LUPIN

ENABLING HIGH PERFORMANCE PNT IN THE LUNAR ENVIRONMENT

NAVISP EL1-069

NAVISP Final Presentation

Contract Number:	4000141801/23/NL/GP/kg
Code:	GMV-LUPIN-PRS-NAVISP
Version:	V1.0
Date:	12/05/2026
Internal Code:	GMV

Agenda

- Company Introduction
- Introduction to the LUPIN Project
- Use Case Assessment
- “ANIME” System Architecture
- Field Test Campaign & Results
- Conclusions & Next Steps

GMV, a European Global Technology Group

Multinational technology group

Headquarters in Spain (Madrid)

Private capital

c.a. 4000 employees

+530 M€ worldwide revenue

Companies in 12 countries, 8 EU MS (ops in 70+)

CMMI level 5

CMMIDEV/5

Space

#1 Worldwide in satellite control segments

Leader in ground segment for space missions (+900 spacecrafts use GMV technology)

Prime contractor of GOVSATCOM Hub

Responsible of GNSS safety critical systems (Egnos and Galileo)

Prime contractor of the Galileo Ground Control Segment (& G2 IOV GCS)

Prime contractor of LEO PNT IOD

Defense and Security

Reference supplier of multidomain C4ISR

Leader in Resilient Position Navigation and Timming systems in all domains

Intelligent Transportation Systems

Leader of Intelligent Transportation Systems for the public transport sector (+100 cities in 5 continents)

Leader on Highly Precise & Safe GNSS Positioning Engine for Autonomous Driving

Information Technologies

Pioneer in security for banking and telcos and Reference Supplier for European Space, Defense and Security Agencies

Worldwide leader cybersecurity protection for ATMs

GMV in the UK

GMV UK is a Leading UK Supplier of Space and PNT Technology

UK based subsidiary of GMV

- ~100 people with offices in Nottingham and Harwell
- Currently based at two sites (Nottingham and Harwell)
- ISO 9001 certified Company
- Undergoing accreditations for UK MOD

Major Customers

- UK Space Agency
- European Space Agency
- UK Ministry of Defence (including DSTL)
- Square Kilometre Array

Project Overview & Objectives

Background:

- Lunar missions are pushing toward longer, more autonomous operations in difficult regions, demanding reliable and continuous PNT.
- Existing navigation is mainly relative (IMU/vision), which drifts over time and depends on intermittent, resource-heavy absolute fixes like terrain matching or Earth-based tracking.
- Future lunar RF systems such as Moonlight/LCNS can provide GNSS-like absolute positioning, reducing drift and easing reliance on computationally intensive methods.
- The LUPIN activity seeks to target this potential, by developing a tightly-coupled multi-sensor PNT solution (ANIME) combining inertial, visual, celestial, and RF inputs, supported by simulation and analogue testing.

Key objectives:

- Define representative lunar surface use cases and ConOps driving navigation needs.
- Study the current state of the art of planetary PNT techniques at user level for surface navigation and operations
- Design a hybrid PNT architecture (ANIME) based on tightly-coupled multi-sensor fusion.
- Develop a simulation environment (LUSIM) to generate representative LCNS and lunar GNSS measurements.
- Implement a breadboard and integrate it on a rover test platform for terrestrial analogue trials.
- Assess expected performance benefits, limitations, and future roadmap for maturation.

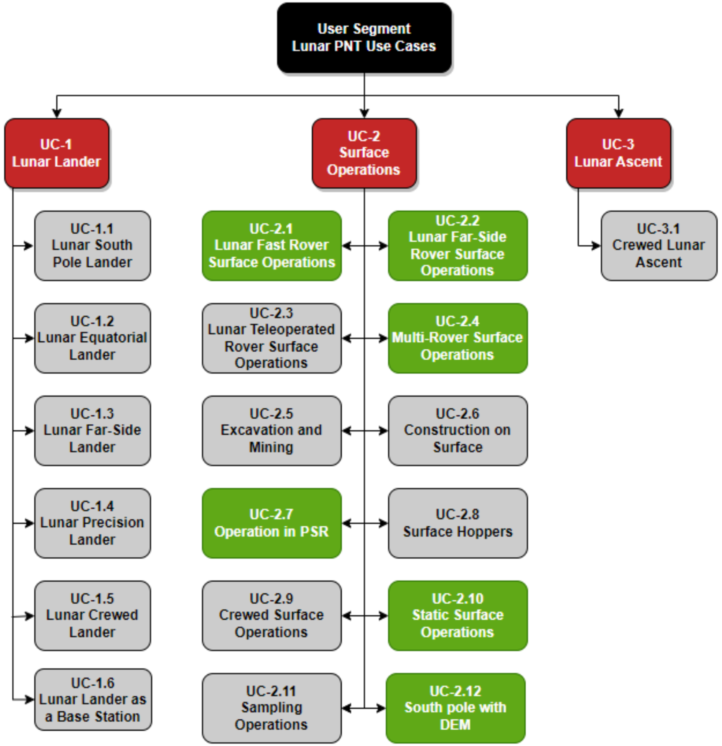
Use Case Analysis

Use Case Analysis & Concept of Operations

Recent European and international lunar mission studies were reviewed to understand driving requirements and priorities.

Four European candidate missions were considered—Polar Explorer, ISRU Pilot Plant, ALO, and the newer GEM concept—each offering representative surface-operation needs, including long-range mobility.

From the full hierarchy of identified use cases, those related to surface operations were prioritised for LUPIN based on maturity, relevance, and strategic value.


