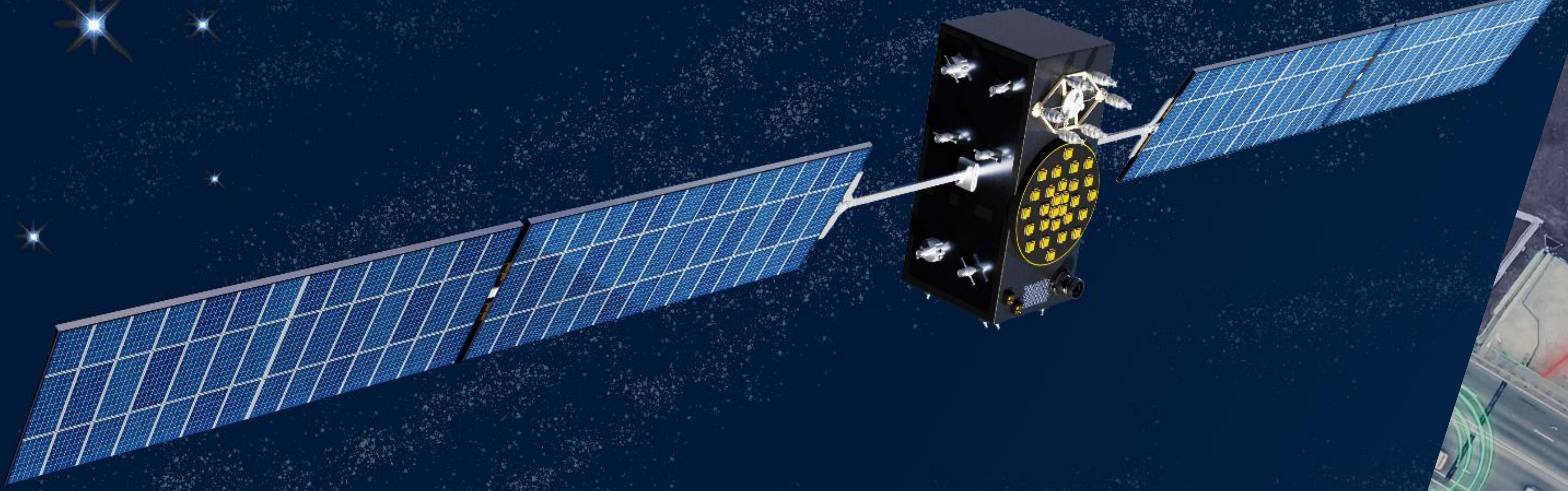
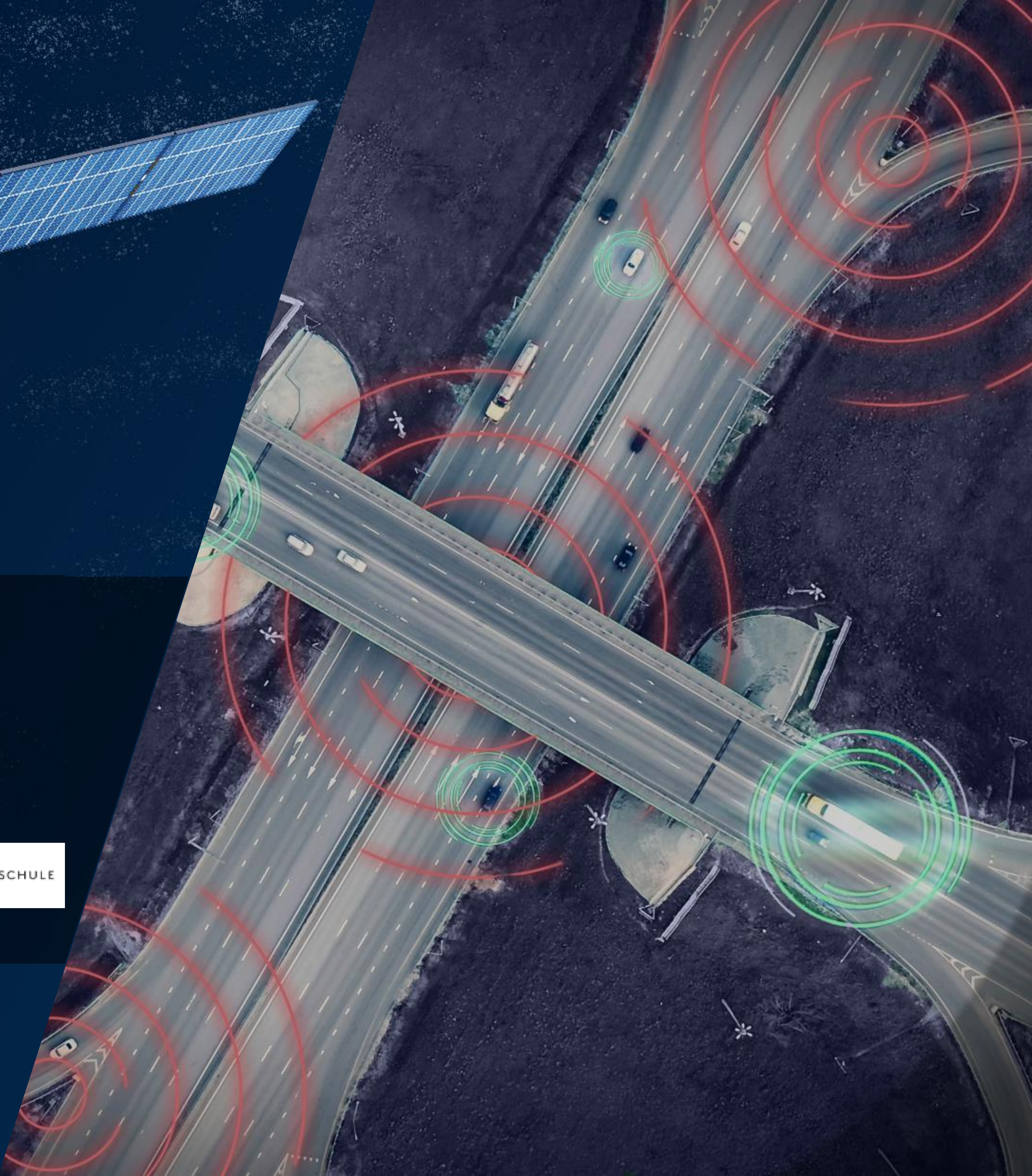




