SpacePNT+

Extending the use of GNSS technology to cislunar space

Agenda

- Introduction
  - SpacePNT 's historical background and products fit to space applications
    by Dr Cyril Botteron, SpacePNT's co-founder and director

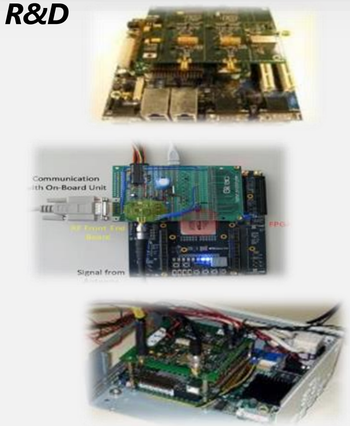
- NaviMoon
  - Extending the use of GNSS technology to cislunar space
    by Michele Scotti, SpacePNT's technical leader and navigation engineer

Historical ownership & Product development

2004	2013	2016	2018	2021	2023

Technology Readiness Level	TRL2/3	TRL3/4	TRL5/6	TRL7/8	TRL8/9
PNT & GNSS R&D	Idea validation	Proof-of-concept	Prototype	Qualification	Flight proven

R&D



EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

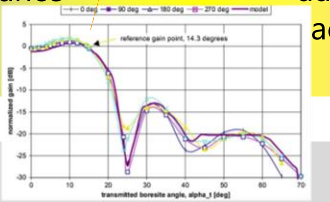
< 1 s TTFF using PCS and assistance

R&D

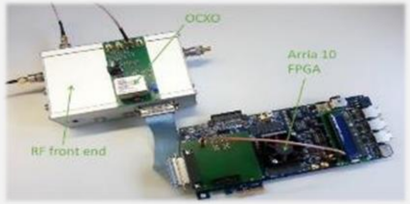
WeakHEO PoC receiver

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

15 dBHz L1 C/A autonomous acquisition



Validation in HIL



SANAG PoC receiver

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Dual-frequ. GPS+Galileo+OF Full HIL validation

EM Prototypes

NaviLEO™ EM

NaviMoon EM

esa

SYDERAL SWISS

NaviLEO/NaviMoon product line development

EM/EQM

TVAC, shocks, vibrations

Radiations (SEE)

csem

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Innosuisse – Swiss Innovation Agency

SERI's Swiss Space Office (SSO)

SpacePNT+

NaviLEO/NaviMoon qualification

PFM TRL8/TRL9

ESA NaviMoon PFM DRB

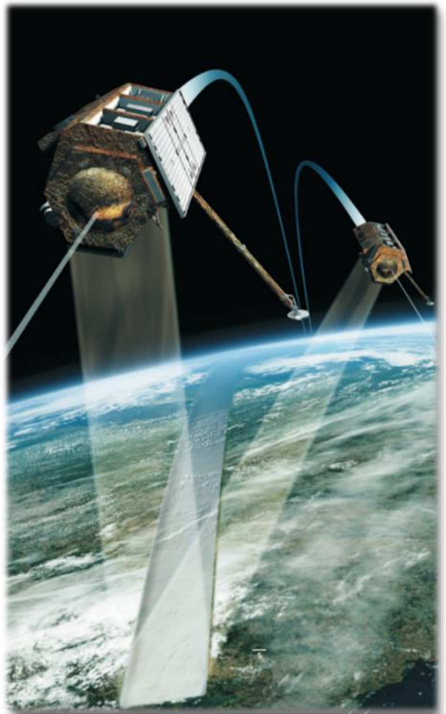
ION-mk02 SCV011

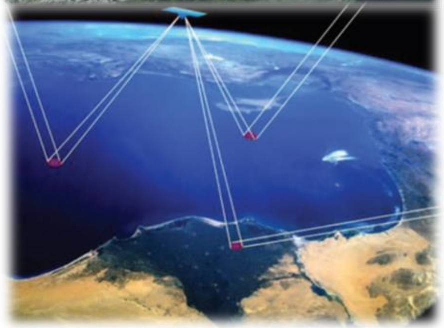
SpacePNT+

Navi-G2 dev & FM deliveries
- LEO IOD mission
- Moon ESA mission
- ISS DLR mission

SpacePNT Products fit to applications

Applications	Market Requirements	Product solutions
Earth observations ✓ Optical observations ✓ SAR / RADAR… ✓ several 30+ sat. constellations	• **Highest performance** • **REAL-TIME & on-board POD option** (sub-dm accuracy)	**NaviLEO™** • 100 cm pos. **NaviLEO-POD**[1] • 10 cm position • 1 cm/s velocity • ns-level timing 
On-orbit servicing / Debris removal / Launchers / Space transportation ✓ Launchers, kick-stages ✓ GTO / GEO telecom ✓ High altitude missions (HEO) ✓ Moon/cislunar missions	Idem above plus: • **Dual- antennas** (sat. attitude independence) • **Ext. LNA, highest sensitivity** (12-15 dBHz) • Upgradable on option for **12 years GEO mission lifetime**	**NaviGEO**[1] **NaviMoon** • 100 m at Moon altitude 
Sat. communications/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**[1] • Weight /size reduction • Optimized for large LEO constellations 
	• **Advanced simulation SW tools**	**SimORBIT** • Orbit propagation tool





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

Agenda

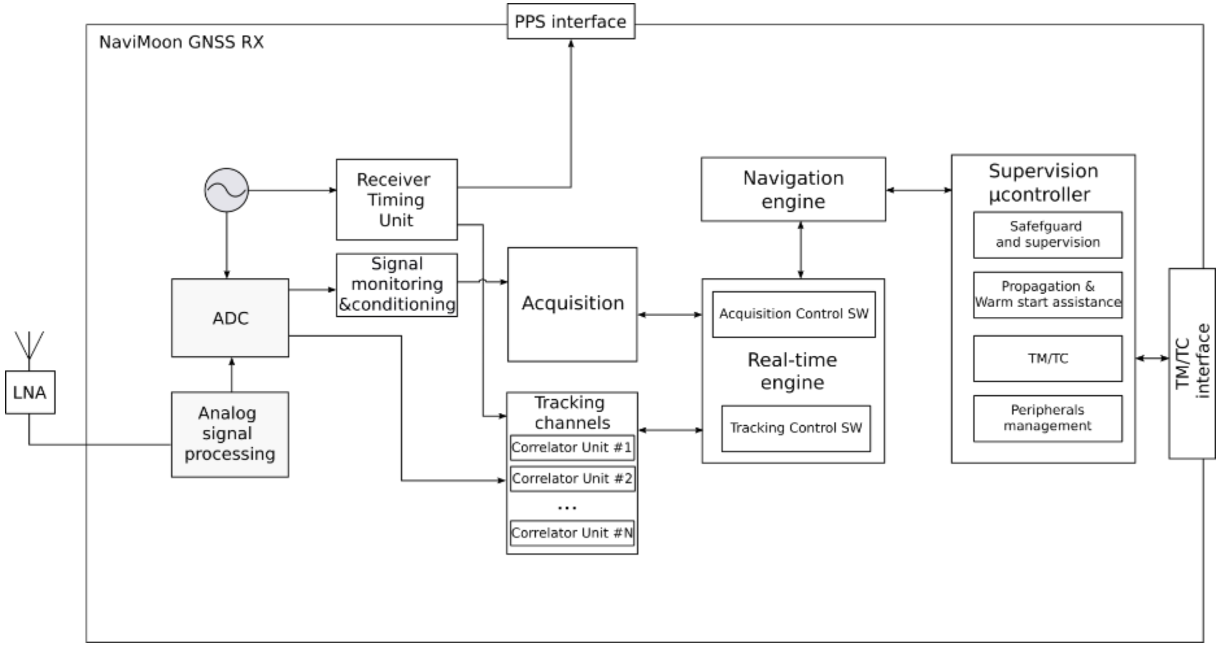
- Introduction
  - SpacePNT and its historical background
    by Dr Cyril Botteron, SpacePNT's co-founder and director

- NaviMoon
  - Extending the use of GNSS technology to cislunar space
    by Michele Scotti, SpacePNT's technical leader and navigation engineer

NaviMoon GNSS receiver – System overview

❖ NaviMoon: evolution of SpacePNT flagship spaceborne GNSS receiver NaviLEO™.

