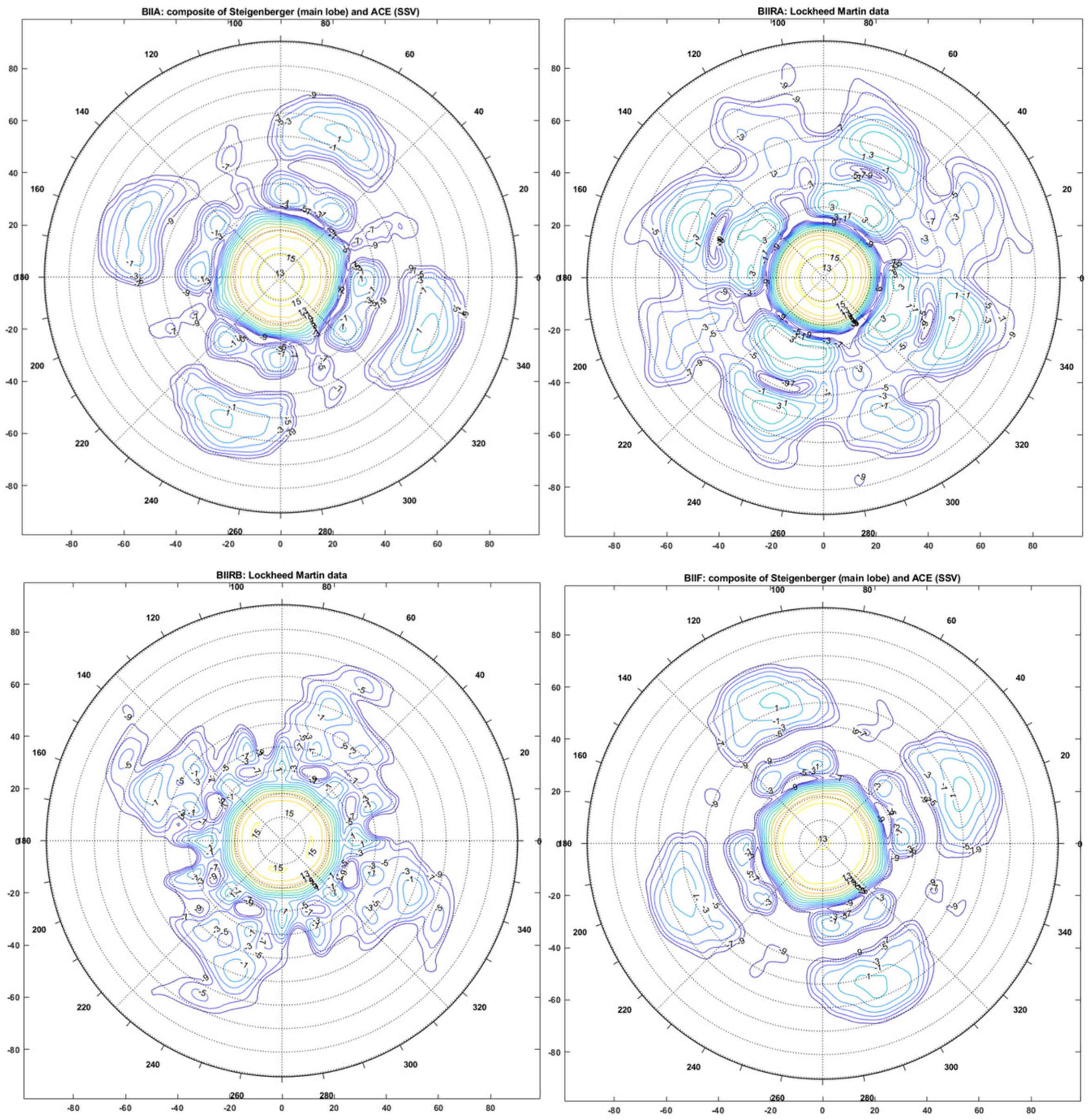
- Design based on a potential orbit for Lunar Pathfinder
- Initial state (see table) propagated with high fidelity force model (GODOT)
  - Moon gravity: GRGM1200A: order = 80; degree = 80
  - Earth gravity: EGM2008: order = 100; degree = 100
  - Point masses: Sun, Mercury, Venus, Mars, Jupiter, Saturn, Jupiter, Uranus, Pluto
  - Solar radiation pressure (reflectivity = 1.0, SRP area = 10 m^2, 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

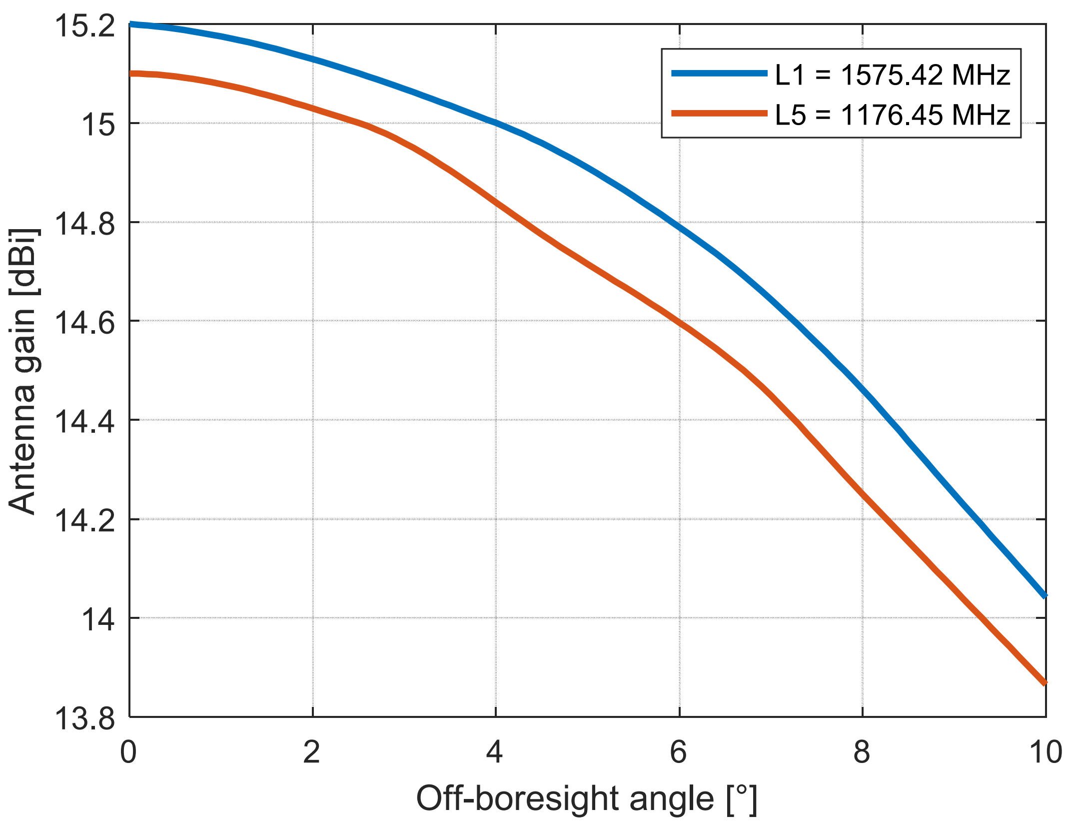
Receiver design – GNSS constellations

- 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**



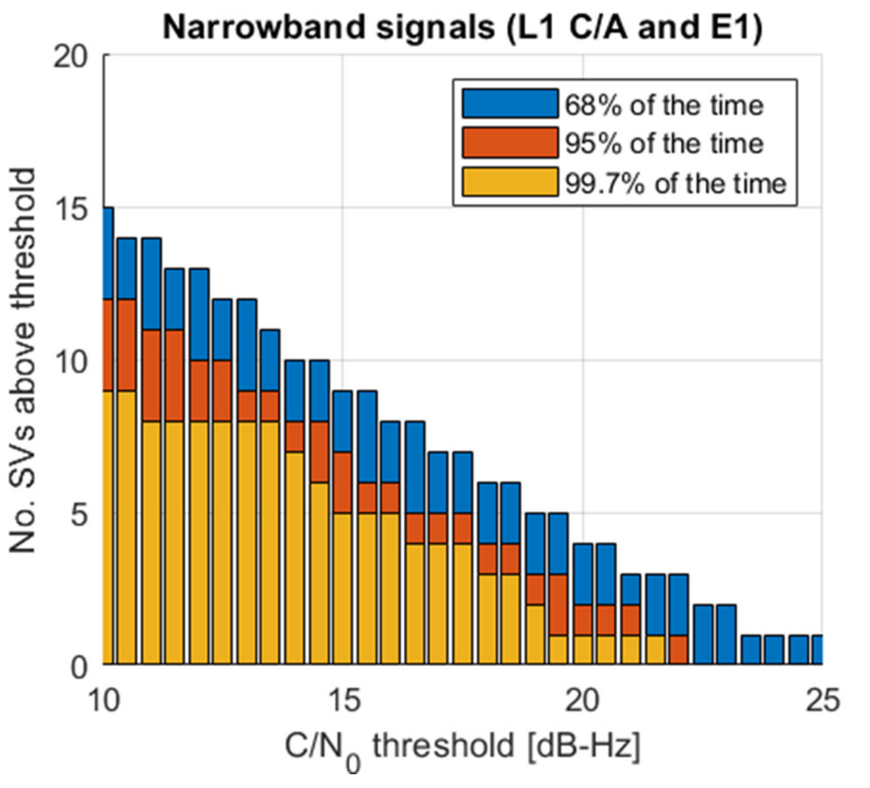
	Gain/Loss		Units	Notes
	dB	linear		
Boltzmann constant	-228.60	1.38E-23	J/K	
Antenna, T_A		34.0	K	Anzalone et al. 2019
Ambient Temperature, T0		300.0	K	
Cable 1 $F_1=1/G_1$	0.20	1.05		Short cable from antenna to LNA
LNA Gain, G_2	29.50	891.25		LNA performance at 1.5 GHz
LNA Noise Figure, F_2	1.40	1.38		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**		
T_{eff}		**167.98**	**K**	