User Segment
Lunar PNT Use Cases

UC-1
Lunar Lander

UC-1.1
Lunar South Pole Lander

UC-1.2
Lunar Equatorial Lander

UC-1.3
Lunar Far-Side Lander

UC-1.4
Lunar Precision Lander

UC-1.5
Lunar Crewed Lander

UC-1.6
Lunar Lander as a Base Station

UC-2
Surface Operations

UC-2.1
Lunar Fast Rover Surface Operations

UC-2.2
Lunar Far-Side Rover Surface Operations

UC-2.3
Lunar Teleoperated Rover Surface Operations

UC-2.4
Multi-Rover Surface Operations

UC-2.5
Excavation and Mining

UC-2.6
Construction on Surface

UC-2.7
Operation in PSR

UC-2.8
Surface Hoppers

UC-2.9
Crewed Surface Operations

UC-2.10
Static Surface Operations

UC-2.11
Sampling Operations

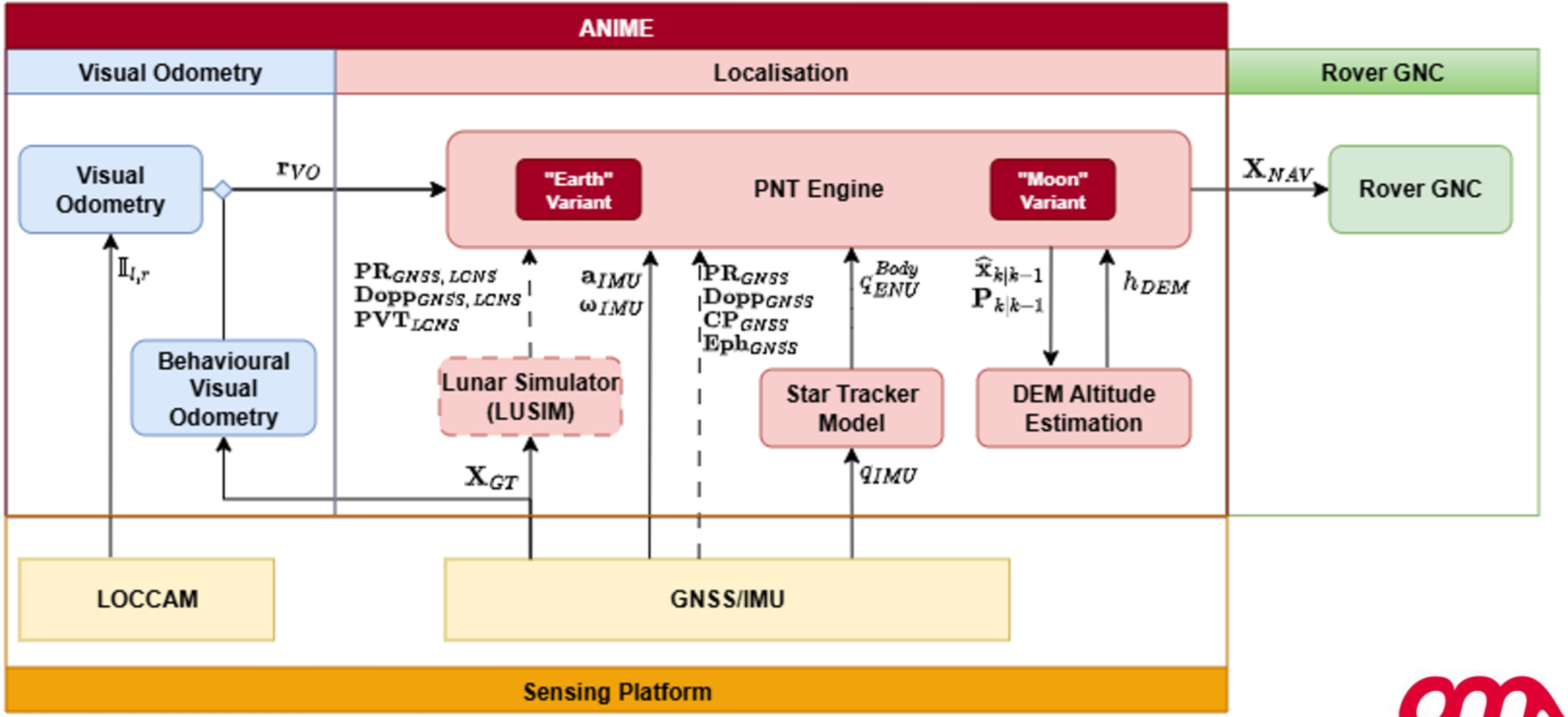
UC-2.12
South pole with DEM

UC-3
Lunar Ascent

UC-3.1
Crewed Lunar Ascent

ANIME Overview

ANIME Architecture – Design & Implementation



ANIME

Visual Odometry

Localisation

Rover GNC

Visual Odometry

$\mathbf{r}_{VO}$

$\mathbb{I}_{l,r}$

Behavioural Visual Odometry

"Earth" Variant

PNT Engine

"Moon" Variant

$\mathbf{X}_{NAV}$

Rover GNC

$\mathbf{PR}_{GNSS,\,LCNS}$
$\mathbf{Dopp}_{GNSS,\,LCNS}$
$\mathbf{PVT}_{LCNS}$

$\mathbf{a}_{IMU}$
$\boldsymbol{\omega}_{IMU}$

$\mathbf{PR}_{GNSS}$
$\mathbf{Dopp}_{GNSS}$
$\mathbf{CP}_{GNSS}$
$\mathbf{Eph}_{GNSS}$

q_{ENU}^{Body}

$\hat{\mathbf{x}}_{k|k-1}$
$\mathbf{P}_{k|k-1}$

h_{DEM}

Lunar Simulator (LUSIM)

Star Tracker Model

DEM Altitude Estimation

$\mathbf{X}_{GT}$

q_{IMU}

LOCCAM

GNSS/IMU

Sensing Platform

PNT Engine

ANIME Architecture – Design & Implementation

The PNT engine has two configurations:

- Earth mode – ECEF and real (subset) GNSS
- Moon mode – ME and simulated LCNS / mapped GNSS

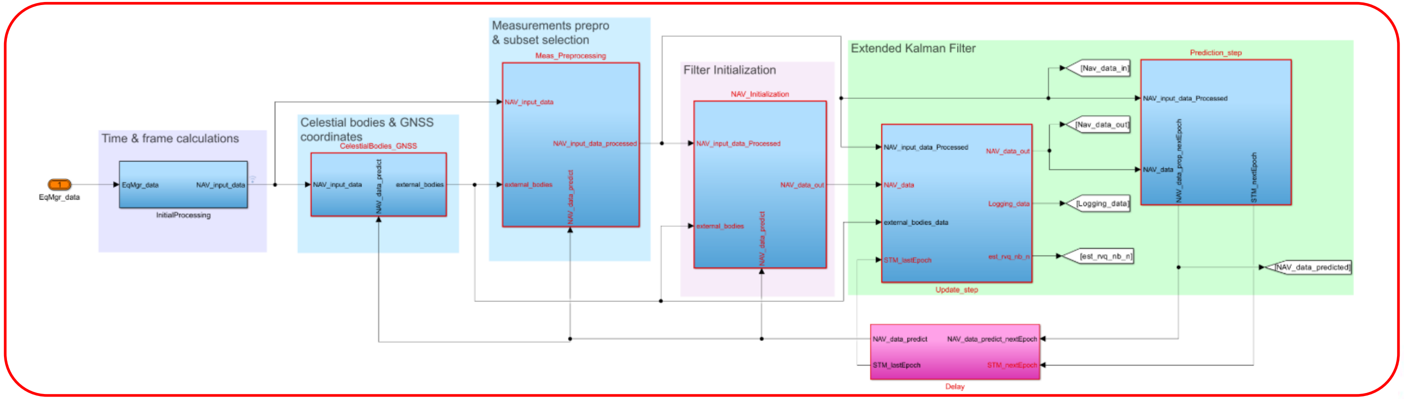
EKF with Tightly coupled Sensor fusion.