Nav4FutureMobility (N4FM) - Final Presentation

NAVISP Element 2
EL2-156

20.08.2025

Agenda - Final Presentation Nav4FutureMobility

Time	Topic	Speaker
14:00 - 14:05	Welcome	**Gonzalo Martin de Mercado** ESA NAVISP Element 2 Manager
14:05 - 14:10	Project Introduction	**Jose Vicente Perello Gisbert** Technical Officer, ESA
14:10 - 15:00	• Project Scope (DiMOS) • Vehicle Simulator (OTH) • Nav Simulator (ANavS) • Mobility Data Center (DiMOS) • Test Results (DiMOS) • Conclusion and next steps (DiMOS)	**Prof. Christian Arbinger** CEO, DiMOS Operations GmbH **Maximilian Möbes** Chief Engineer, DiMOS Operations GmbH **Philipp Bolig** Team Lead GNSS, ANavS GmbH **Mathias Gerstner** Software Developer, OTH Regensburg
15:00 - 15:30	Questions & Answers	<u>Moderator:</u> **Jose Vicente Perello Gisbert** Technical Officer, ESA

Project Partners - Nav4FutureMobility

DiMOS Operations GmbH (Prime)

- DiMOS Operations GmbH is a spin-off of the German Aerospace Center (DLR), founded in 2020, that specializes in enabling safe and efficient autonomous vehicle operations bringing advanced positioning, navigation and timing (PNT) services, such as an GNSS early warning service, on the road using aerospace-derived technologies.

ANavS GmbH (Subcontractor)

- ANavS GmbH (Advanced Navigation Solutions) was founded in 2011 and has three lines of business: precise positioning systems, precise mapping systems and snow monitoring systems. The core of the ANavS positioning systems is a modular and flexibly configurable sensor fusion of GNSS, inertial, odometry, UWB, camera and Lidar measurements.

OTH Regensburg (Subcontractor)

- OTH Regensburg (Ostbayerische Technische Hochschule Regensburg) is a research-intensive university of applied sciences in Bavaria with eight faculties and ~11,000 students, offering more than 30 bachelor's and 20+ master's programmes across engineering, computer science, business, social & health sciences, and design.

Introduction - Nav4FutureMobility
Why are safe & secure PNT services essential for automated Mobility?