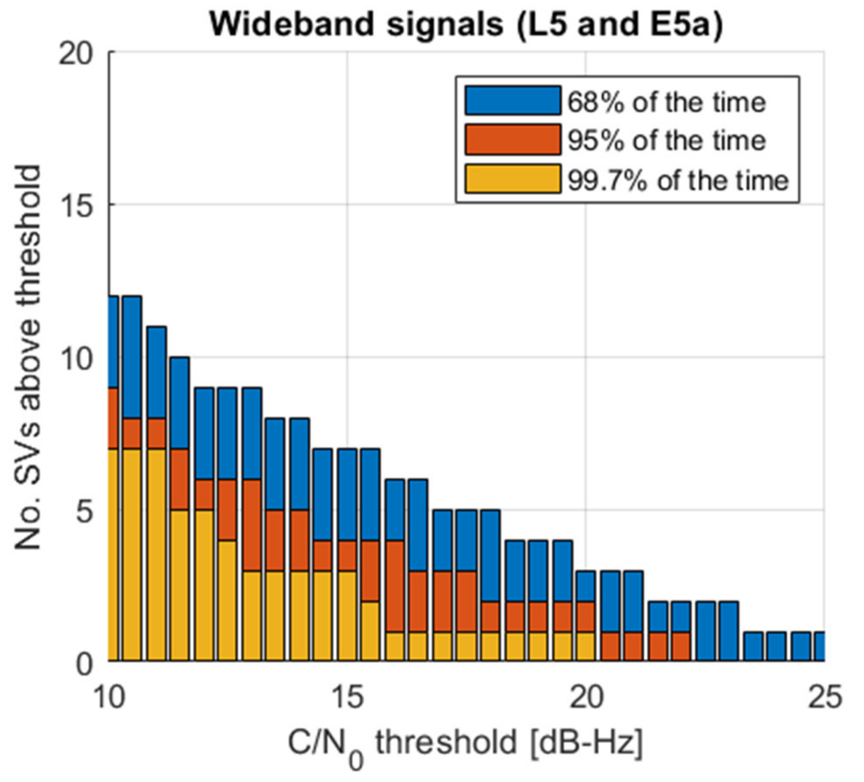
Receiver design – C/N_0 analysis

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

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

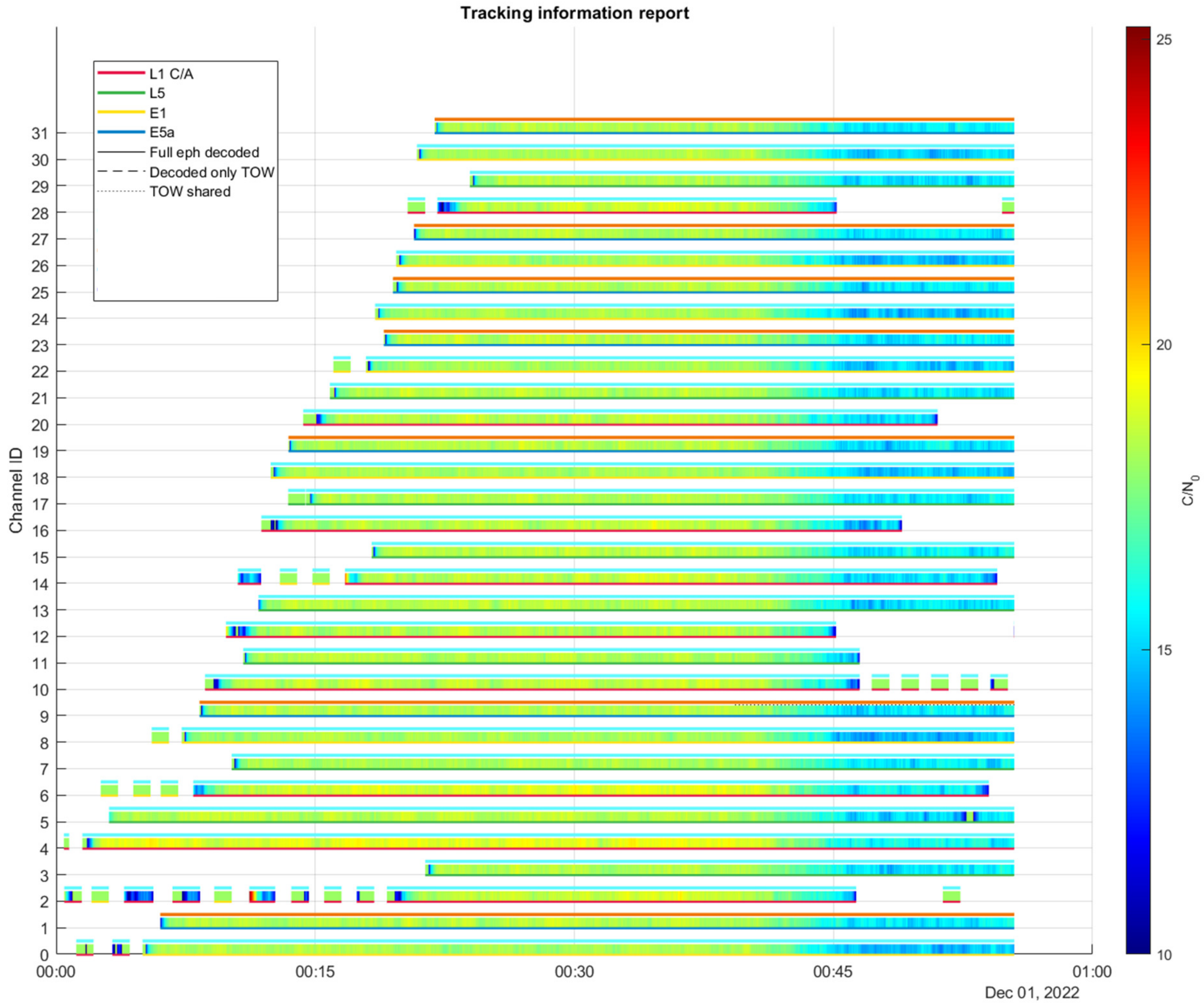
- Setting the acquisition to C/N_0 18 dB Hz ensures that at least 5 satellites are visible and within acquisition threshold for 99.7% of the time
- Less availability for the wideband components (E5a and L5), mostly because several GPS do not transmit L5
- Even in these conditions, 5 satellites are in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





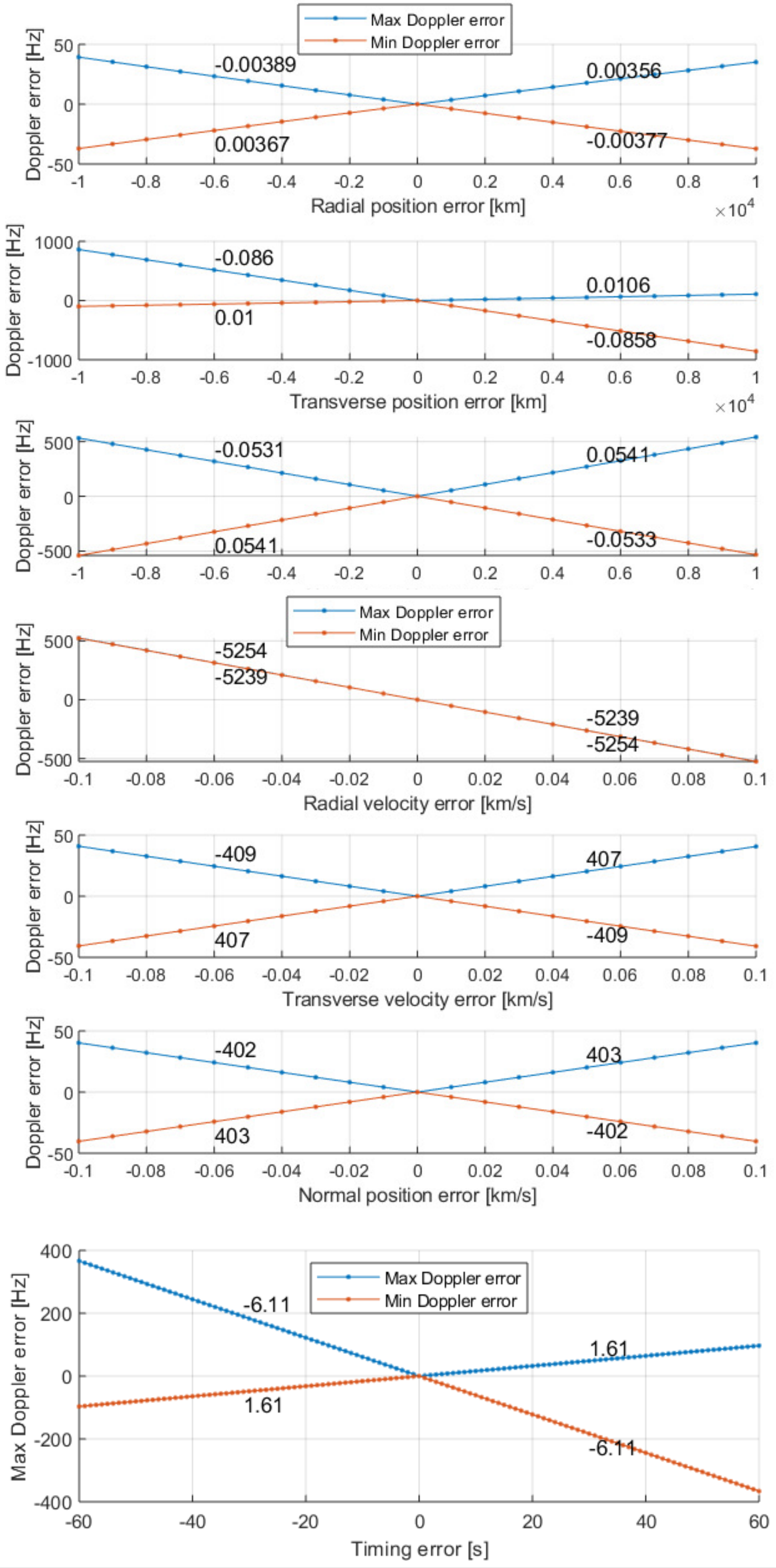
Receiver design – DSP for high-sensitivity