The filter state is :

- Attitude quaternion (rover body to ECEF/ME)
- Position, velocity, clock bias and bias drift
- IMU acceleration and gyro biases

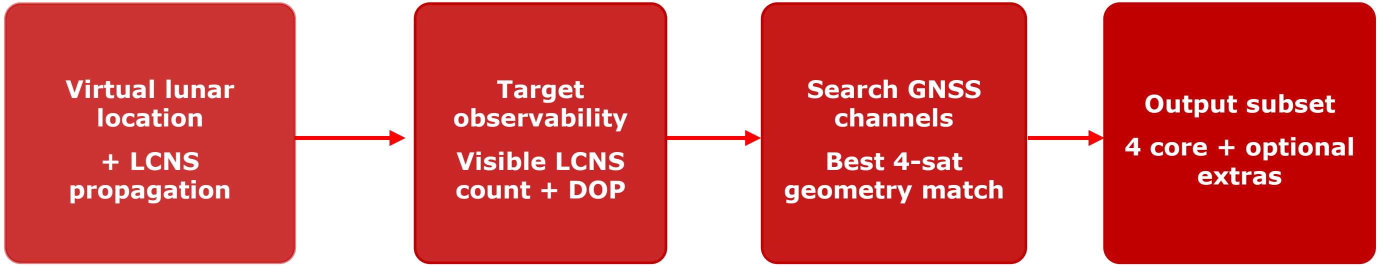
Sensors include:

- IMU – for prediction, 100 Hz
- GNSS / LCNS – absolute position and velocity
- VO – relative pose
- STR – absolute attitude
- DEM – height



GNSS Subset Selection

ANIME Architecture – Design & Implementation



Virtual lunar location

+ LCNS propagation

Target observability

Visible LCNS count + DOP

Search GNSS channels

Best 4-sat geometry match

Output subset

4 core + optional extras

What it emulates

- Number of visible satellites
- Satellite geometry via DOP
- Visibility evolution over time

What it does not emulate

- LCNS signal-in-space error budget
- LCNS receiver/clock/noise behaviour
- Lunar RF propagation effects

Main takeaway

The first four GNSS measurements are chosen to reproduce the LCNS-like geometry.

Extra channels can be appended only to test the filter with more measurements.

LUSIM

ANIME Architecture – Design & Implementation

- **Earth field trial data**
  - RTK rover state, attitude, receiver clock and GNSS ephemerides
- **Virtual Moon mapping**
  - Rotate/scale Earth trajectory into selected lunar site geometry
- **LUSIM RF observables**
  - Synthetic LCNS + GNSS pseudorange, Doppler and C/N_0
- **Geometry + visibility**
  - LCNS/GNSS line-of-sight, occultation, DOP-driving geometry
- **Signal strength**
  - Carrier-to-noise ratio from link budget and antenna pointing
- **Error budget**
  - Broadcast SISE, receiver noise, multipath and clock terms
- **Failure injection**
  - Frozen, predetermined and time-dependent interface failures

Main takeaway

LUSIM project the real rover motion into a lunar virtual location, producing simulated LCNS/GNSS measurements, including the key visibility, geometry and error mechanisms that drive Moon-Navigation performance.

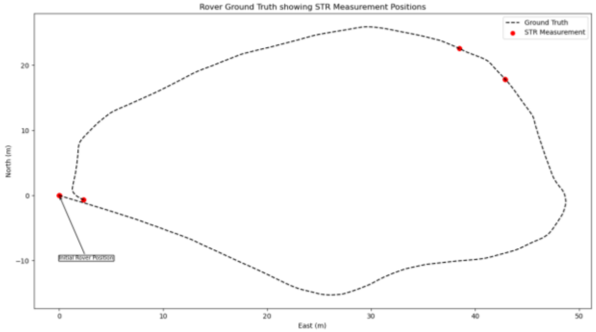
Star Tracker (Simulation)

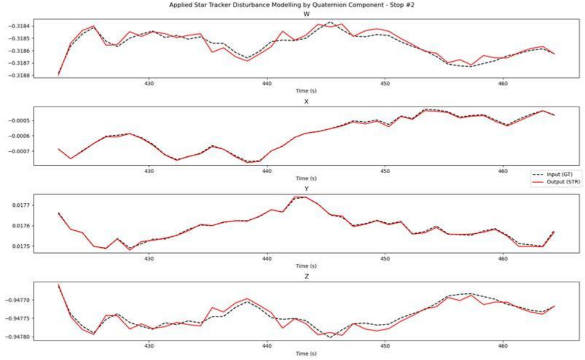
ANIME Architecture – Design & Implementation

- **A Behavioural STR model was used to model the key error sources:**
  - Constant bias for misalignment
  - white noise for high-frequency temporal error
  - First-order Gauss–Markov processes for pixel spatial and field-of-view errors.

- **The STR model uses the ENU aligned Ground Truth rover orientation as input and outputs the STR measurement.**

- **Operationally, the STR model is only active when stationary during a navigation stop.**

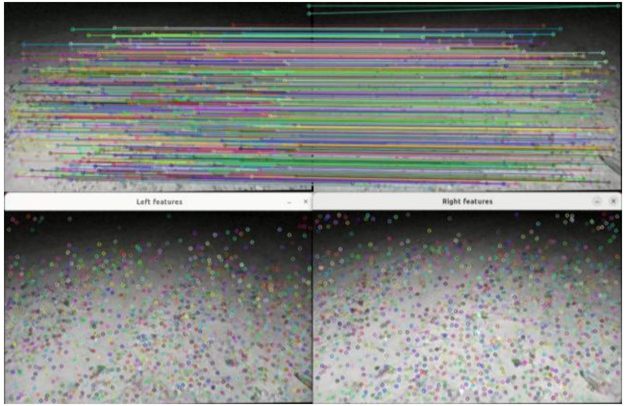




Visual Odometry

ANIME Architecture – Design & Implementation

- **SPARTAN VO was used initially to provide ego-motion inputs to the PNT Engine.**
  - However, unstable cameras during testing drove the need for a more reliable solution over long-duration tests.
- **A configurable Behavioural VO error model was developed capturing the main error sources of stereo-VO.**
- **The error model takes the rover ground-truth relative motion at each step and perturbs the instantaneous relative motion, capturing*:***
  - *Systematic drift & scale bias*
  - *Random noise*
  - *Distance & motion effects*
  - *Calibration & environment*
- **VO errors are modelled during traverses, with navigation stops used to reset the VO frame.**



DEM Range Measurements

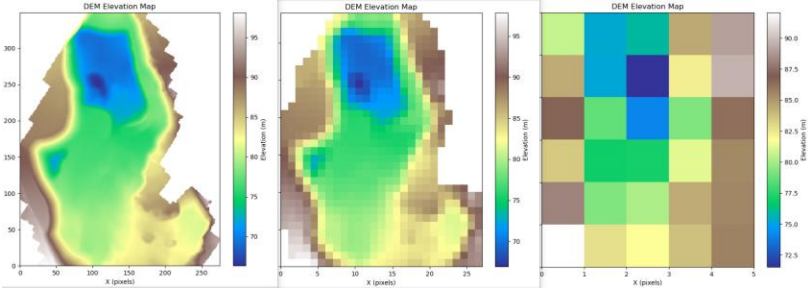
ANIME Architecture – Design & Implementation