- Main inherited features:
  - Multi-GNSS (GPS + Galileo) & multi-frequency rx
  - Proprietary HW/SW/FW
  - COTS EEE + Radiation mitigations
  - Fast DSP in HW FPGA
  - Acquisition & tracking control & navigation in SW
  - Dedicated uC for interface management/supervision
  - Reprogrammable in flight and scalable
- NaviMoon hardware upgrades:
  - OCXO
  - Larger FPGA
- NaviMoon software upgrades:
  - Improved acquisition & tracking engine
  - Navigation engine (tightly coupled KF; orbital forces model tailored for lunar orbits)



NaviMoon GNSS receiver – Initial target requirements

- Acquisition sensitivity: 18 dB Hz
- Tracking sensitivity: 15 dB Hz
- Positioning accuracy: 1000 m (3D RMS)
- Velocity accuracy: 1 m/s (3D RMS)
- Propagation accuracy: 1000 m and 1 m/s (3D RMS) after 5 hours with no measurements

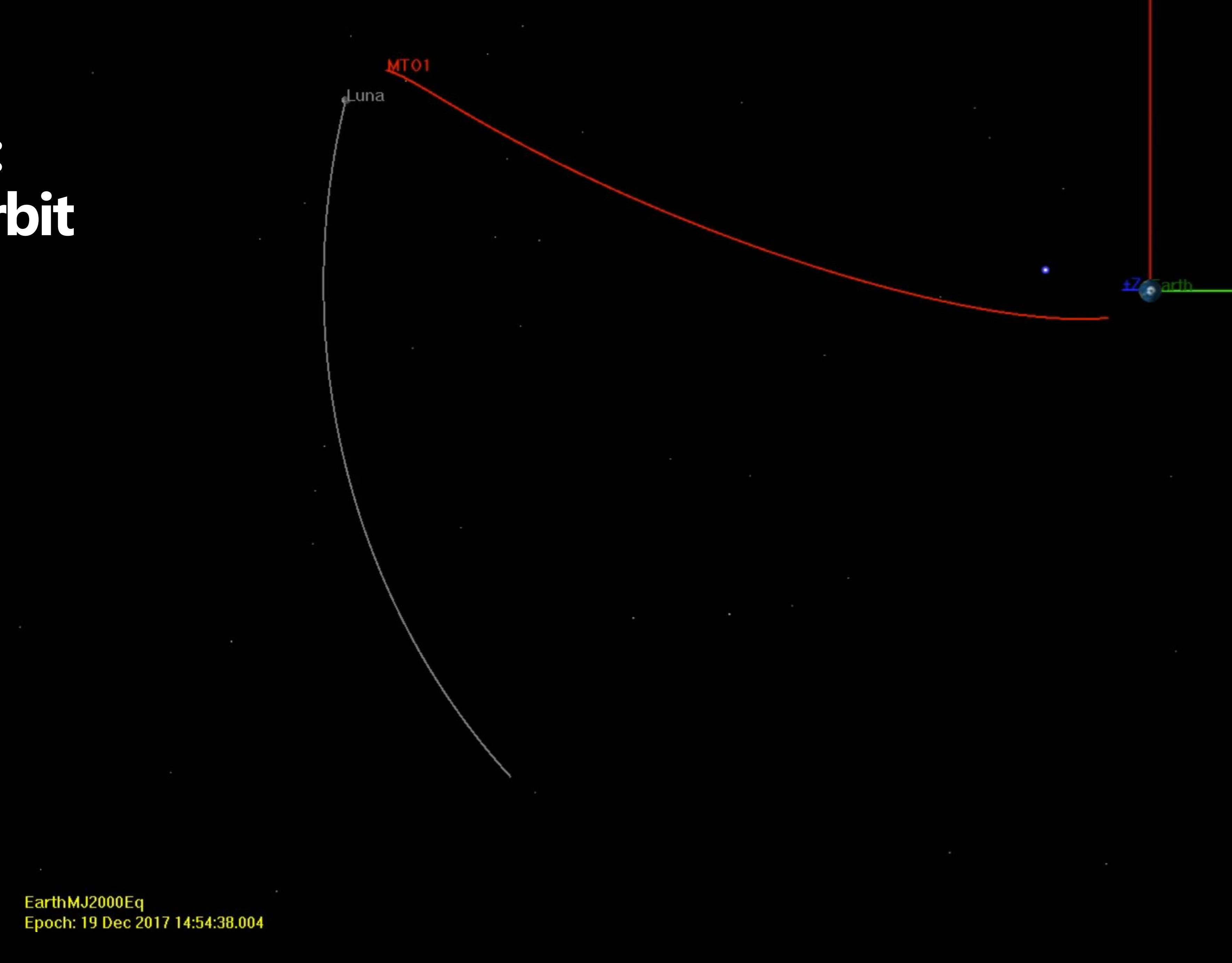
Navigation engine

- Extended Kalman Filter architecture
  - Processes pseudorange and pseudorange-rate measurements (tightly coupled)
  - Can be initialized either with a Least Squares solution or with a coarse PVT solution

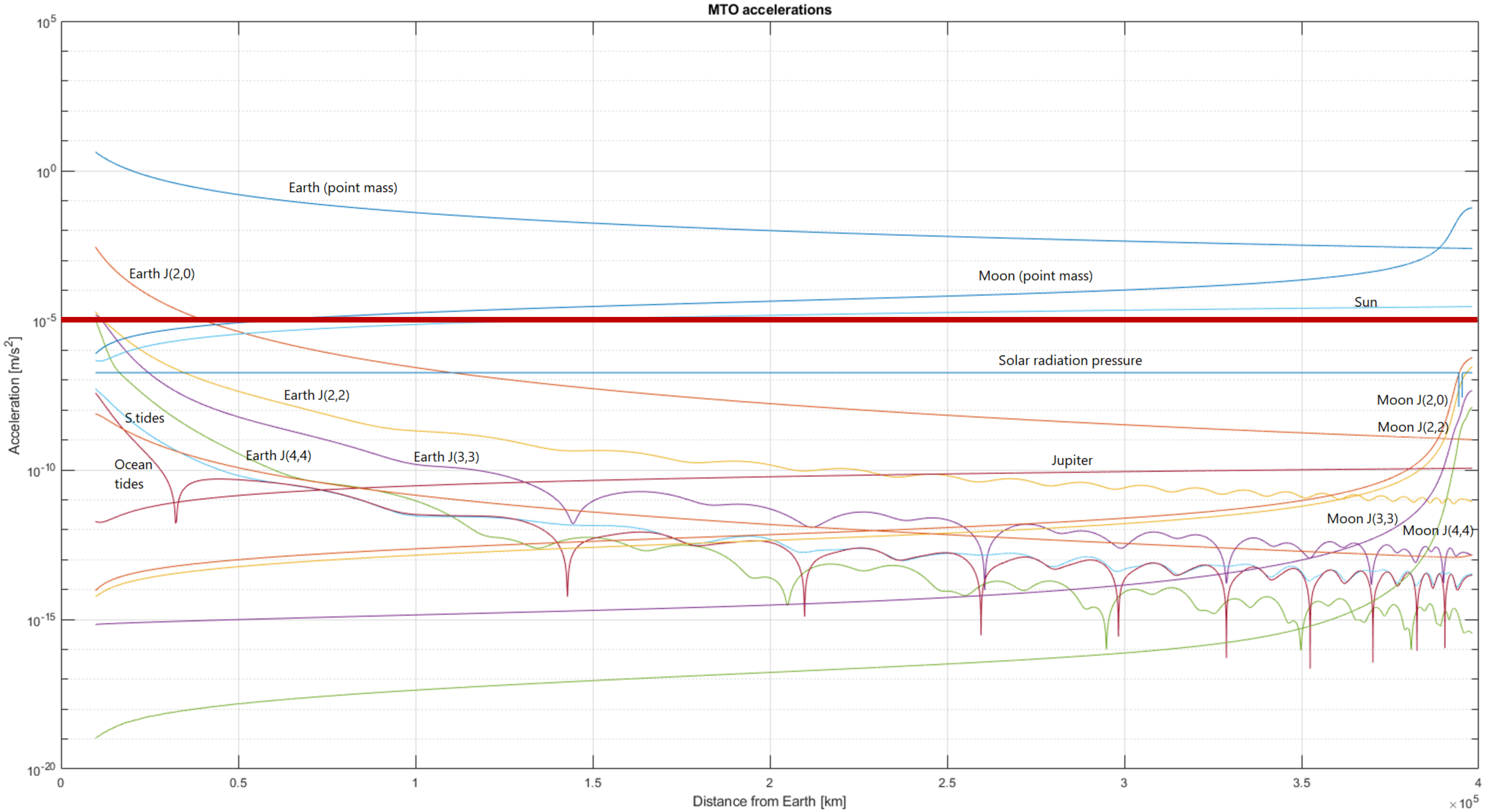
- Dynamics model
  - Earth and Sun as point masses + Expanded lunar gravity field (12x12) + SRP
  - Needs precise Moon ephemerides/orientation (JPL DE440)
  - …and precise ITRF/ICRF rotation matrix (SOFA routines)