- **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 – Aided start

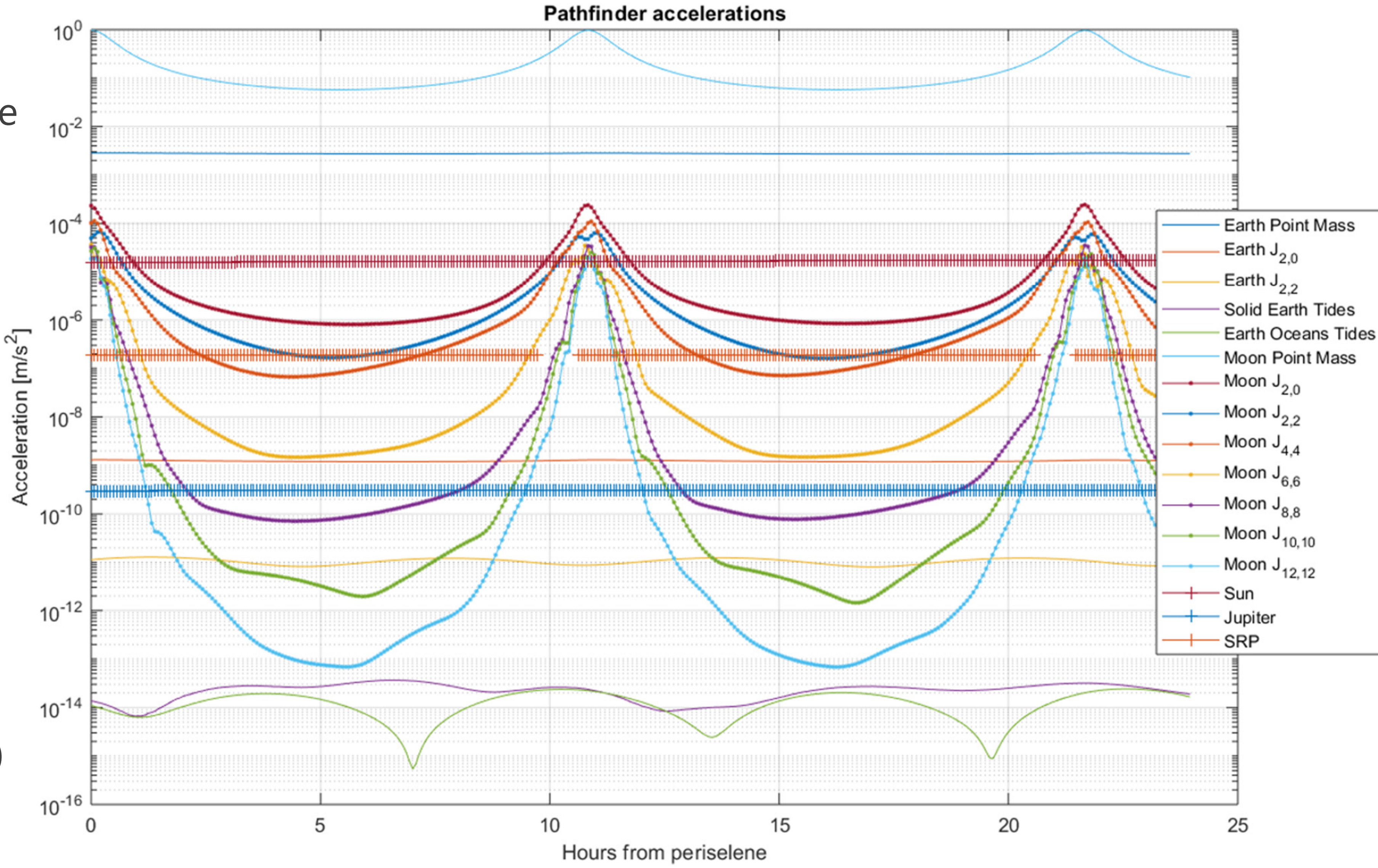
- **Aided start: required information**
  - Predicted long term ephemerides and clocks
  - Coarse PVT solution
  - LO frequency offset
- **Doppler sensitivity to error on Coarse PVT solution**
  - Evaluated over LPF trajectory wrt both GNSS constellations
  - Highest sensitivity to radial velocity
  - Relatively low sensitivity to positioning errors
  - Timing errors translate to trajectory lag
- **Aided start error budget**
  - Available budget: ± 300 Hz (aided start search space)
  - Half of the budget allocated to errors on coarse PVT solution
  - The other half is allocated to LO frequency offset uncertainty (~0.1 ppm translates to ~158 Hz on L1)



	Component budget	Doppler budget
Radial position	100 km	0.39 Hz
Transverse position	100 km	8.6 Hz
Normal position	100 km	5.4 Hz
Radial velocity	0.01 km/s	52.5 Hz
Transverse velocity	0.02 km/s	8.18 Hz
Normal velocity	0.02 km/s	8.06 Hz
Timing	10 s	61.1 Hz
	Total	144.3 Hz