- **DEM range measurements provide a geometric rover-to-Moon centre distance, independent of receiver clock bias.**

- **Multiple DEM products with different resolutions (0.5, 10, 50 m/px) were produced from the UAV survey of the Fuerteventura test site.**

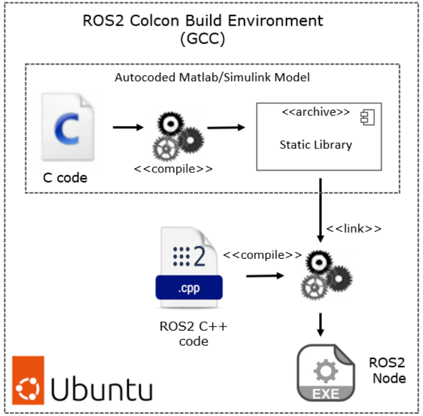
- **The PNT Engine extracts the DEM height estimate h_{DEM}, taken as the height in the closest DEM pixel, using:**
  - Predicted rover position (in ENU frame)
  - Rover position covariance

- **The DEM height covariance is estimated from the pose uncertainty and a square neighbourhood of DEM pixels.**

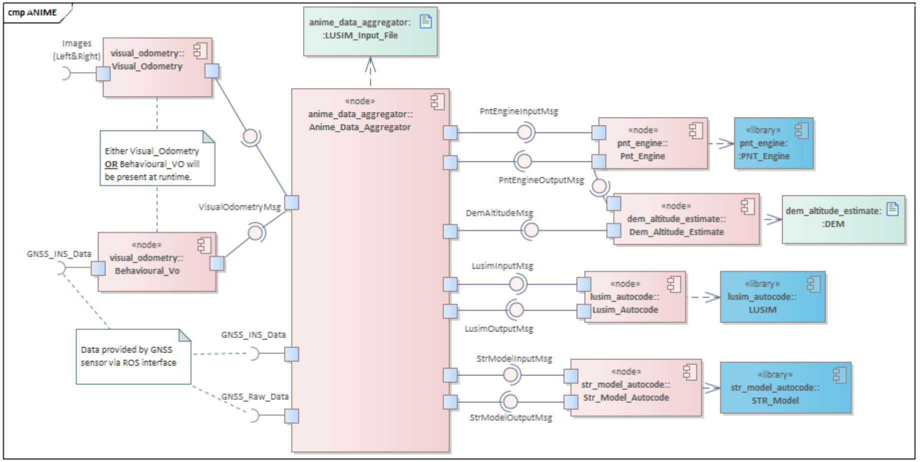


ANIME Implementation

ANIME Architecture – Design & Implementation

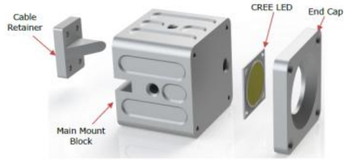


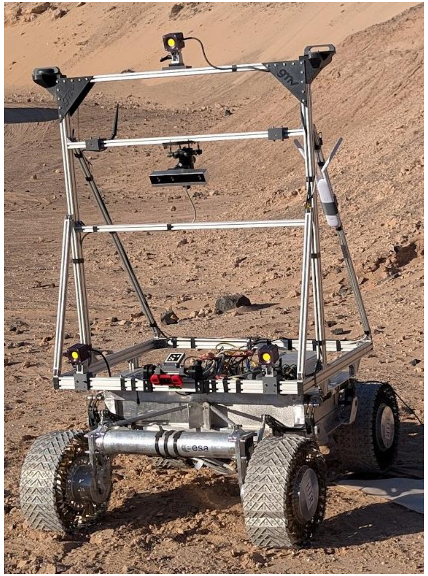
- **ANIME implementation based on containerised ROS2 Humble target (Ubuntu 24.04 LTS).**
- **PNT Engine, LUSIM and Sar Tracker (STR) are autocoded to C then integrated to create corresponding ROS2 nodes.**
  - Other ANIME SW components natively coded as ROS2 nodes in C++.
- **A dedicated aggregator coordinates the runtime execution of ANIME, by:**
  - Collecting the latest sensor data to the various ANIME SW components with consistent timing
  - Driving several event timers to periodically trigger LUSIM, STR and PNT Engine measurements
  - Processing the raw measurements coming from the Platform and the GNSS sensor

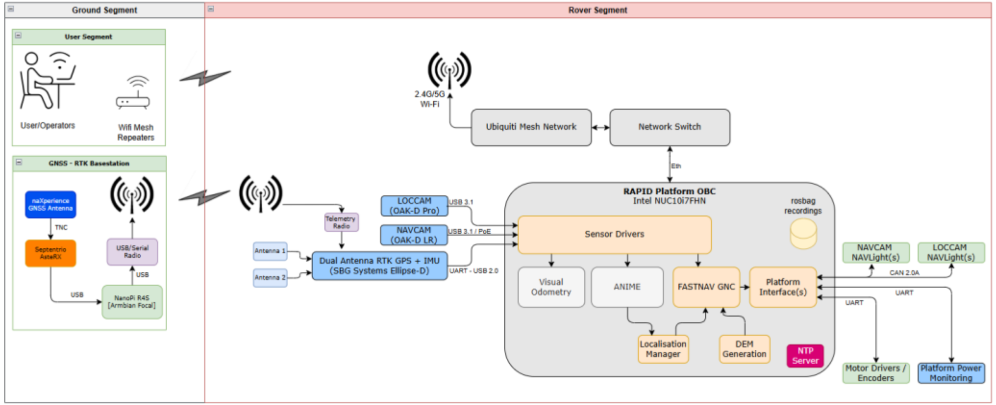


Field Trial Rover System – RAPID

- Prototype Future "Fast" Lunar Rover Platform
- Upgrades made to facilitate long-duration testing, including "hot-swappable" battery and power monitoring
- Existing rover avionics reused – OBC, LOCCAM, NAVCAM
- Navigation Lighting developed and integrated for night testing
- Dual-Antenna RTK GNSS/IMU sensor installed for ground truth and raw measurement
- RTK Basestation upgraded