- Process noise covariance: State Noise Compensation
  - Velocity error: uncorrelated random walk in RTN reference frame
  - (same for clock drift error)
  - Empirically tuned with end-to-end simulation environment

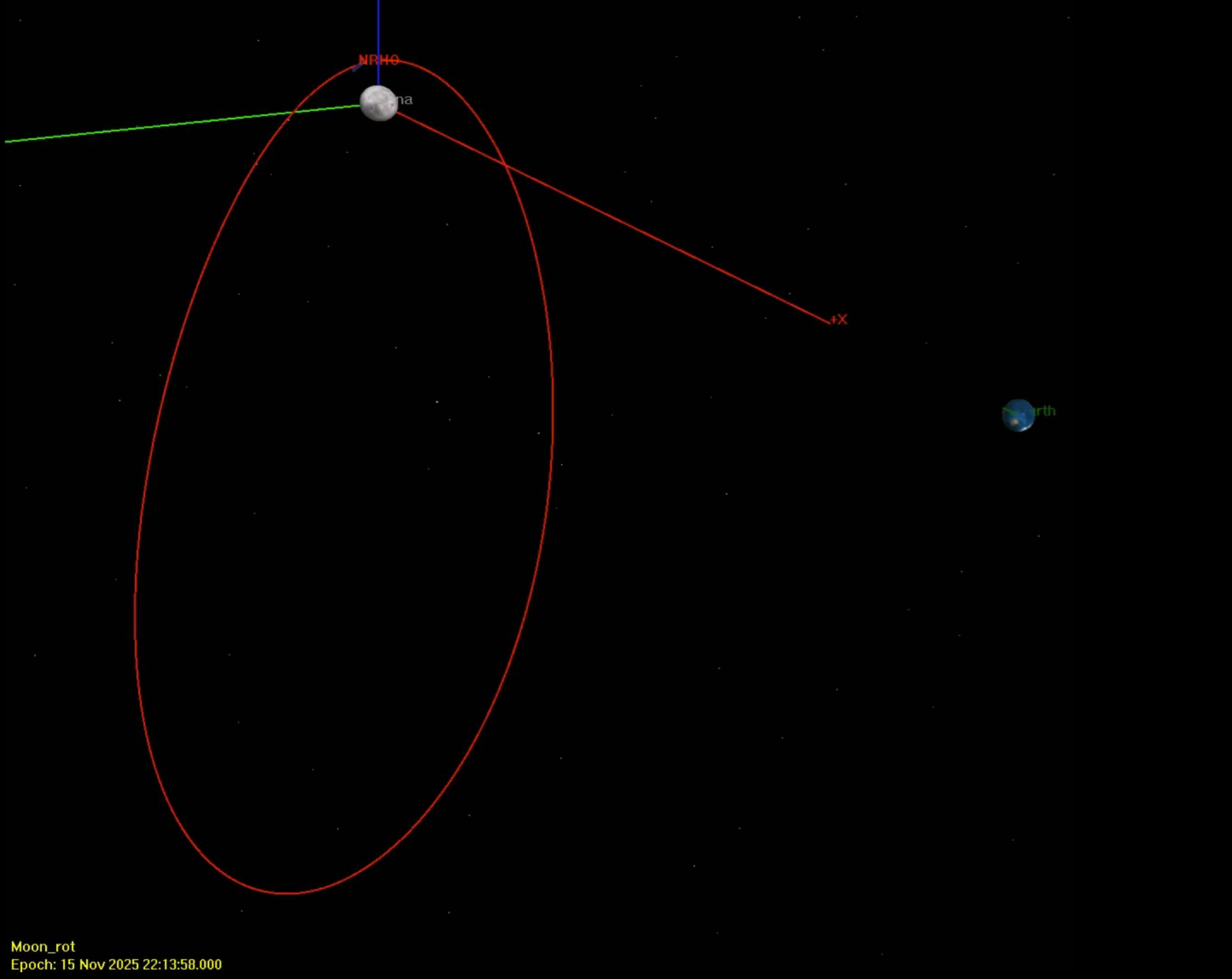
Reference orbit 1: Moon Transfer Orbit



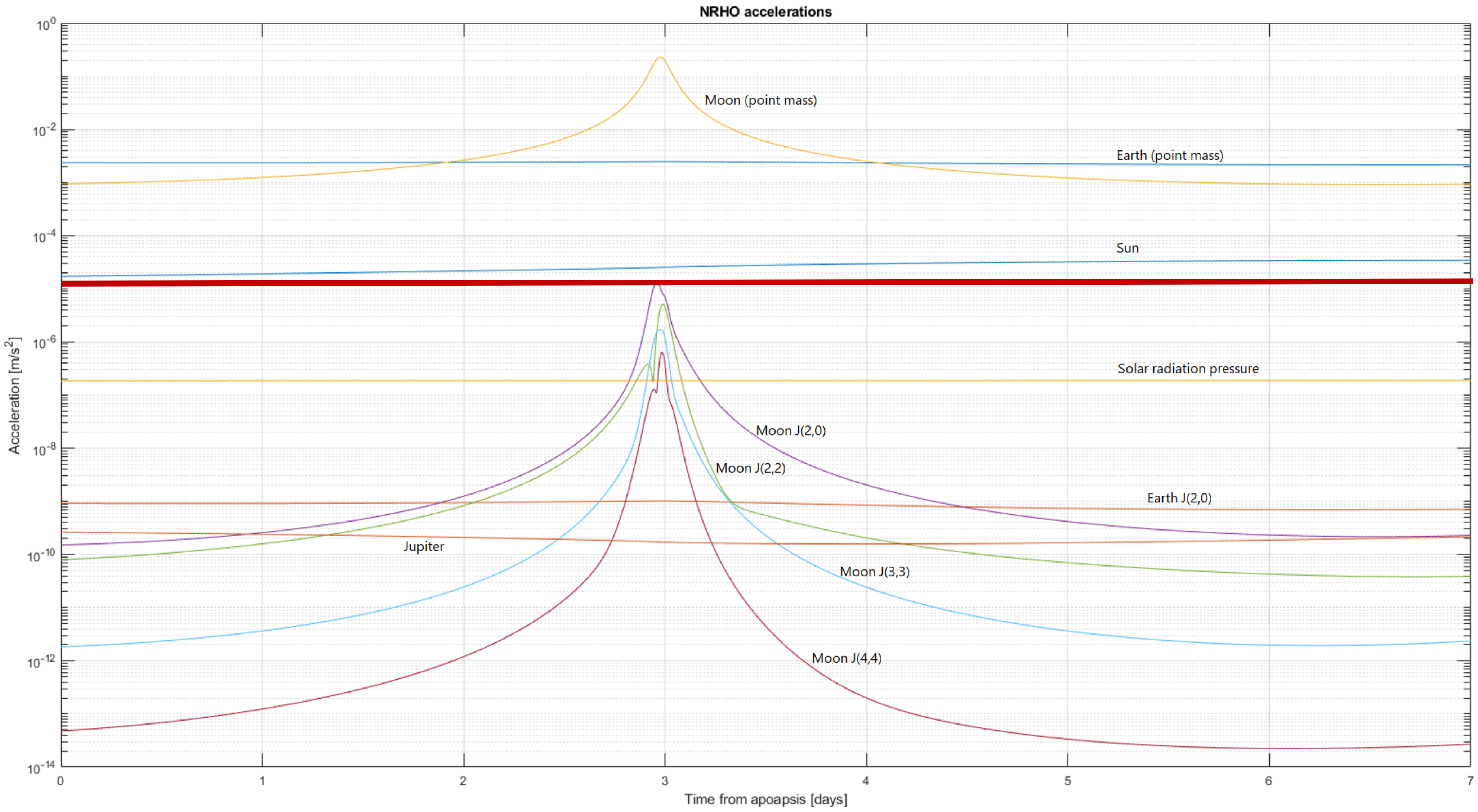