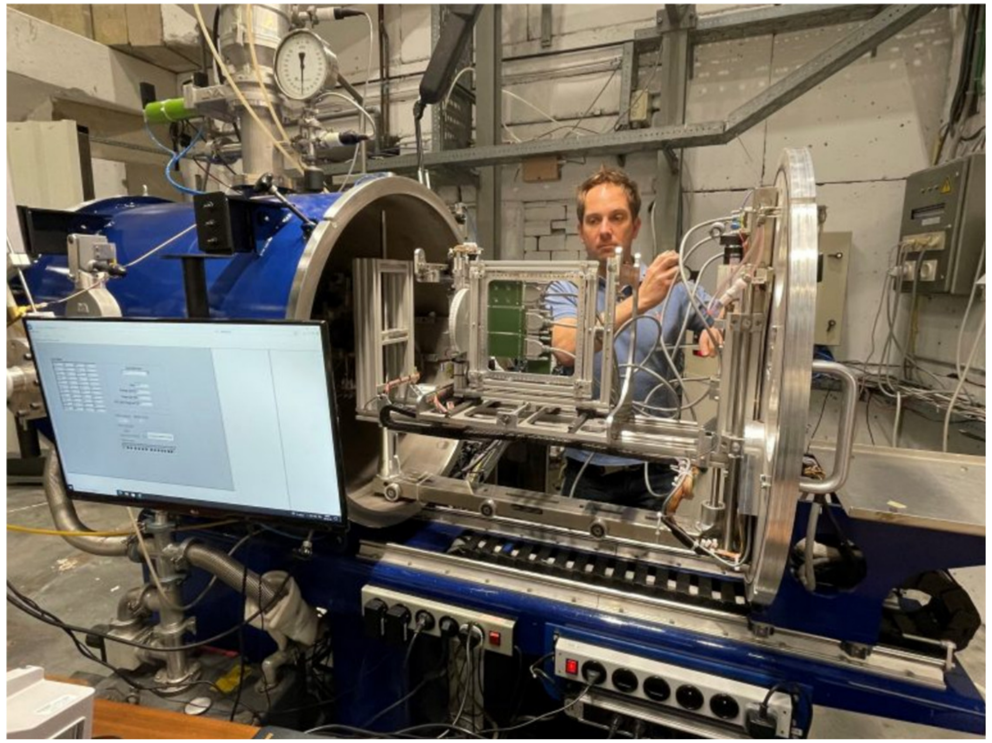
Receiver design – Navigation engine

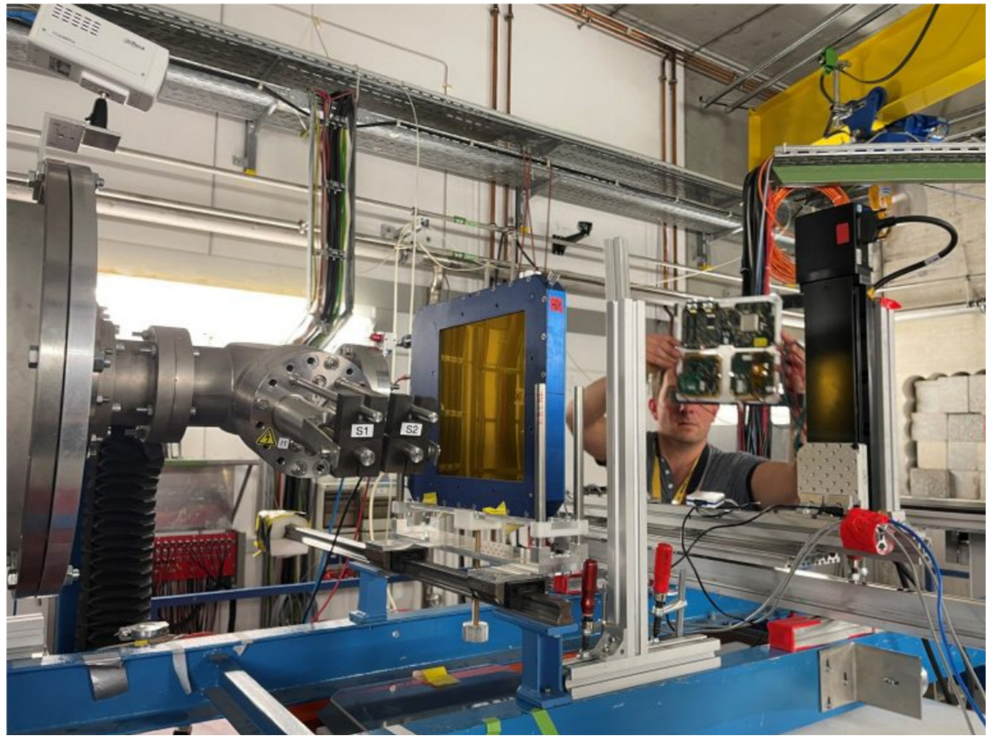
- Tightly coupled Extended Kalman Filter
  - Initialised with Least Squares Solution (if enough observables are available) or coarse PVT solution
- Dynamics model sized to warrant propagation error < 1 km after 24 hours
  - 12 x 12 Moon gravity field
  - Earth and Sun point masses
  - Solar Radiation Pressure
- Reference frames models:
  - ECEF ↔ ICRF: IAU 2006 precession, IAU 2000A nutation
  - Moon Fixed ↔ ICRF: simplified closed form model (accuracy ~ 150 m at Moon surface)
  - JPL ephemeris for Moon position
  - Simplified model for Sun position



Radiation test campaigns

- 3 radiation test campaigns
  - March 2022: test campaign in **UCL Heavy Ion Facility**. 7 different components were characterized under heavy ions, for LET ranging from 3.3 to 62.5 MeV cm^2/mg
  - April 2022: test campaign in **GSI Helmholtzzentrum für Schwerionenforschung GmbH Synchrotron Facility**, which provides heavy ion beams with energy up to 350 MeV/u. 6 different components were tested for LET ranging from 20 to 60 MeV cm^2/mg.
  - September 2022: additional tests in UCL Heavy Ion Facility to improve the characterisation of two key components.
- Based on the radiation test campaigns results:
  - the components selection was validated;
  - the radiation effects mitigation strategy was tuned accordingly.





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Environmental test campaign

❖ Mechanical tests

- **Sine excitation:** one sweep per axis, at 2 octaves/minute

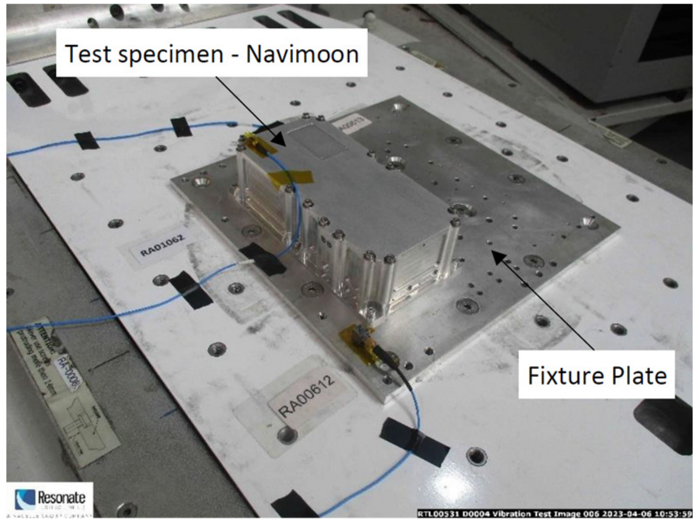
Frequency (Hz)	Amplitude
5 – 20	10 mm
20 – 100	20 g

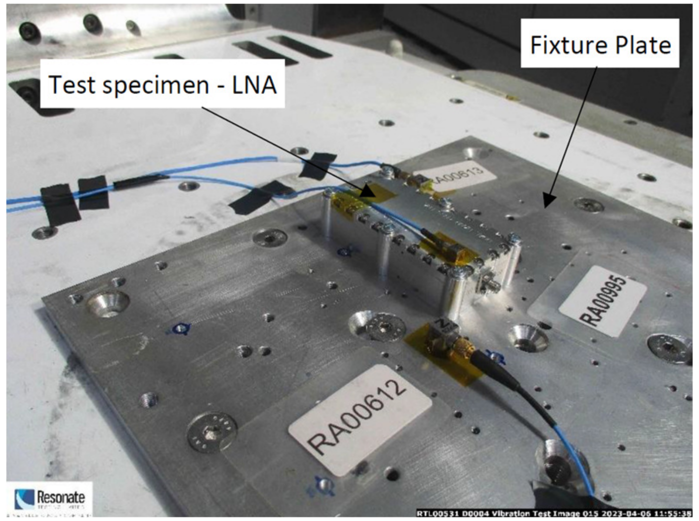
- **Random vibration:** three axes, 120 seconds per axis

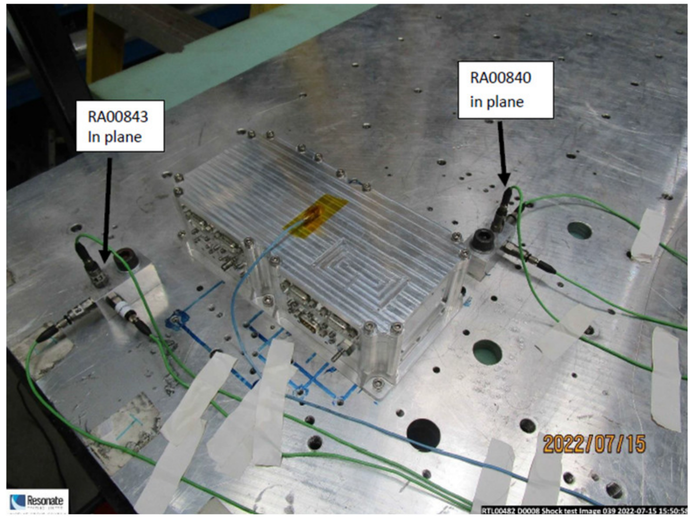
Frequency (Hz)	PSD (g2/Hz)
20	0.052
20 - 50	+ 6 dB/oct.
50 - 800	0.32
800 - 2000	- 6 dB/oct.
2000	0.052
GRMS	**20.0**

- **Shock:** three axes, tested on EM (not PFM)