Field Testing Strategy

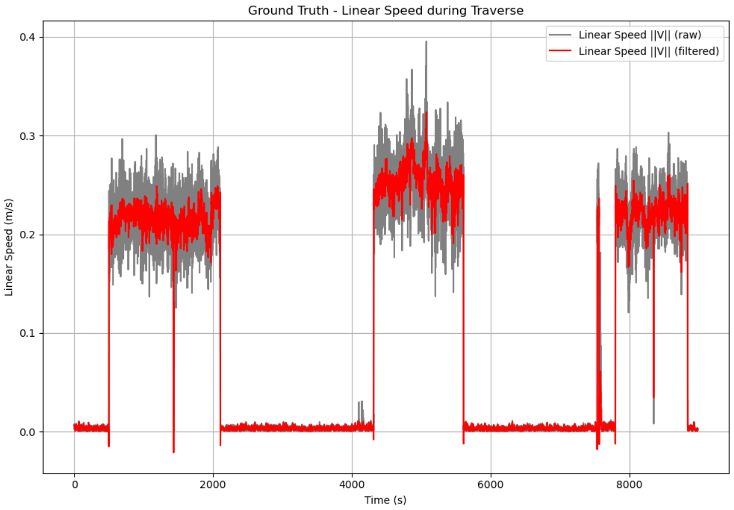
- **A series of Shakedown tests were performed to generate representative datasets for ANIME in a Quarry local to the Harwell Campus in Oxfordshire, UK in March 2025.**
  - These shakedown test days verified the integration of the sensors and demonstrated the robustness of the upgraded RAPID platform

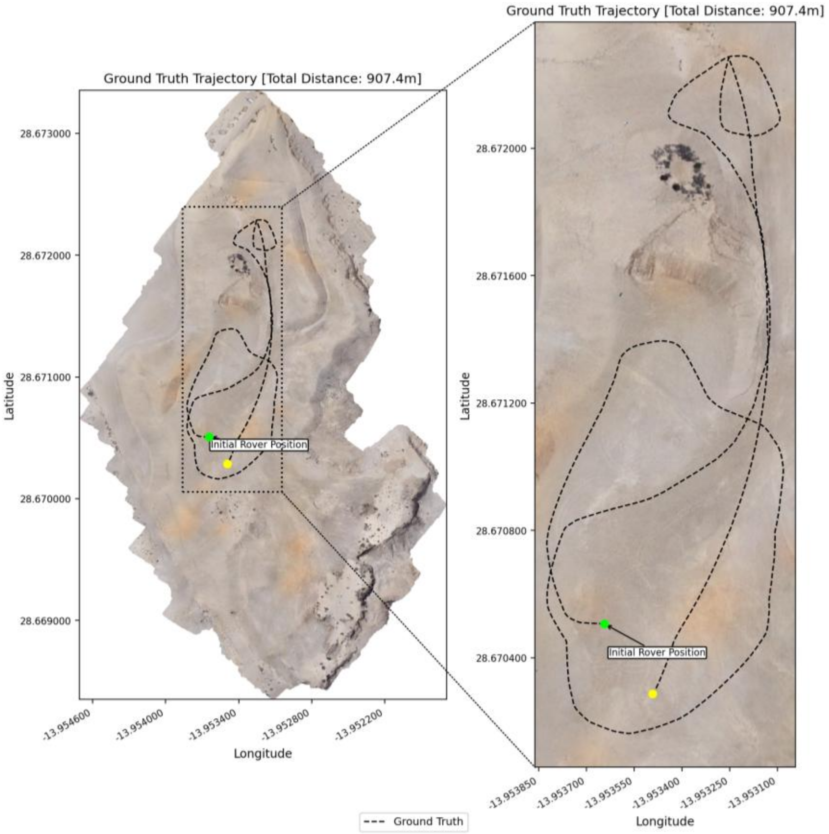
- **The final field test was conducted between 26th April and 10th May 2025 in Fuerteventura, Canary Islands, Spain.**
  - A combination of tests in day and night conditions were performed, with different durations and rover speeds.
  - The public event was a great success!

Ground Truth

FT-0010 - Nominal Rover Operations, 0.25m/s, Day, Lunar South Pole

Ground Truth Metric	Value
Total Dataset Time [s / hr-min]	8999.382s [2hrs 29mins]
Total Distance [m]	908.4
Number of Motion Segments	6
Duty Cycle of Time Spent in Motion [%]	44.1
Average Speed [m/s]	0.101
Average Speed in Motion [m/s]	0.228

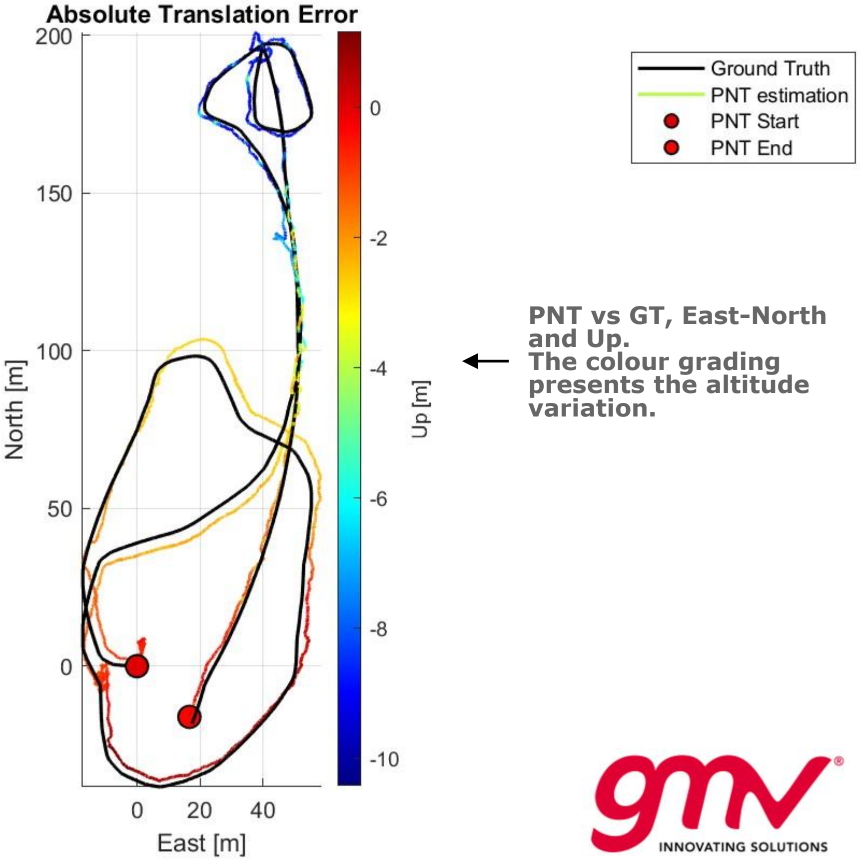




Test Results ANIME PNT (Earth config)