Reference orbit 1: Moon Transfer Orbit



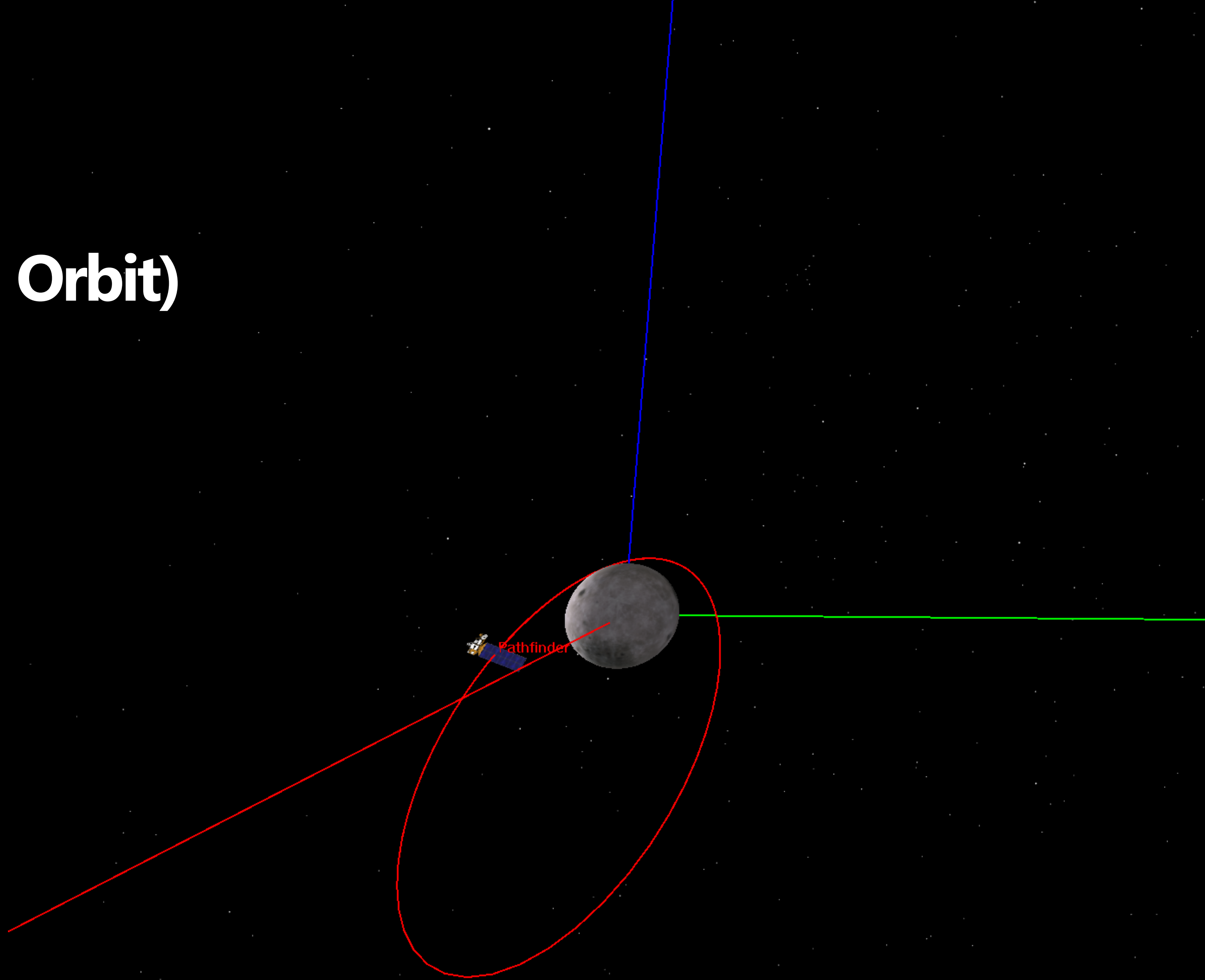
Reference orbit 2: Near-rectilinear Halo Orbit



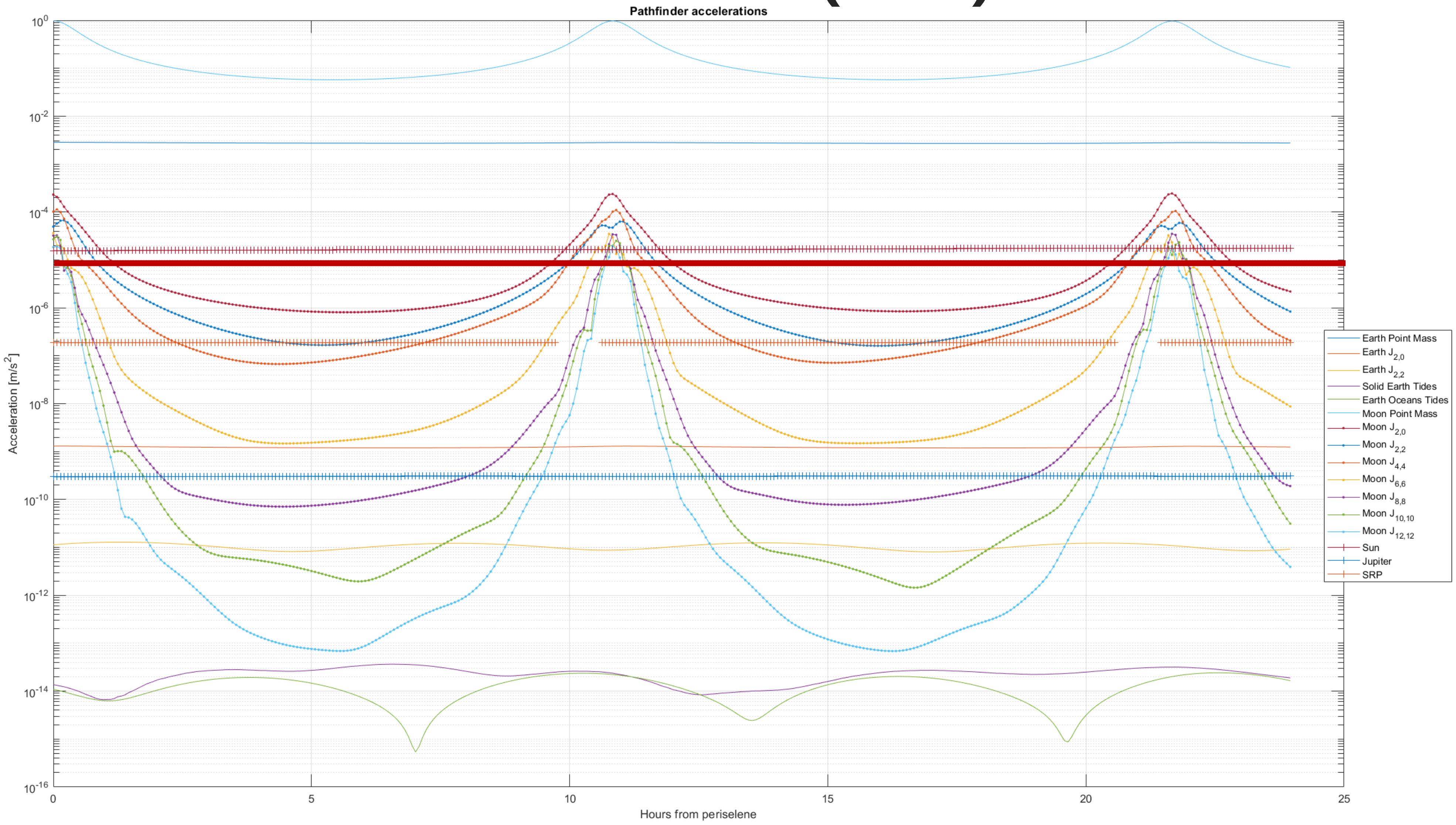
Reference orbit 2: Near-rectilinear Halo Orbit



Reference orbit 3: Lunar Pathfinder (Elliptical Lunar Frozen Orbit)



Reference orbit 3: Lunar Pathfinder (ELFO)