Frequency (Hz)	SRS level (g)
10	20
1200	1000
10000	1000



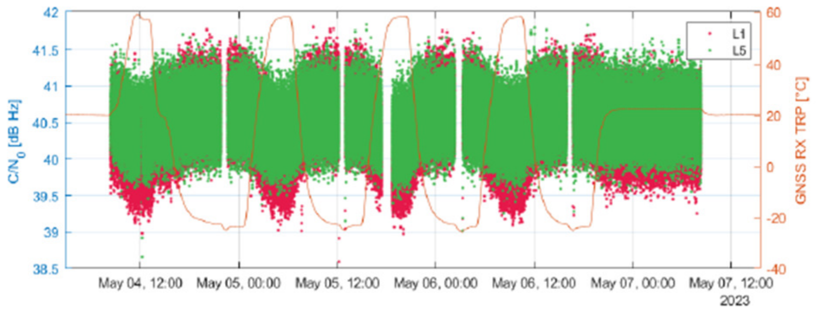


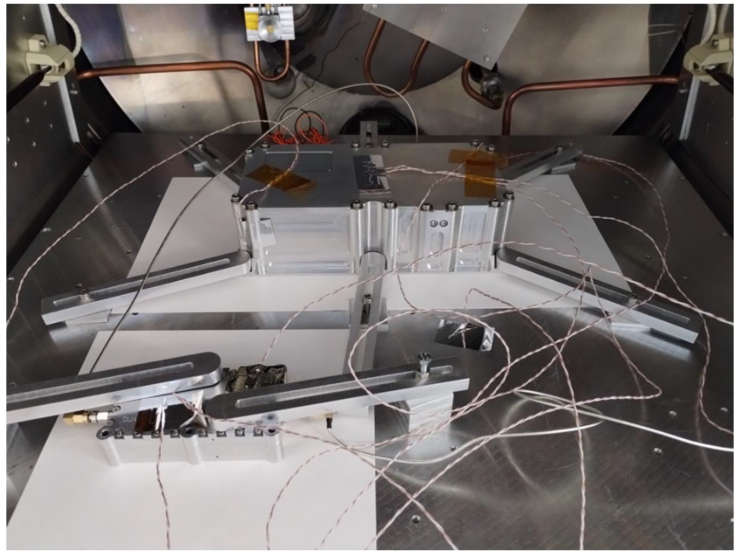


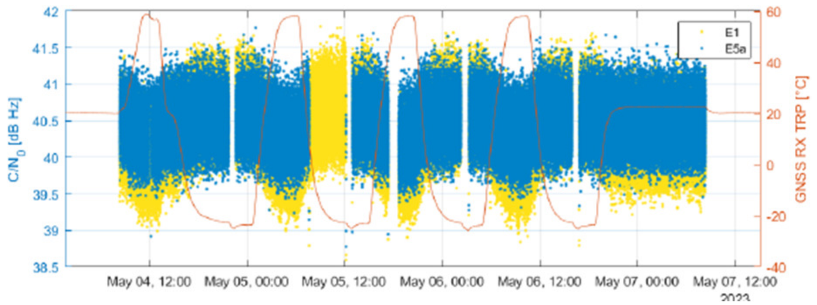
Environmental test campaign

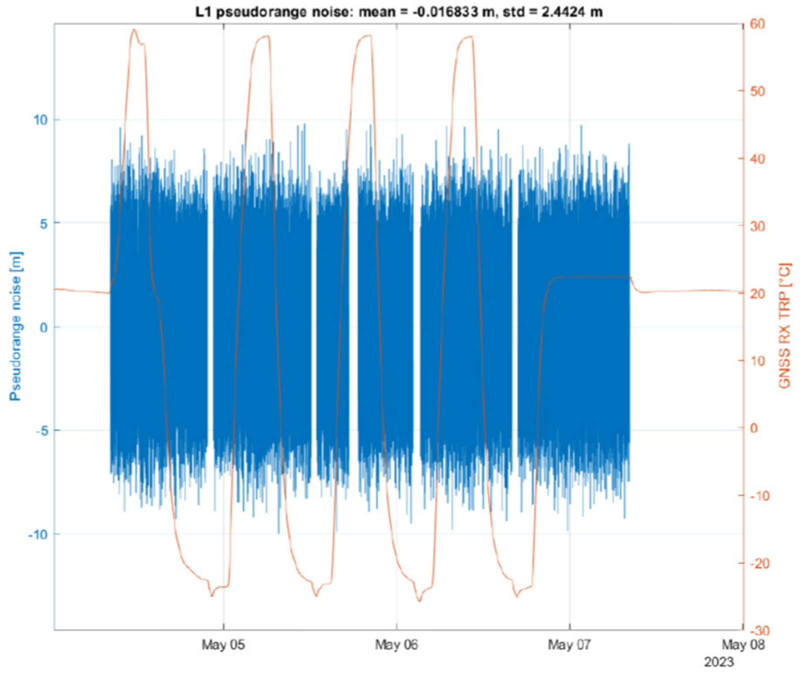
❖ **Thermal vacuum test**

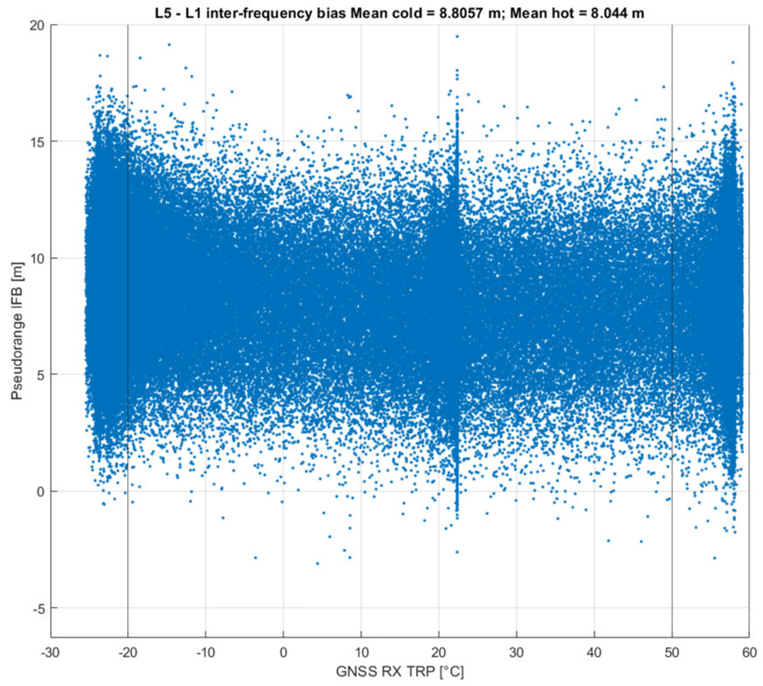
- Tested in vacuum (10^{-5} mbar)
- 1 cycle ranging from -40 °C to + 70 °C (non-operating temperature limits)
- 4 cycles ranging from -20 °C to + 55°C (operating temperature limits)
- Outgassing well below limit
- Measurements noise and interfrequency bias characterised continuously while cycling





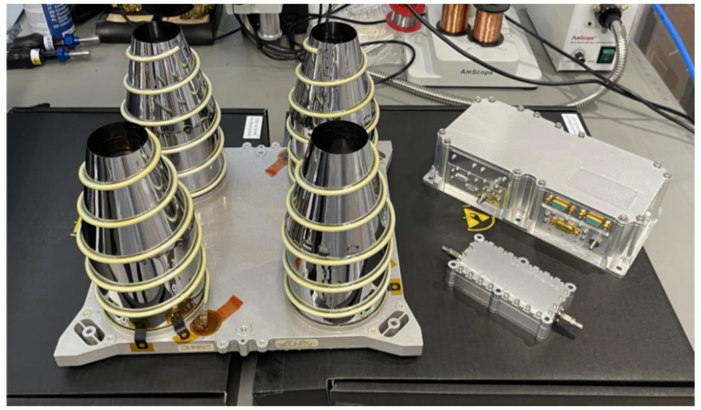


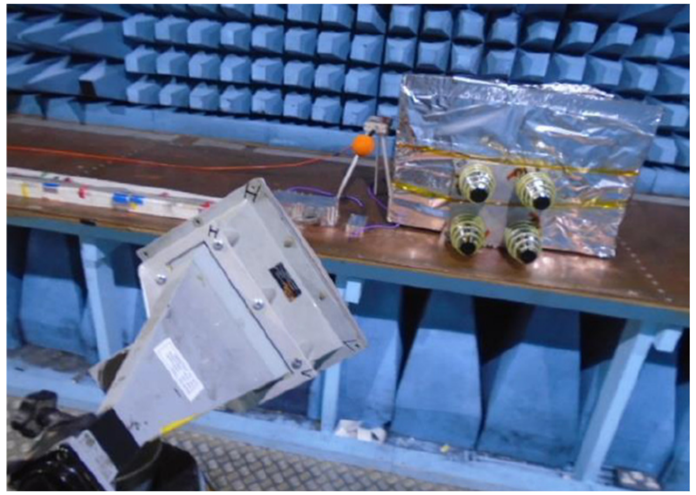




Environmental test campaign

- ❖ **Electro-Magnetic Compatibility test**
- ❖ According to MIL-STD-461F:
    - o CE102. Conducted Emissions, (10kHz – 10MHz)
    - o CE106. Conducted Emissions, (1 MHz – 18 GHz)
    - o RE102. Radiated Emissions, Electric Field
    - o RS103. Radiated Susceptibility, Electric Field (with antenna)



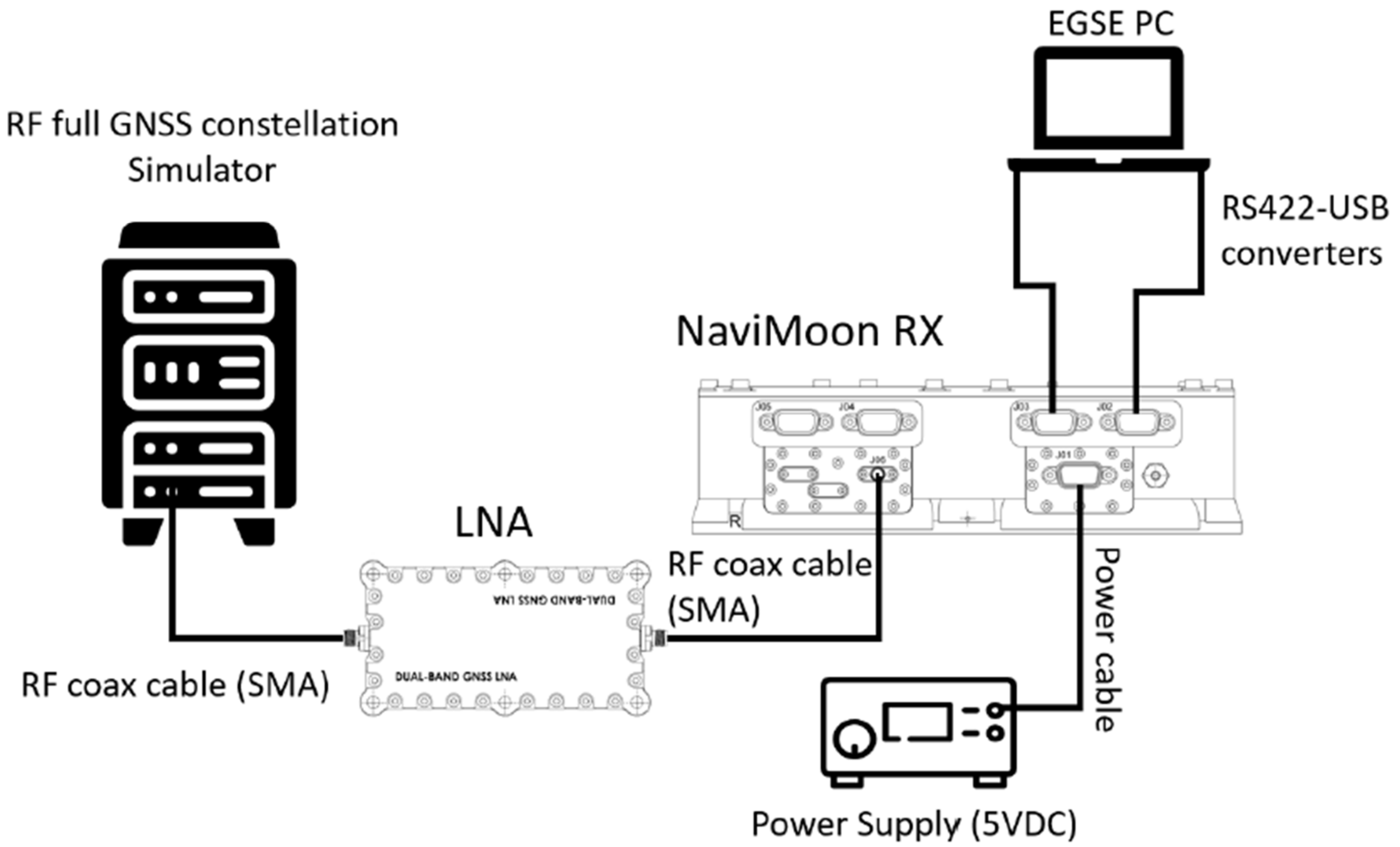


Environmental test campaign – summary

Test description	Result
Sine excitation	PASS
Random vibration	PASS
Shock (on EM)	PASS
TVAC	PASS
Thermal at ambient pressure	PASS
CE102 Conducted Emissions	PASS
CE106. Conducted Emissions	PASS
RE102. Radiated Emissions	PASS
RS103. Radiated Susceptibility	PASS