FT-0010 - Nominal Rover Operations, 0.25m/s, Day, Lunar South Pole

Position, velocity and attitude metrics	Horizontal, 95th [m, m/s, deg]	Horizontal, 99th [m, m/s, deg]	3-D norm, 95th [m, m/s, deg]	3-D norm, 99th [m, m/s, deg]
Position (LSQ)	[-]	[-]	7.39	9.73
Position (TC EKF)	5.84	7.8209	5.91	7.94
Velocity (LSQ)	0.60	1.6772	1.89	5.32
Velocity (TC EKF)	0.089	0.1292	0.093	0.13
Attitude	0.68	1.13	1.92	2.98
DOP metrics	95th [-]		99th [-]	
GDOP	107.27		295.21	
H-HDOP	1.82		1.87	

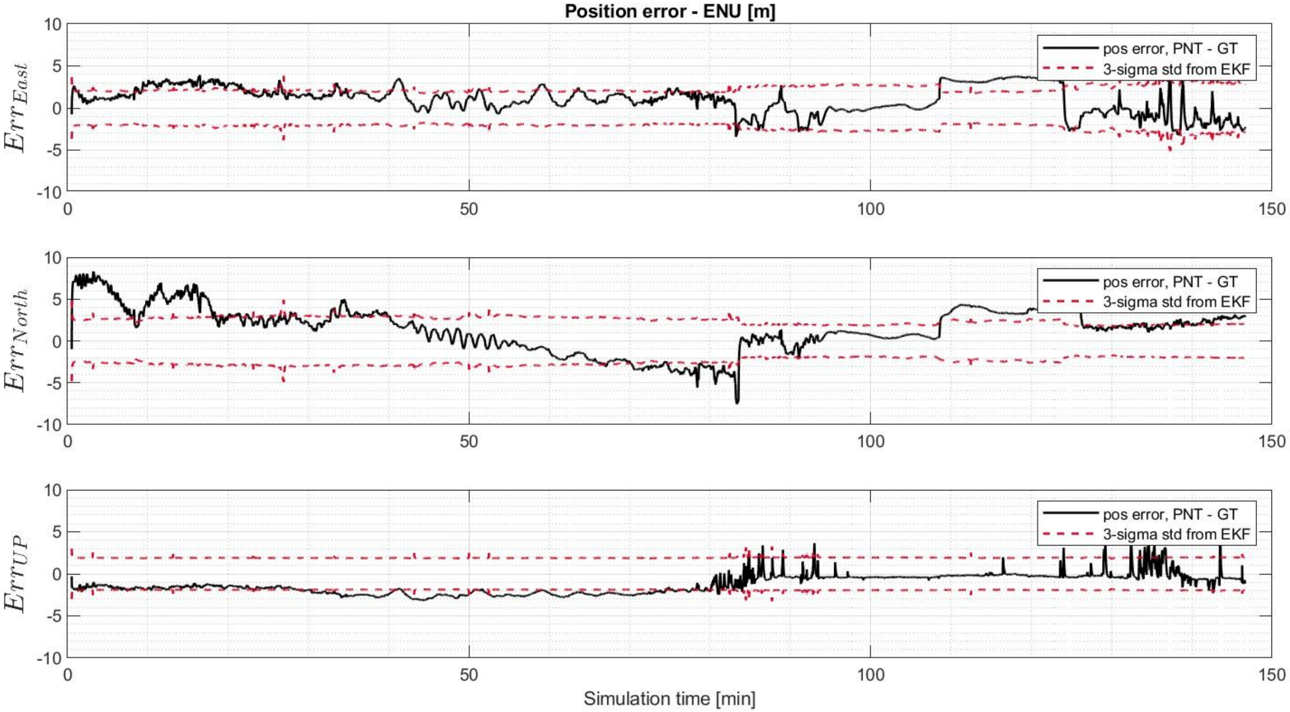


PNT vs GT, East-North and Up.
The colour grading presents the altitude variation.

Test Results ANIME PNT (Earth config)

FT-0010 - Nominal Rover Operations, 0.25m/s, Day, Lunar South Pole

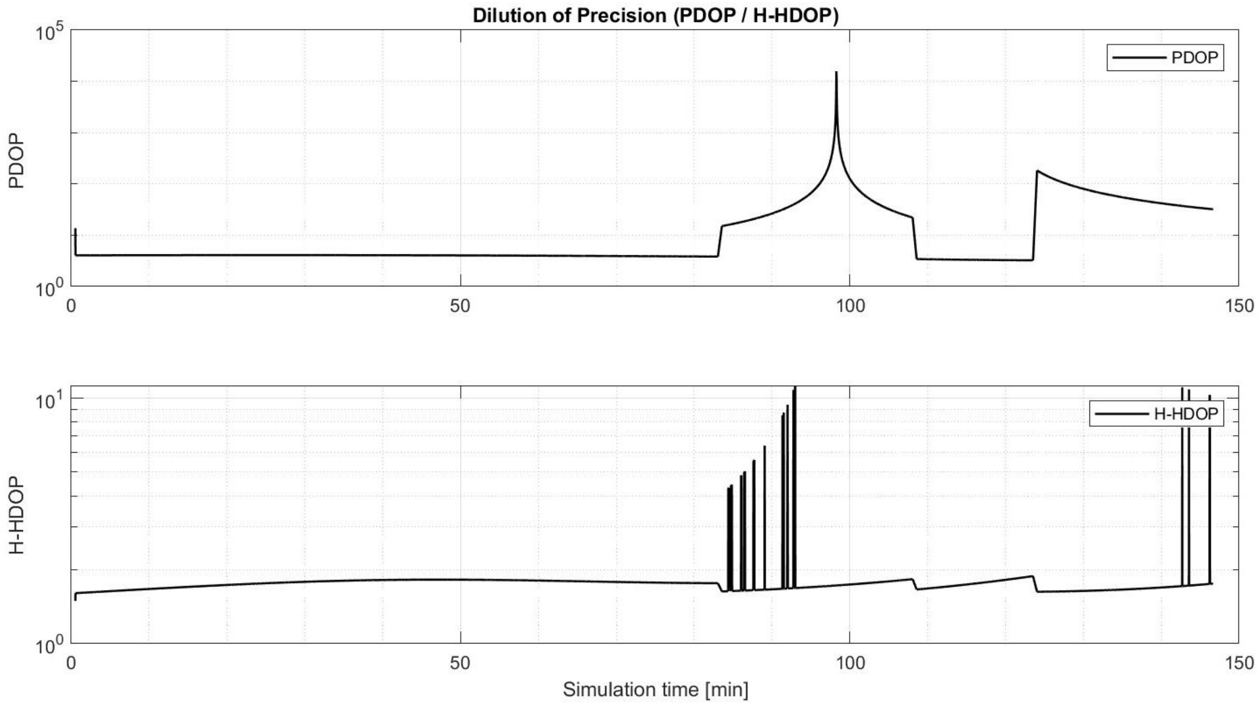
- **PNT Position error and 3-σ - ENU**



Test Results ANIME PNT (Earth config)