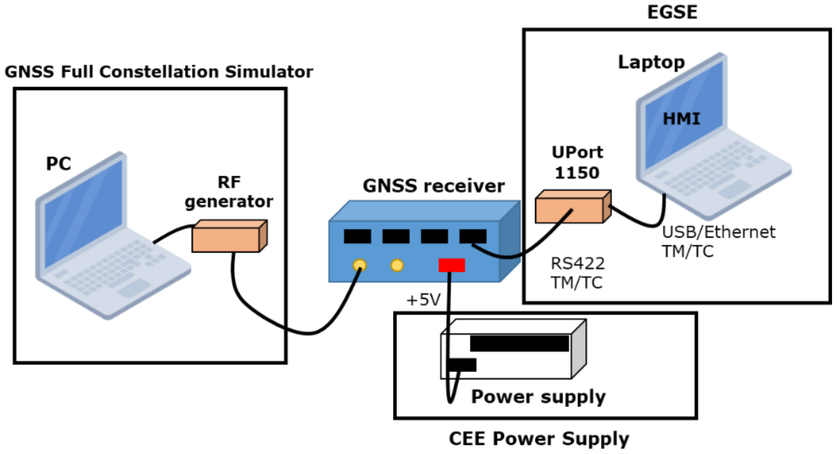
HWIL test setup

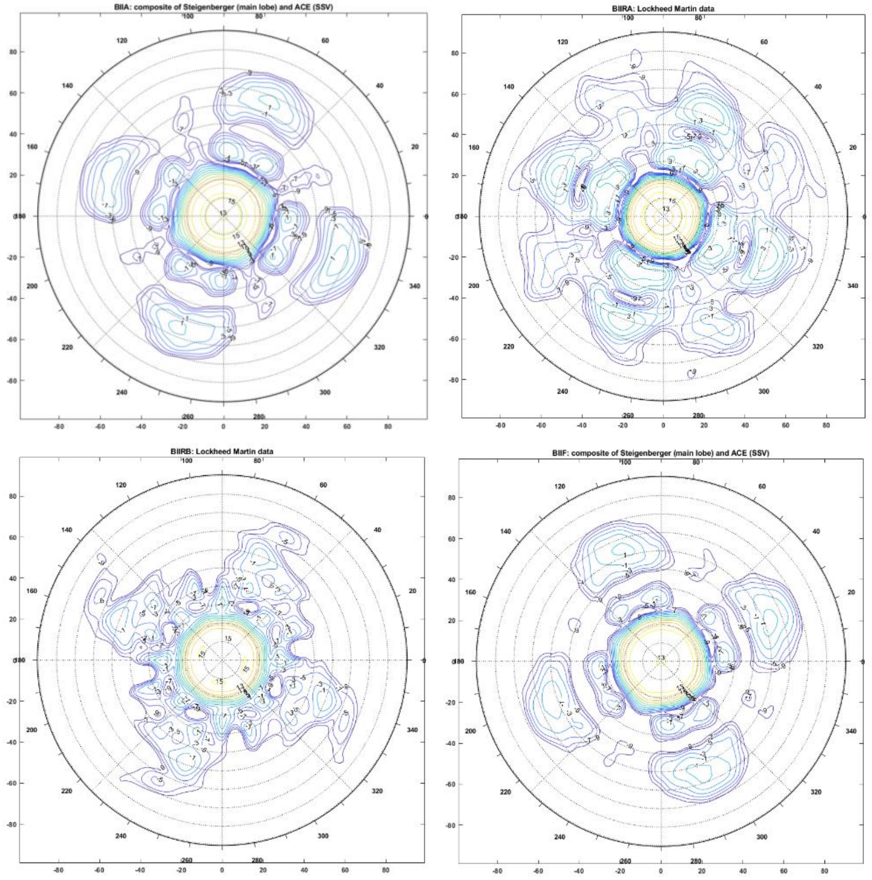
- ❖ RX antenna: high gain, narrow main lobe
  - ~axialsymmetric
  - Peak gain ~ 14 dB on L1/L5

- ❖ TX antenna patterns
  - GPS: according to available literature (e.g. Lockheed Martin data, ACE experiment)
  - Galileo: 3D pattern models provided by ESA

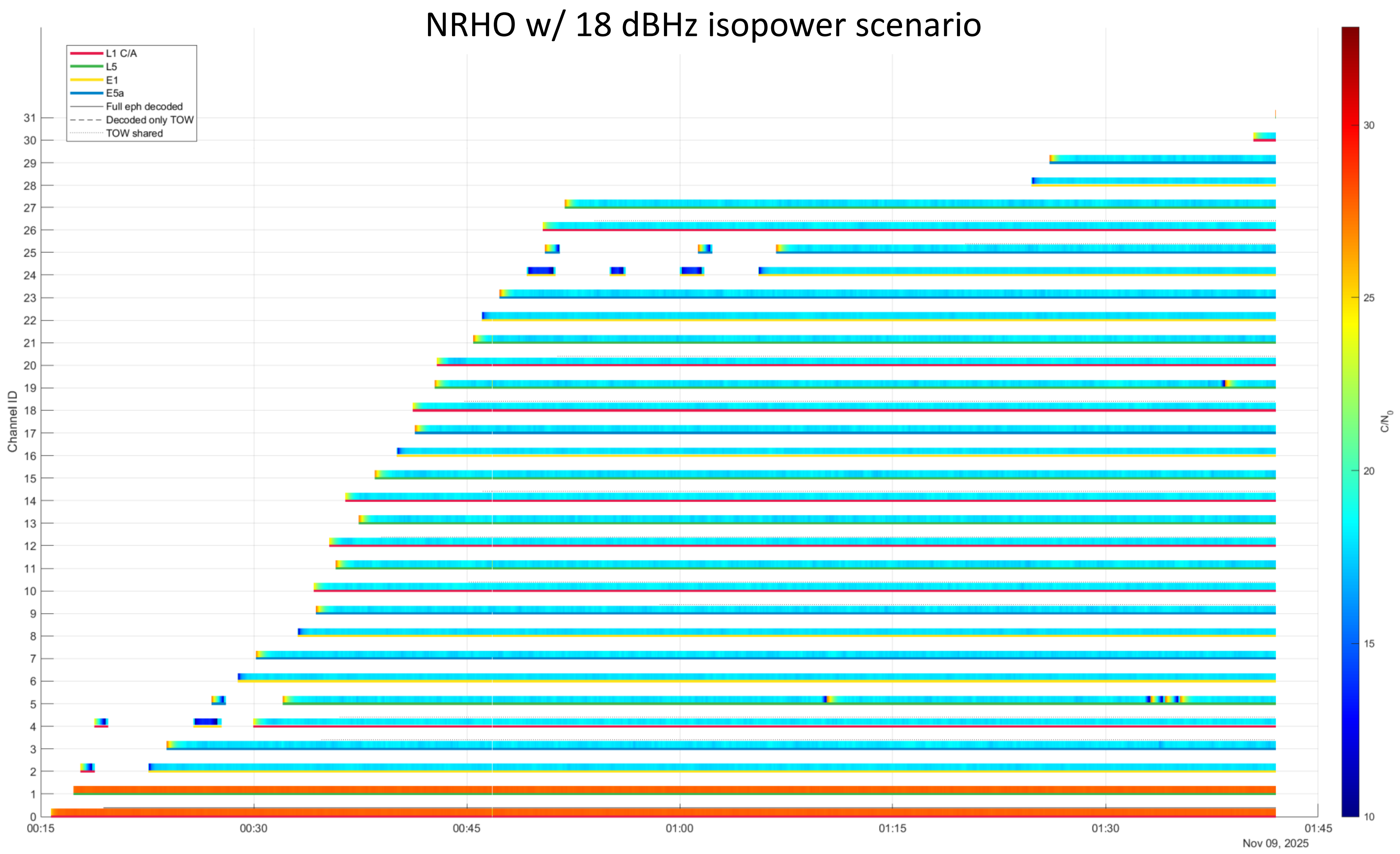
- ❖ Reference trajectories: precise propagation with GMAT, then imported in the simulator

- ❖ Received power calibration with ground scenario (ICD levels + 1.5 dB)