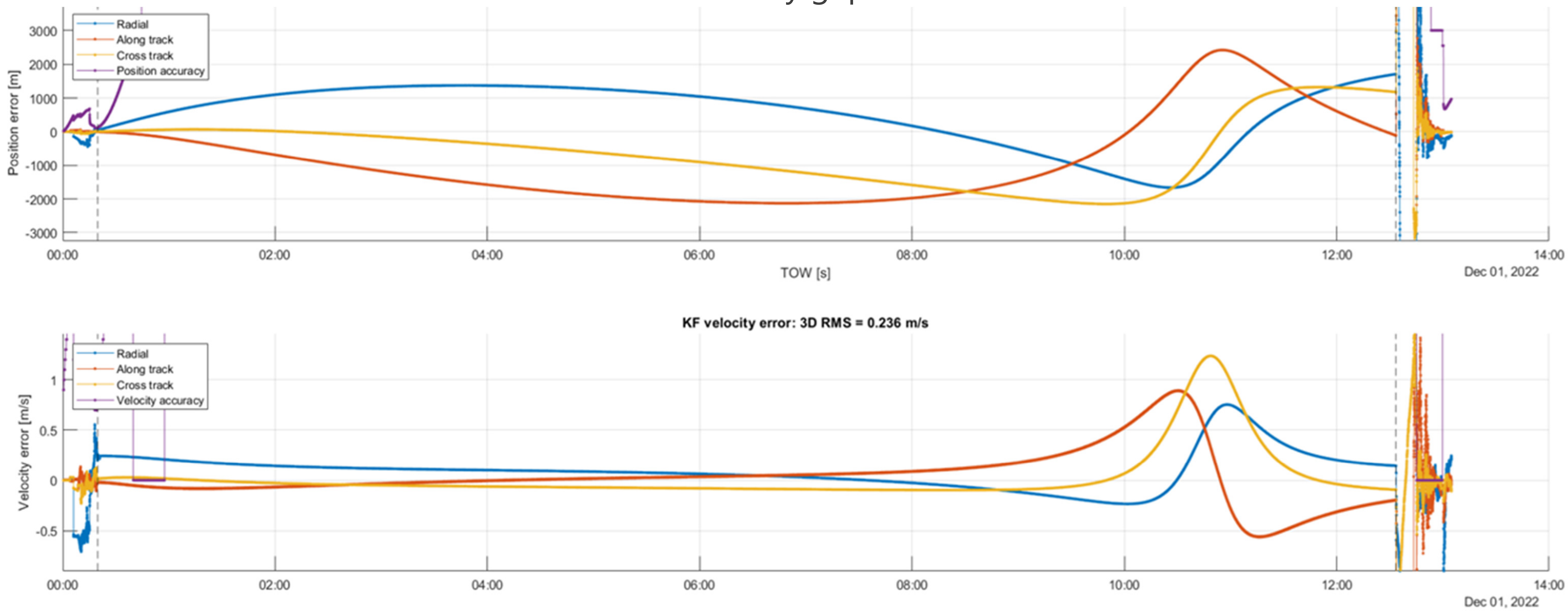
Functional and performance test campaign

- 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



Functional and performance test campaign - results

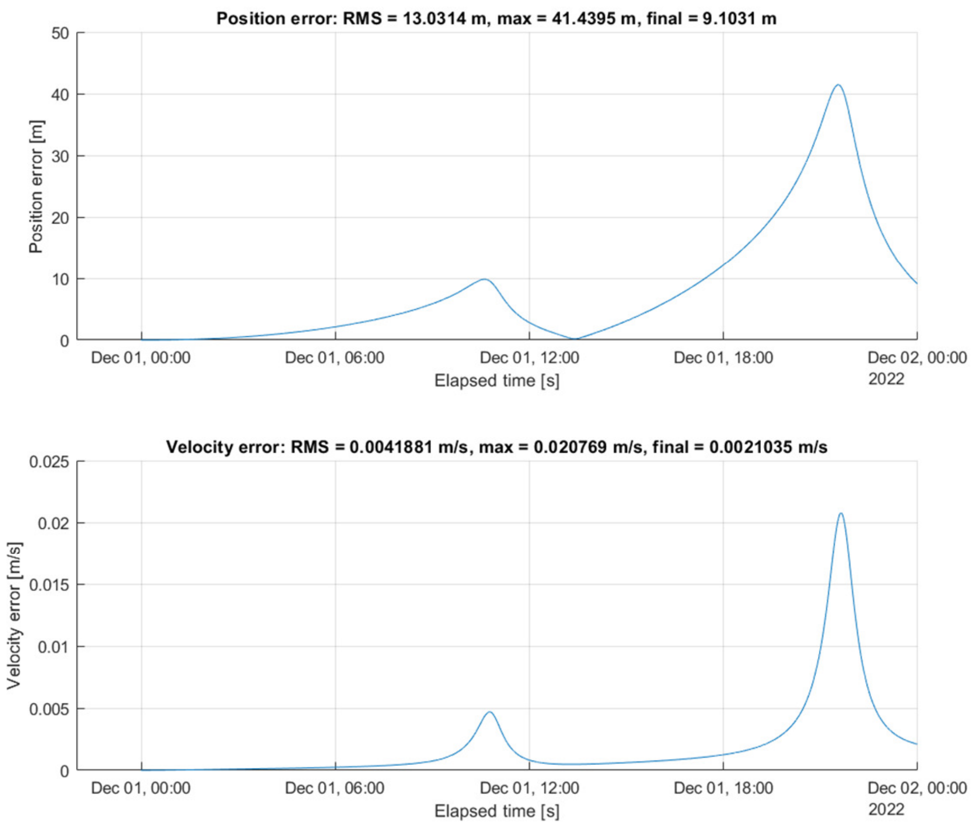
Visibility gap



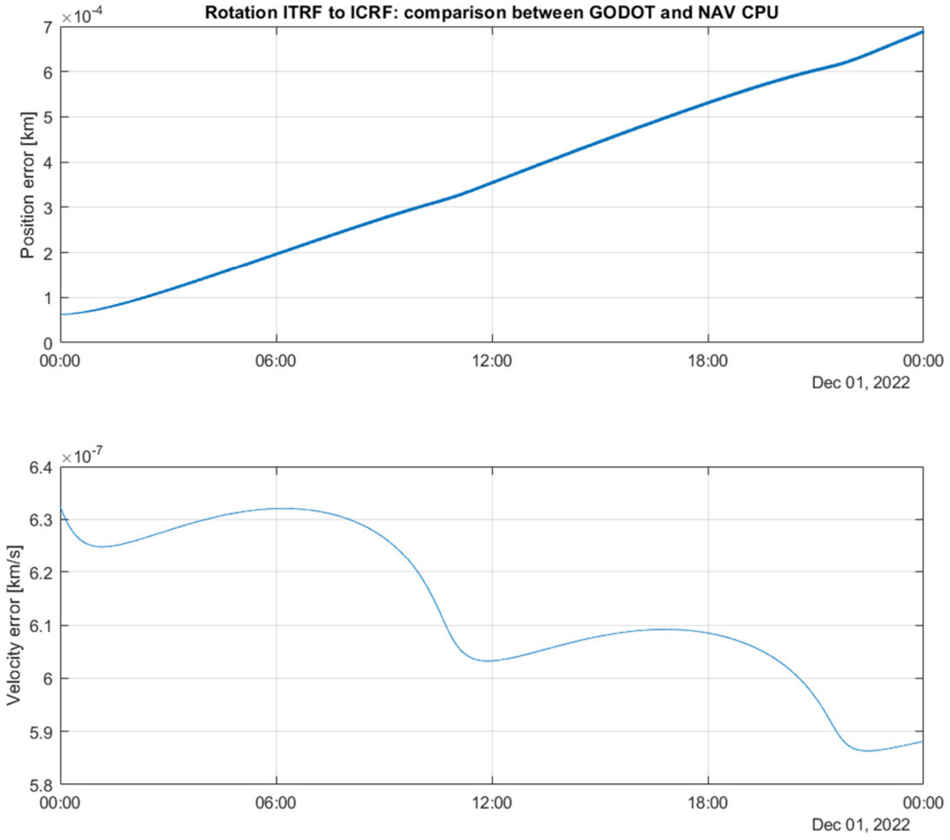
Propagation error exceeded target threshold (1 km) because of the error affecting the starting state. Reconvergence was achieved nevertheless after a 12 hours visibility gap (no GNSS measurement available).