FT-0010 - Nominal Rover Operations, 0.25m/s, Day, Lunar South Pole

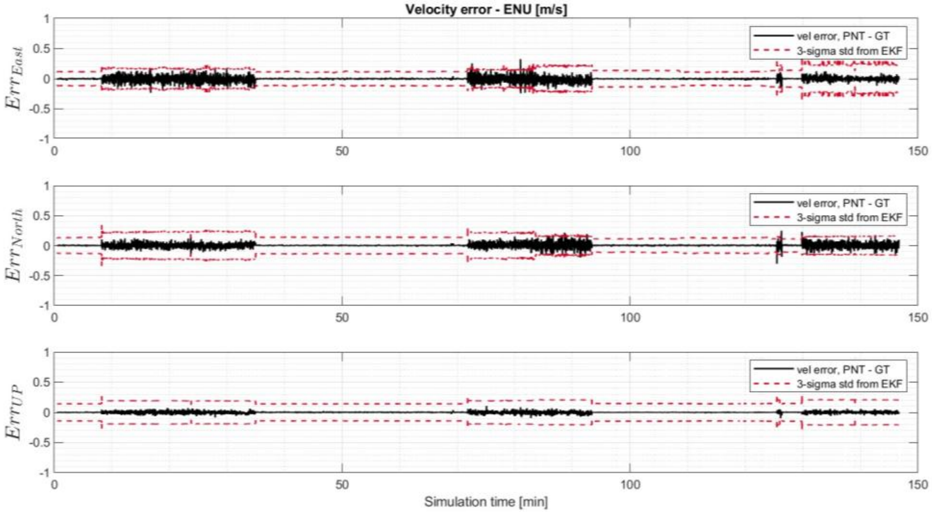
- ❑ **DOP**

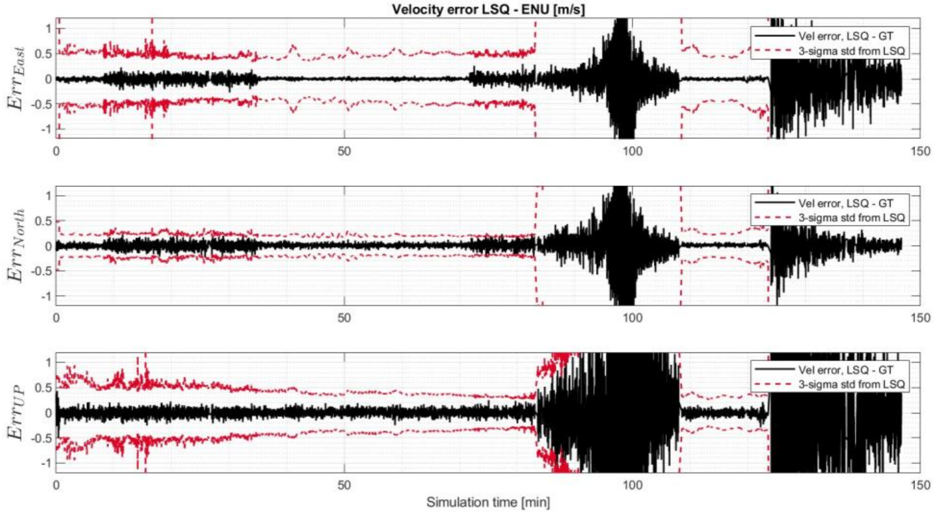


Test Results ANIME PNT (Earth config)

FT-0010 - Nominal Rover Operations, 0.25m/s, Day, Lunar South Pole

- ❑ **PNT velocity error and 3-σ – ENU, EKF and LSQ**

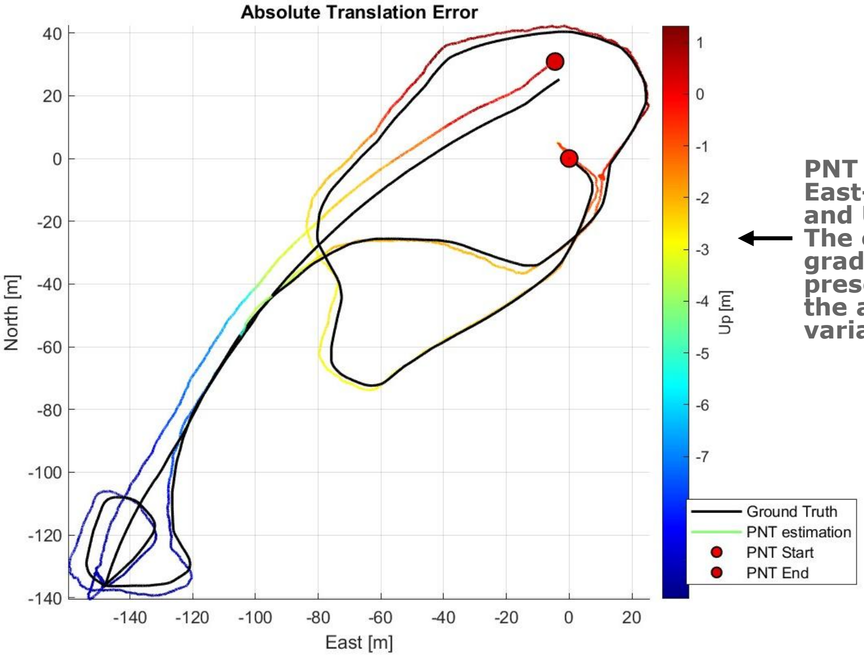




Test Results ANIME PNT (Moon config)

FT-0010 - Nominal Rover Operations, 0.25m/s, Day, Lunar South Pole

Position, velocity and attitude metrics	Horizontal, 95th [m, m/s, deg]	Horizontal, 99th [m, m/s, deg]	3-D norm, 95th [m, m/s, deg]	3-D norm, 99th [m, m/s, deg]
Position (LSQ)	[-]	[-]	7.41	7.74
Position (TC EKF)	7.43	7.61	7.43	7.61
Velocity (LSQ)	0.89	1.23	1.90	2.62
Velocity (TC EKF)	0.18	0.26	0.18	0.27
Attitude	1.09	1.57	1.40	2.07
DOP metrics	95th [-]		99th [-]	
GDOP	3.24		3.35	
H-HDOP	1.21		1.22	