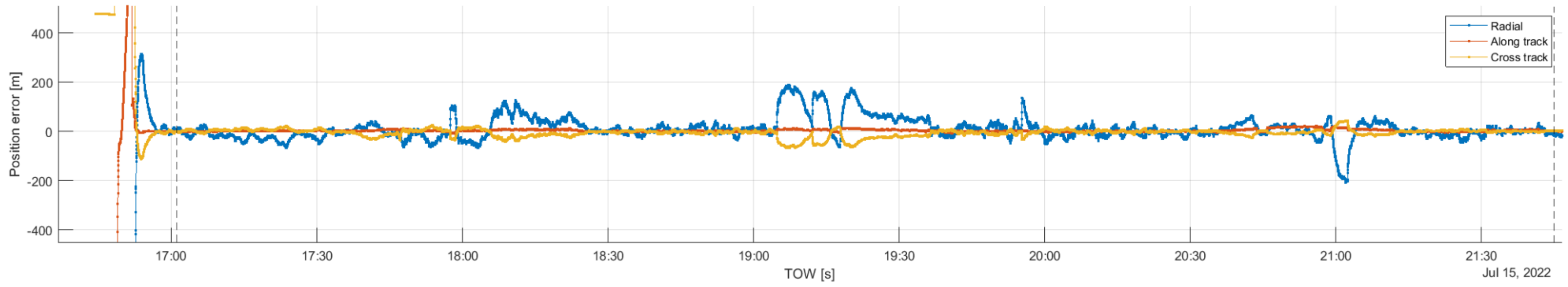
Receiver sensitivity



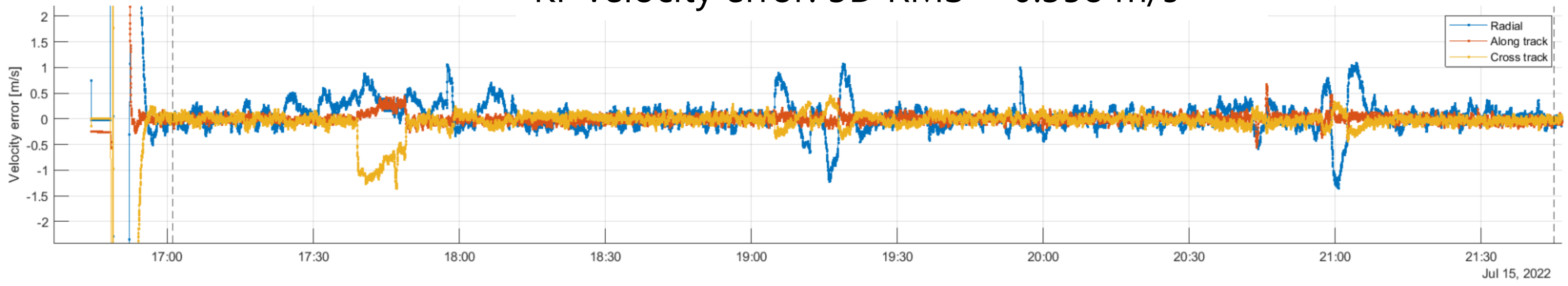
SpacePNT+

MTO test result

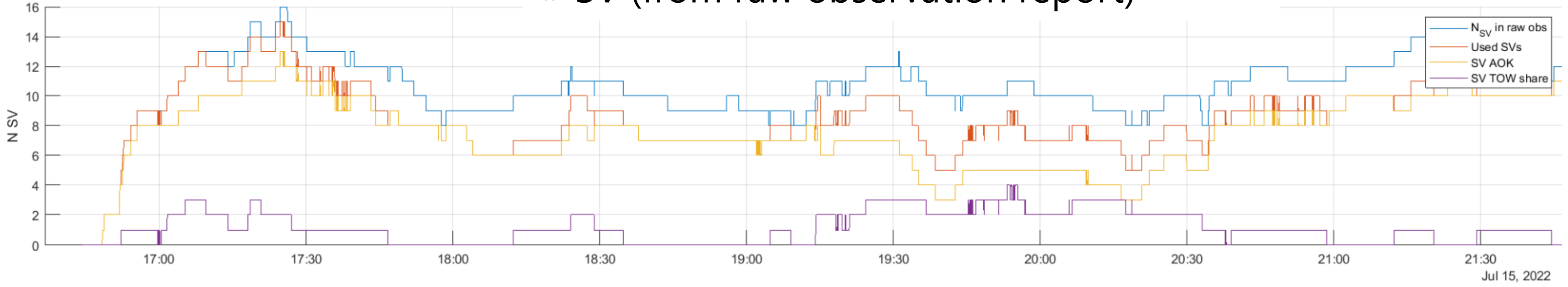
KF position error: 3D RMS = 50.7 m



KF velocity error: 3D RMS = 0.358 m/s

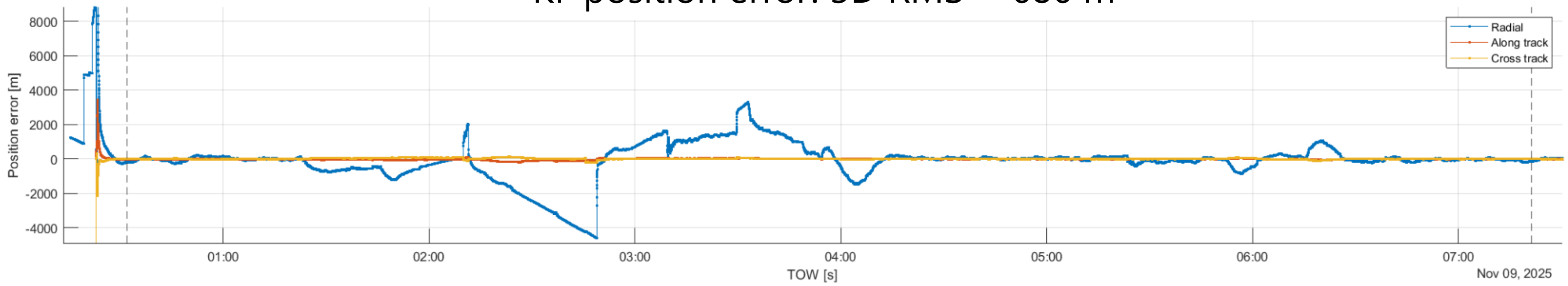


SV (from raw observation report)

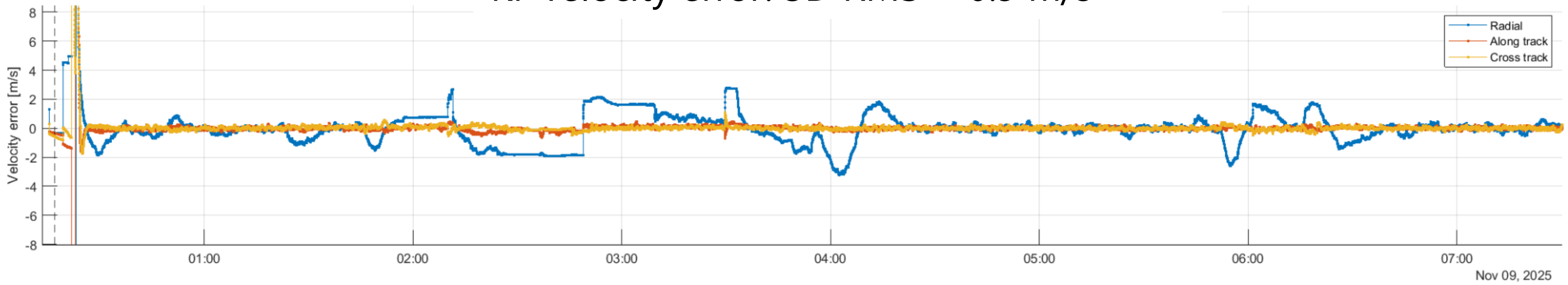


NRHO test - including poor visibility conditions

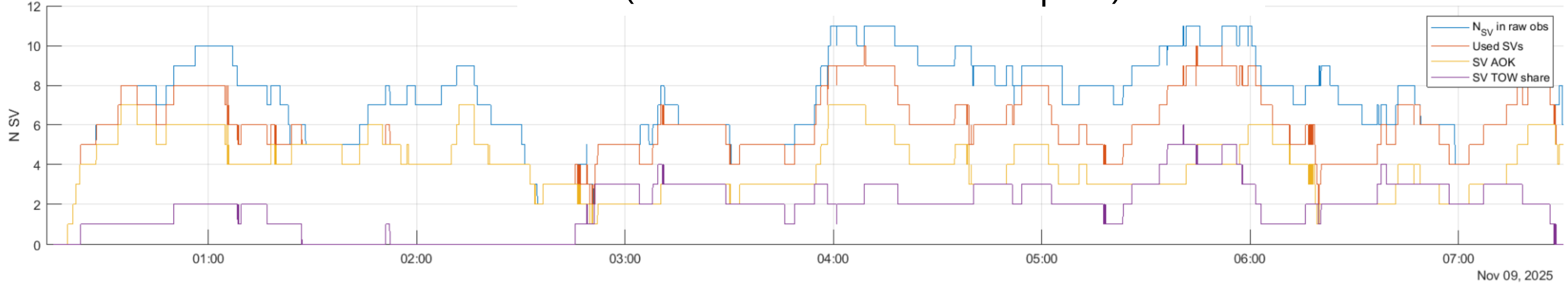
KF position error: 3D RMS = 686 m



KF velocity error: 3D RMS = 0.9 m/s

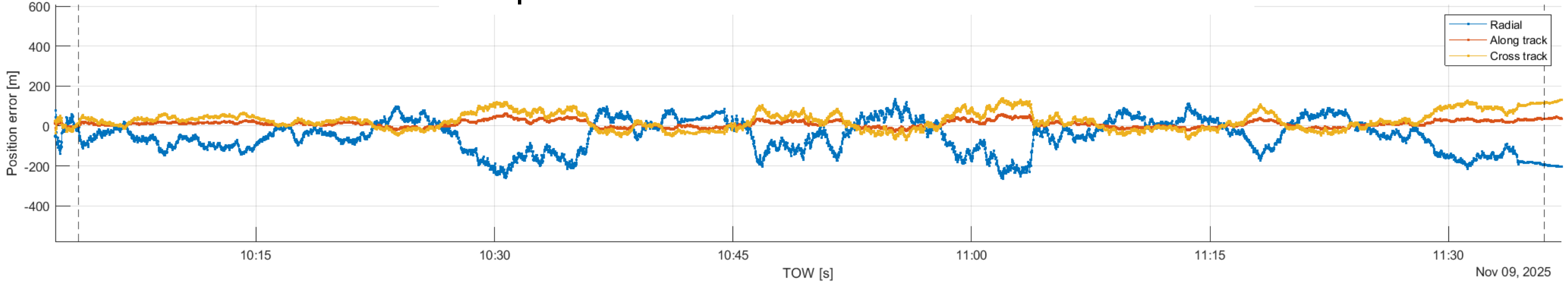


SV (from raw observation report)