Functional and performance test campaign - results

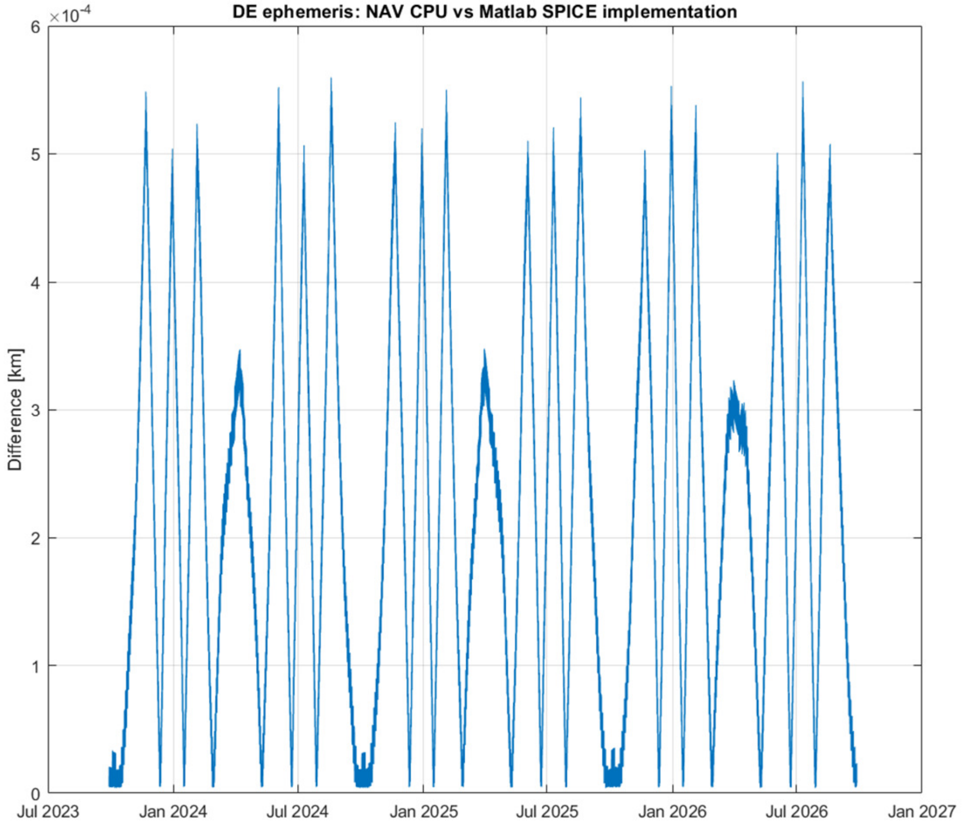
Pure propagation

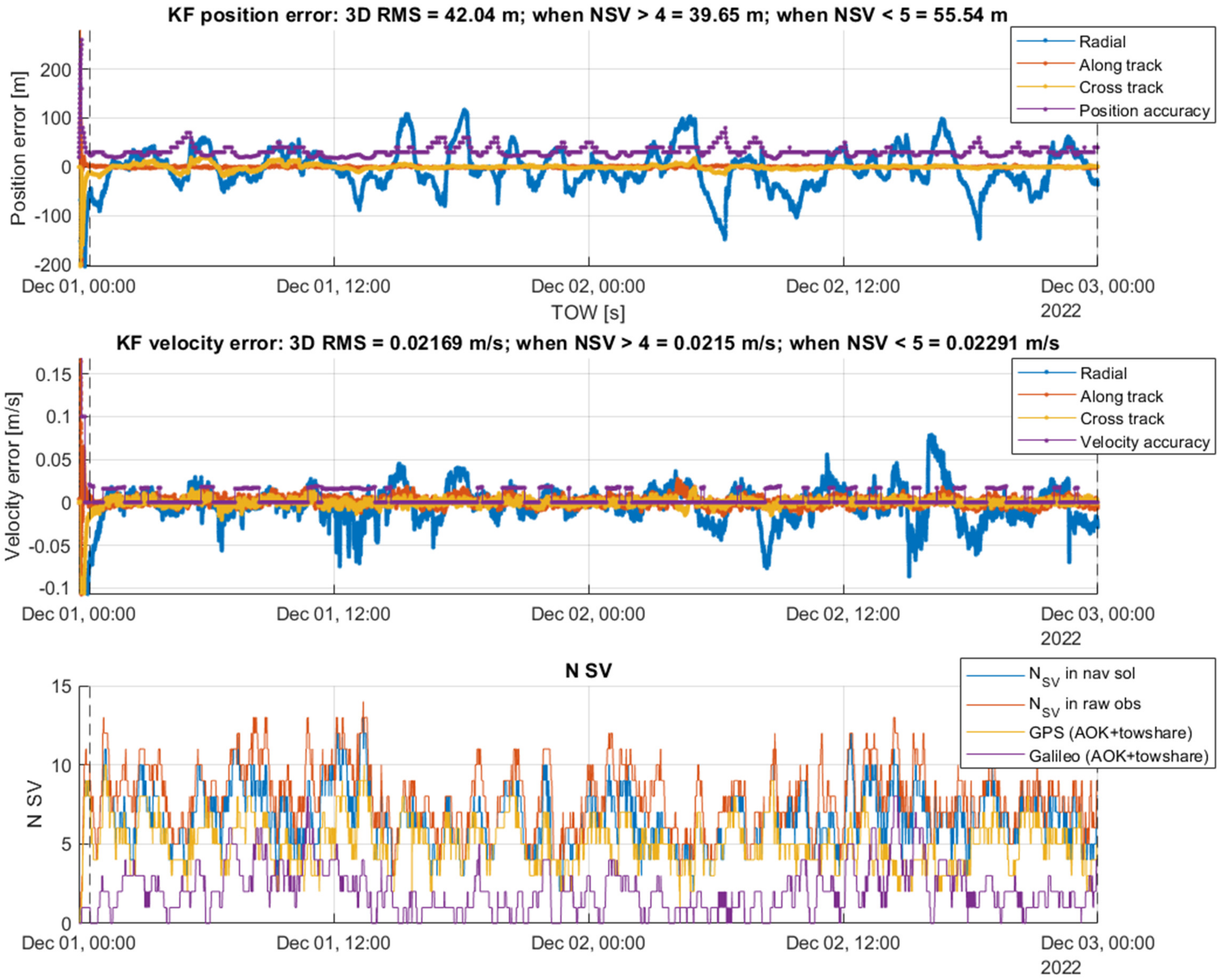


ITRF-to-ICRF rotation matrix



Moon ephemeris





KF position error: 3D RMS = 42.04 m; when NSV > 4 = 39.65 m; when NSV < 5 = 55.54 m
Radial
Along track
Cross track
Position accuracy
Position error [m]
TOW [s]
KF velocity error: 3D RMS = 0.02169 m/s; when NSV > 4 = 0.0215 m/s; when NSV < 5 = 0.02291 m/s
Velocity accuracy
Velocity error [m/s]
N SV
N_{SV} in nav sol
N_{SV} in raw obs
GPS (AOK+towshare)
Galileo (AOK+towshare)
Dec 01, 00:00
Dec 01, 12:00
Dec 02, 00:00
Dec 02, 12:00
Dec 03, 00:00
2022

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Functional and performance test campaign - results

Boot software test campaign

Test case	Description	Result
Nominal System turn-on and checkout	Verify nominal turn-on sequence and housekeeping telemetry.	PASS
BSW PUS Interface Edge Cases	This serves to verify the implementation of PUS module for the BSW by sending a collection of faulty TCs that either have problems in their headers, are malformed in some way, or whose command parameters are invalid.	PASS
BSW failure modes	This test verifies the BSWs behaviour in case of a set of anticipatable failure modes that can be triggered by manipulated the BSWs memory in some fashion. (through TC or debugger).	PASS
Reboot test	Verify capability to reboot in all required conditions	PASS
Redundant TM/TC interface	Verify the redundant TM/TC interface	PASS
Memory dump and check	Verify the memory patch, dump and check (compute crc) functionalities. For this test we will target valid addresses for the following memory ids. The basic concept is to use a Patch command to write a pattern of random bytes to a typically unused memory segment of each memory, then read back those bytes with TC dump, to verify proper write, then request the crc be computed with TC check and compare the result with the CRC of the original payload.	PASS
Reprogramming ASW and FPGA	Verify the reprogramming functionality (ASW and FPGA image)	PASS
UART noise filtering and masking during processing and reception	This is a manual test without scripted output results. The script described below was run, and data was manually sent via Putty onto the second interface. All scripted TCs were successfully processed	PASS

Application software test campaign

Test case	Description	Result
CSL	Verify that triggering CSLs and (overcurrent) will cause the receiver to reboot.	PASS
SW/HW watchdog test	Verify the software watchdog trigger if an of the monitored thread blocks, Also verify the HW watchdog resets the receiver if the Monitoring thread locks	PASS
Reboot test and version check	Verify it is possible to reboot the receiver via TC and verify the versions under test	PASS
Redundant TMTC test	Verify the ASW can be operated over both TMTC interfaces	PASS
Parameter Test	Verify that onboard parameters can be set and retrieved via TM/TC interface and that modified parameters are non-volatile	PASS
Reporting test	Verify that Housekeeping and reporting frequency can be changed modified over TMTC interface	PASS
Packet integrity test	Verify that the receiver responds correctly when corrupted telecommands are sent	PASS