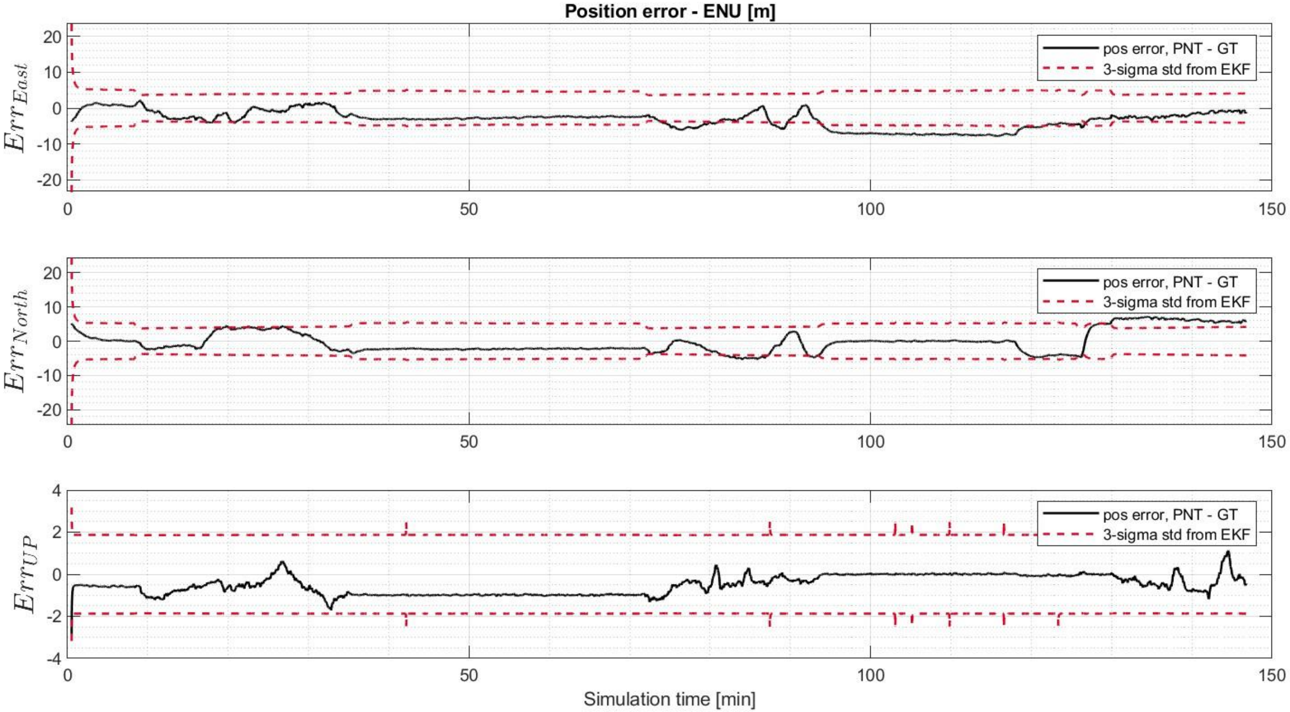


PNT vs GT, East-North and Up. The colour grading presents the altitude variation.

Test Results ANIME PNT (Moon config)

FT-0010 - Nominal Rover Operations, 0.25m/s, Day, Lunar South Pole

- **PNT Position error and 3-σ - ENU**



Test Results Summary

Summary table of all tests available on FR and ESR.

Summary of the KPM for all the 9 tests, in both configuration, is presented in the Final Report as well as in the Executive Summary report.

Below an example of the first 2 test cases:

Test case ID and configuration	Brief test case description	Position, velocity and Attitude metrics	Horizontal, 95th [m, m/s, deg]	Horizontal, 99th [m, m/s, deg]	3-D norm, 95th [m, m/s, deg]	3-D norm, 99th [m, m/s, deg]
FT-0010-Earth	Nominal Rover Operations, 0.25m/s, Day, Lunar South Pole	Position	5.84	7.82	5.91	7.94
		Velocity	0.089	0.13	0.093	0.13
		Attitude	0.69	1.13	1.92	2.98
FT-0010-Moon		Position	7.42	7.60	7.43	7.60
		Velocity	0.18	0.26	0.18	0.27
		Attitude	1.09	1.57	1.39	2.07
FT-0020-Earth	Nominal Rover Operations, 0.25m/s, Night, Lunar South Pole	Position	7.68	9.50	7.76	9.54
		Velocity	0.10	0.15	0.11	0.15
		Attitude	1.93	2.53	19.43	21.64
FT-0020-Moon		Position	10.88	11.59	10.88	11.61
		Velocity	0.17	0.25	0.18	0.26
		Attitude	1.45	3.59	6.71	9.97
…						

Main Lessons Learned

Findings

The best navigation performances achieved (95th percentile) were:

Metric	**Best Earth Configuration**	**Best Moon Configuration**
3D Position Error	< 6 m	< 8 m
3D Velocity Error	< 0.1 m/s	< 0.2 m/s
3D Attitude Error	< 2°	< 2°

The activity also highlighted several limitations and future development needs:

- ❑ RF geometry and signal availability remain the dominant drivers of navigation performance.
- ❑ Relative sensors (IMU, VO) improve continuity and robustness but do not significantly improve absolute global positioning.
- ❑ 3 RF measurements + DEM constraints were required for stable dynamic operation.
- ❑ Bias-dominated RF errors (SISE) remain one of the main challenges for Lunar PNT.

Key Outcome of the Activity

Main technical outcomes

The **LUPIN** activity successfully demonstrated a hybrid **Lunar Position, Navigation and Timing (PNT)** solution combining:

- ❑ RF-based absolute positioning (LCNS / GNSS), IMU, VO, celestial navigation, and Digital Elevation Model (DEM) aiding.

The developed **ANIME platform** was validated through:

- ❑ representative terrestrial analogue testing,
- ❑ real rover operations and realistic Lunar RF simulation using the **LUSIM** environment.

The developed **PNT** engine successfully operated under:

- ❑ limited RF signal visibility,
- ❑ degraded satellite geometry, with high GDOP conditions,
- ❑ long-duration rover traverses,

Operational Benefits of LCNS

In the context of Lunar Rover Navigation

The activity demonstrated that MoonLight / LCNS services can provide significant operational benefits for future Lunar surface missions.

- **LCNS measurements provide a direct real-time link between the rover local map and a global reference frame**
- **Capability fundamental for long-range rover traverses and persistent localisation over extended operations.**
- **LCNS enabled longer and faster traverses and higher rover traverse speeds.**
- **The results indicate that future Lunar rovers could operate over significantly longer distances with reduced operational complexity.**

Future Work

Conclusions

Specialisation, systematic tuning and **PNT improvements**

- ❑ Focus on fewer use cases and Perform **dedicated filter tuning**
- ❑ Improved VO use, solve attitude state instabilities

Increased signal availability (multi-constellation)

- ❑ Extend scenarios with additional Lunar PNT providers, such as NASA's and JAXA's

Differential corrections from external sources

- ❑ Integrate correction data from a lunar surface stations (e.g. NovaMoon) to mitigate dominant bias-driven errors (SISE)

Closed-loop integration with rover GNC and **LCNS signal-level simulation**

- ❑ Move from open-loop to **full GNC integration**
- ❑ Prototype LunaNet-compatible receiver to potentially explore experimental validation, e.g. using drone-based LunaNet's RF transmitter

Thank you

Steven Kay (skay@gmv.com)

Danilo Forte (danilo.forte@gmv.com)