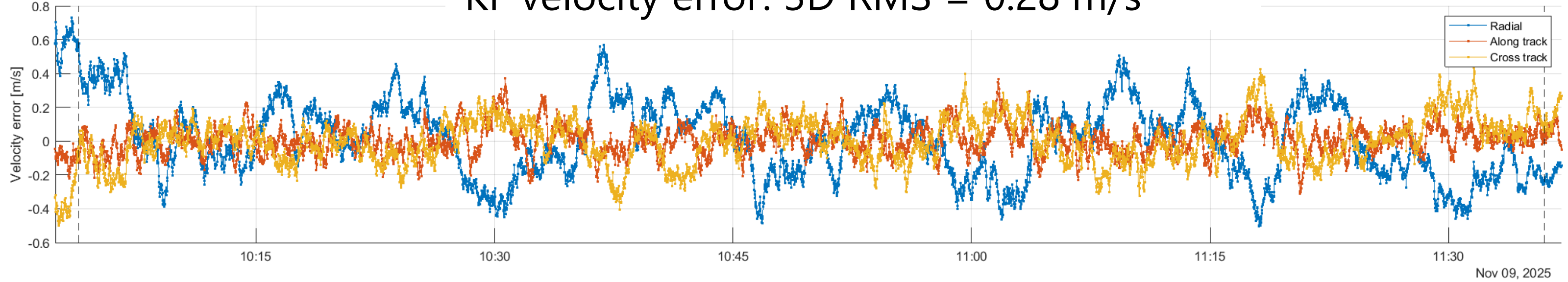


NRHO test - when 3 or more satellites are tracked

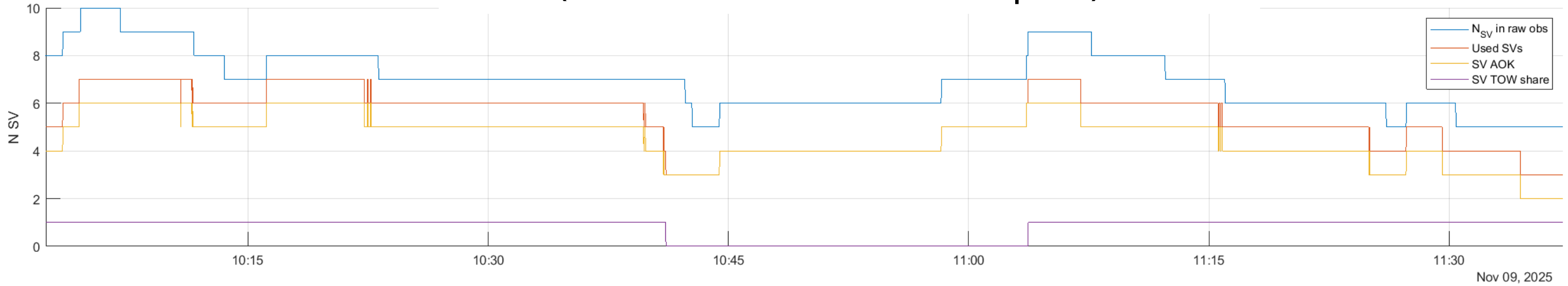
KF position error: 3D RMS = 123 m



KF velocity error: 3D RMS = 0.28 m/s



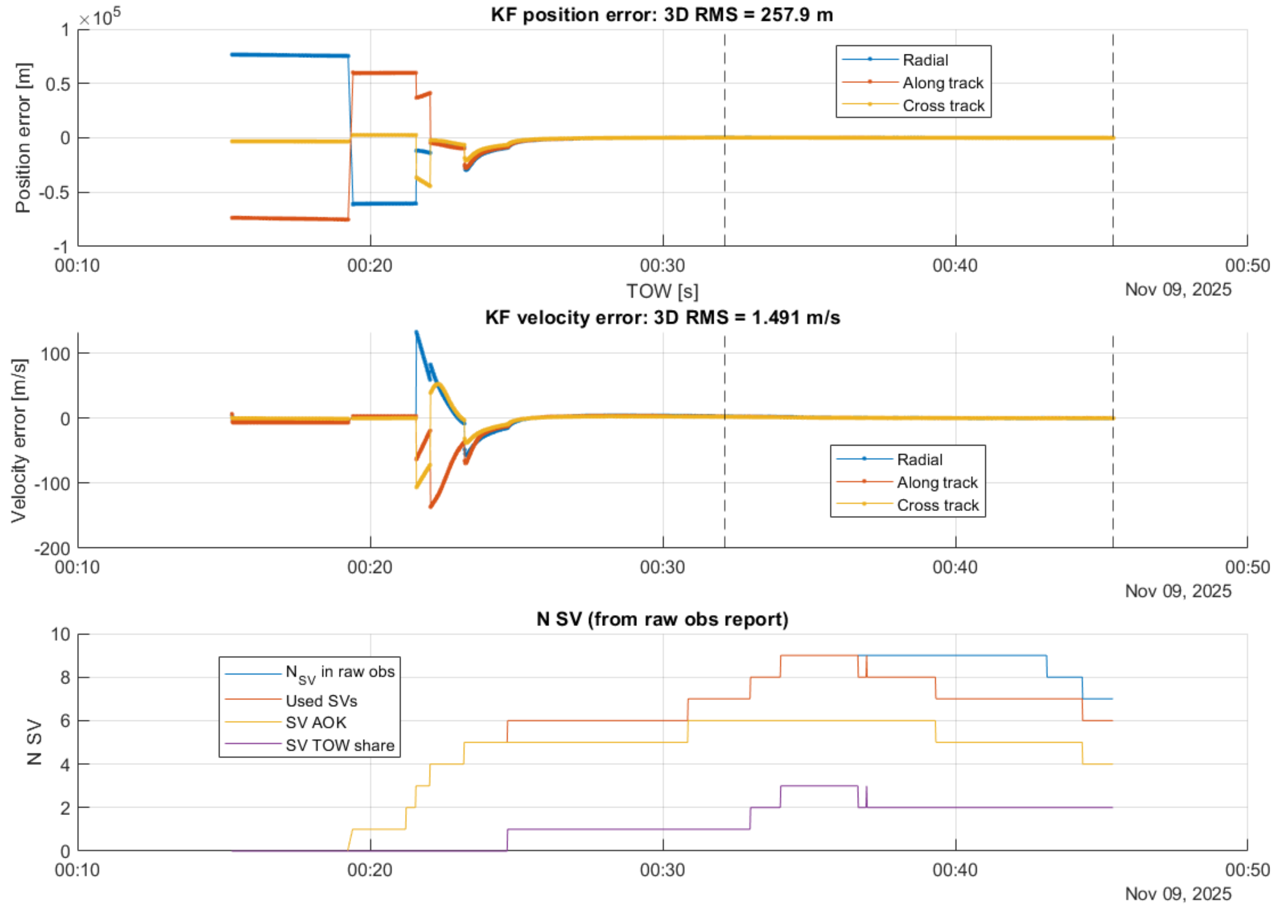
SV (from raw observation report)



Warm start TTFF with PVT error (NRHO)

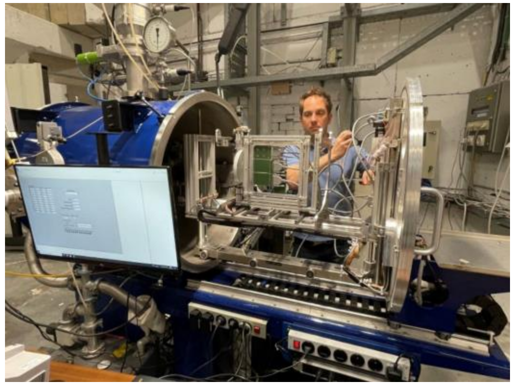
- Ephemerides provided via TC
- Coarse PVT solution provided via TC
  - Affected by error (as per table below)