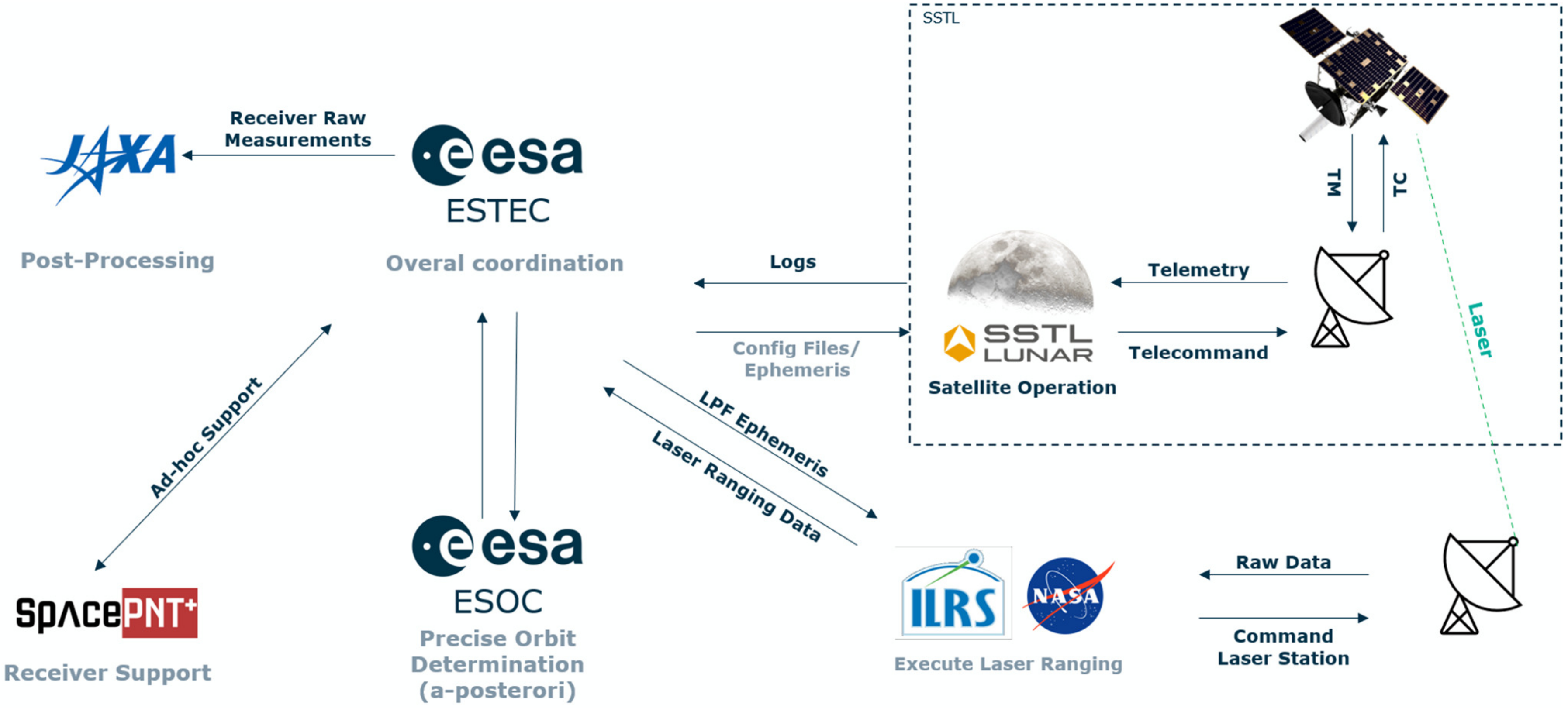
GNSS test campaign

Test	Description	Result
Static user test	Verify basic GNSS functionalities with simulated signal for a static ground user	PASS
Live sky test	Verify basic GNSS functionalities with live sky signals	PASS
Hard switch-off	Switch off and on during any phase and verify it's possible to recover full functionality after it.	PASS
Navigation engine configuration	Verify the functionality of the navigation engine in different configurations	PASS
DSP parameters test	Verify the effects of changing the DSP parameters	PASS
Propagation parameters test	Verify the effect of changing the parameters of the propagation engine	PASS
Model Error Covariance parameters test	Verify the effect of changing the parameters of the model error covariance	PASS
FDIR parameters test	Verify the effect of changing the parameters of the FDIR algorithm	PASS
Acquisition sequence	Verify that the acquisition of satellites that have the chance to be seen through the main lobe are prioritised	PASS
Ephemeris and Almanac	Verify the capability to receive, store and report ephemeris and almanacs	PASS
Warm start	Verify the warm start performance on the LPF orbit	PASS
Drift uncertainty	Verify the warm start performance on the LPF orbit when the PVT solution is affected by the worst-case clock drift uncertainty.	PASS
PPS steering	Verify the sampling time (synchronous with the PPS signal) is steered to the integer second of the required system time within the required accuracy.	PASS
Acquisition and tracking sensitivity (18 dBHz)	Verify the acquisition and tracking sensitivity	PASS
Visibility gap	Verify the propagation performance	(partial) PASS*
Recurring PVT provision	Verify the behaviour upon provision of periodic PVT solutions: • Verify that periodic PVT solution TCs are ignored in nominal operations • Verify that periodic PVT solution TCs are used to trigger warm start upon unexpected reboot • Verify that periodic PVT solution TCs are used to reset the receiver when it diverges	PASS
Long test	Verify the functionality and performance over a full experimental window	PASS
Dynamics model	Verify the propagation performance of the dynamics model	PASS
Moon ephemeris	Verify the accuracy of the Moon ephemeris algorithm	PASS
ITRF to GCRF rotation	Verify the accuracy of the ITRF-to-GCRF rotation	PASS

* Propagation error exceeded target threshold because of the initial PVT error. Reconvergence was achieved nevertheless after 12 hours without GNSS measurements

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...)

Conclusions

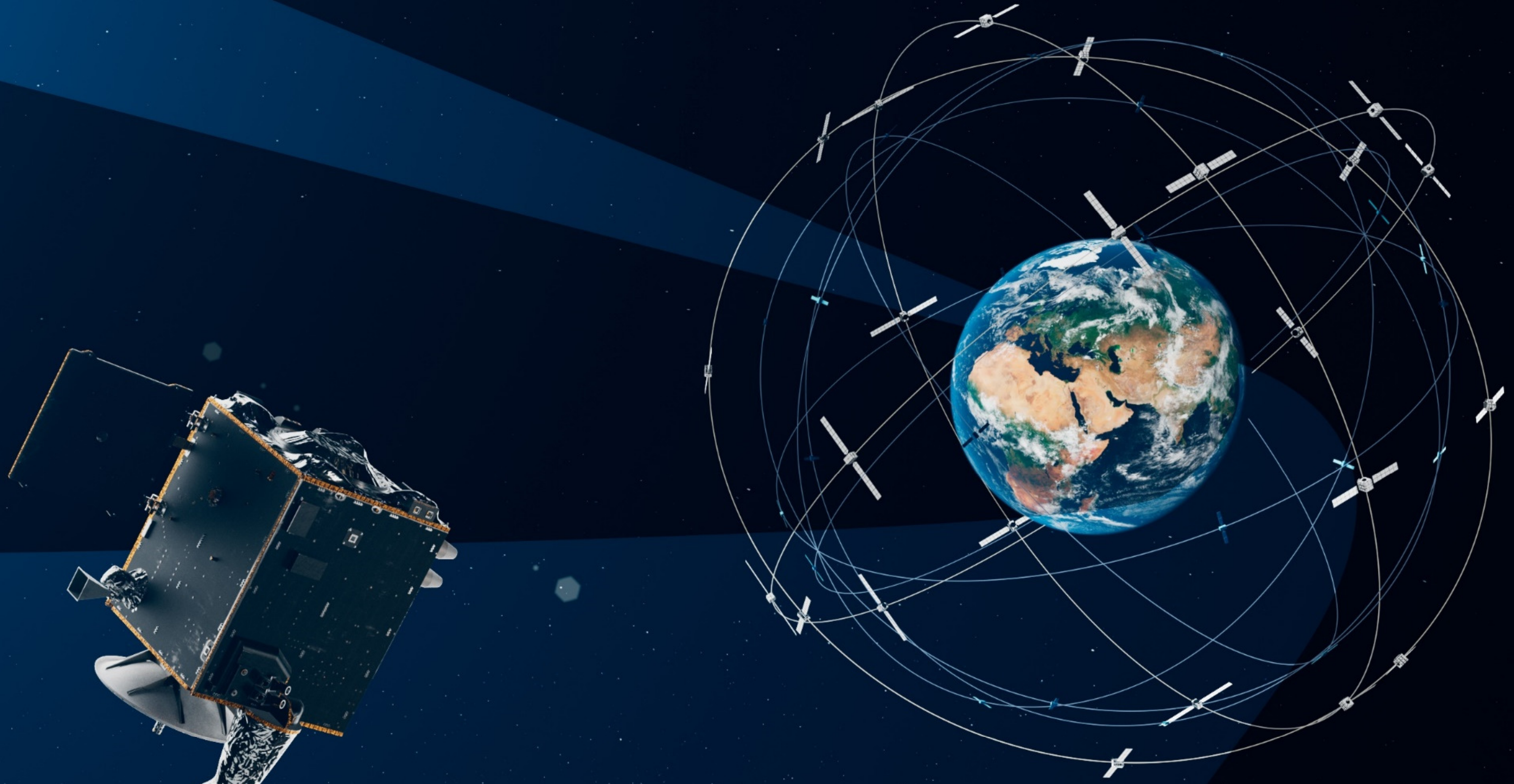


Image: ©ESA

- 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 (42 m, 0.02 m/s)
- In-orbit experiment will demonstrate the technology is mature for operational use
- RHA options available