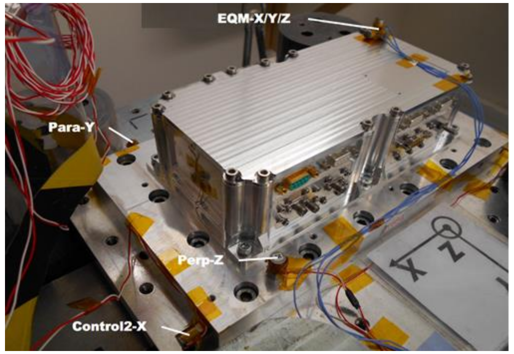
Run ID	Error
1	Radial position = -100 km
2	Radial position = +100 km
3	Along-track position = -100 km
4	Along-track position = +100 km
5	Cross-track position = -100 km
6	Cross-track position = +100 km
7	Radial velocity = -30 m/s
8	Radial velocity = +30 m/s
9	Along-track velocity = -30 m/s
10	Along-track velocity = +30 m/s
11	Cross-track velocity = -30 m/s
12	Cross-track velocity = +30 m/s
13	Time error = -5 seconds

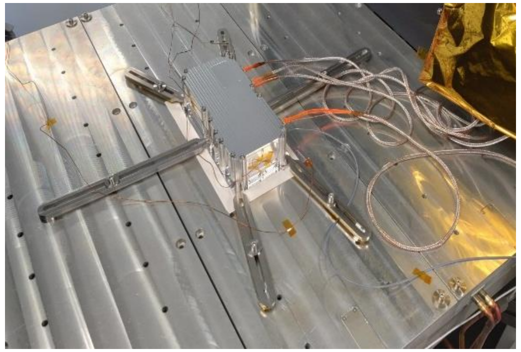


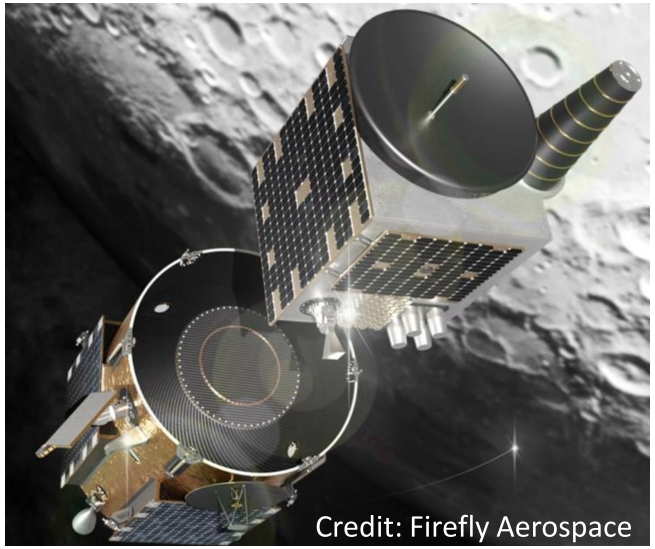
What's next: NAVISP-EL1-039

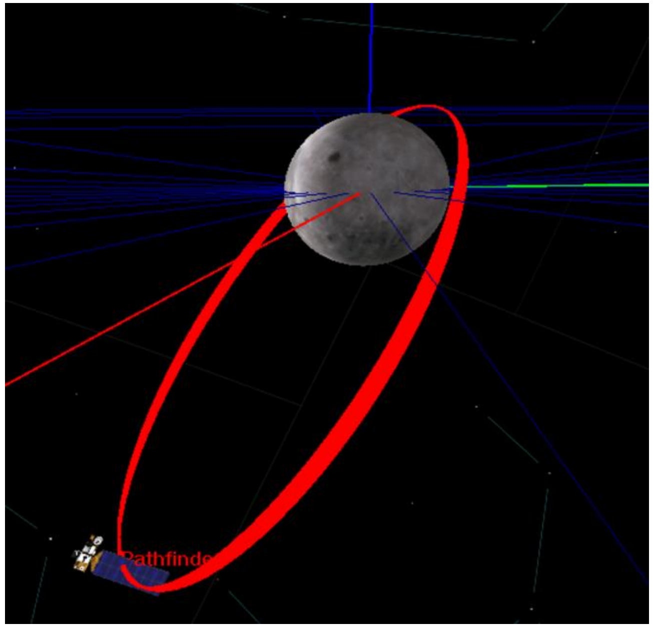
- NaviMoon will be embarked on SSTL's Lunar Pathfinder for In-Orbit Demonstration.
- Major milestones have been met (PDR, CDR, TRR, radiation test campaigns, DRB), final review in Q4 2023.
- Spacecraft integration in 2024/2025. Launch end 2025/ beginning 2026

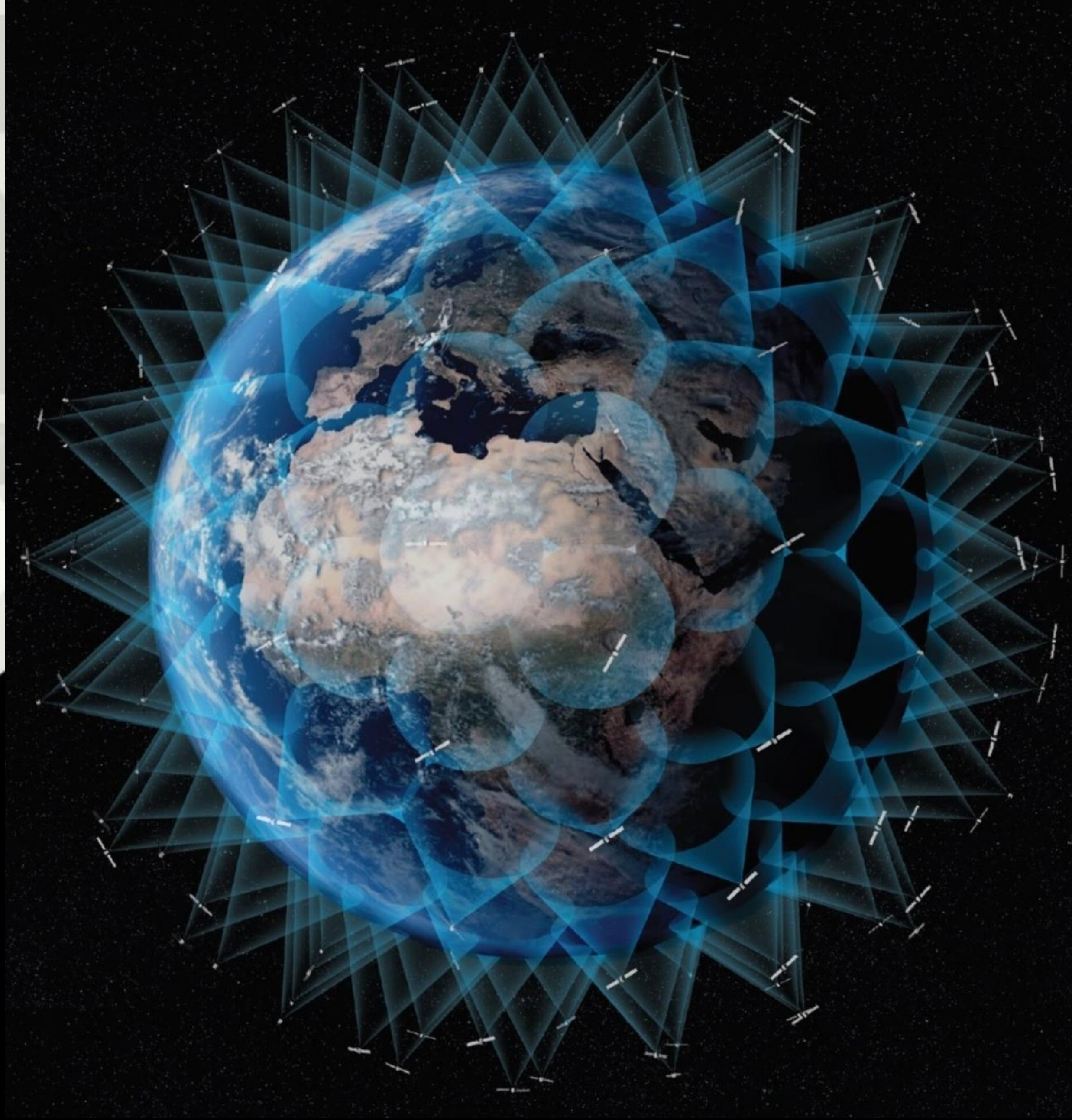












SpacePNT+

SpacePNT SA
Rue du Puits-Godet 6a
2000 Neuchâtel – Switzerland
info@spacepnt.com
https://spacepnt.com

Enabling Novel Applications for the Space and the Earth Users

Images credit: ESA