Introduction - Nav4FutureMobility
German Law for Automated Driving (§AFGBV): Operational Domain Monitoring

Technical supervision

- In planning: Approved operating area (route)
- Weather warning (speed reduction)
- Degraded/disrupted navigation
- Detection of non-cooperative road users
- Degraded/disrupted communication (L4 -> L3)
- Technical supervision
- Dynamic Geofence (BOS activity)
- System limit, minimum risk state is activated

Introduction - Nav4FutureMobility

Project Goals

- ➢To ensure accurate, reliable, and secure positioning using mixed GNSS and simulated LEO-PNT data
- ➢To develop a prototype (TRL3) Technical Supervision System in compliance with the German Act on Autonomous Driving (§AFGBV) and anticipated EU-level regulations (EU 1426)
- ➢To demonstrate the viability of remote supervision as an enabler for Level 4 automation in public transport and logistics use cases
- ➢To improve navigation robustness through real-time performance monitoring and threat detection mechanisms

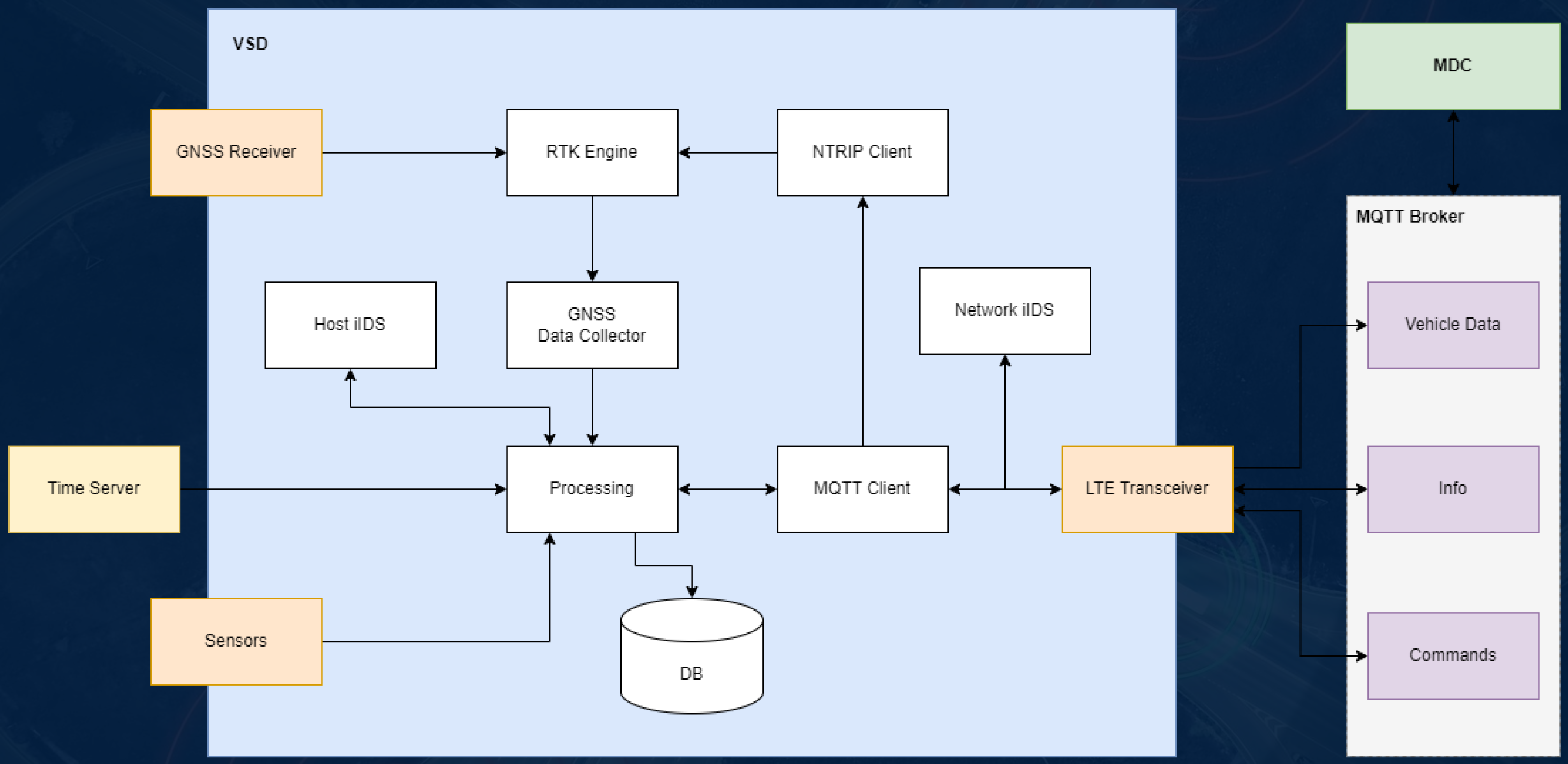
VSD Hardware Setup

Vehicle Simulator Demonstrator:
for Level 4 Navigation
and Communication

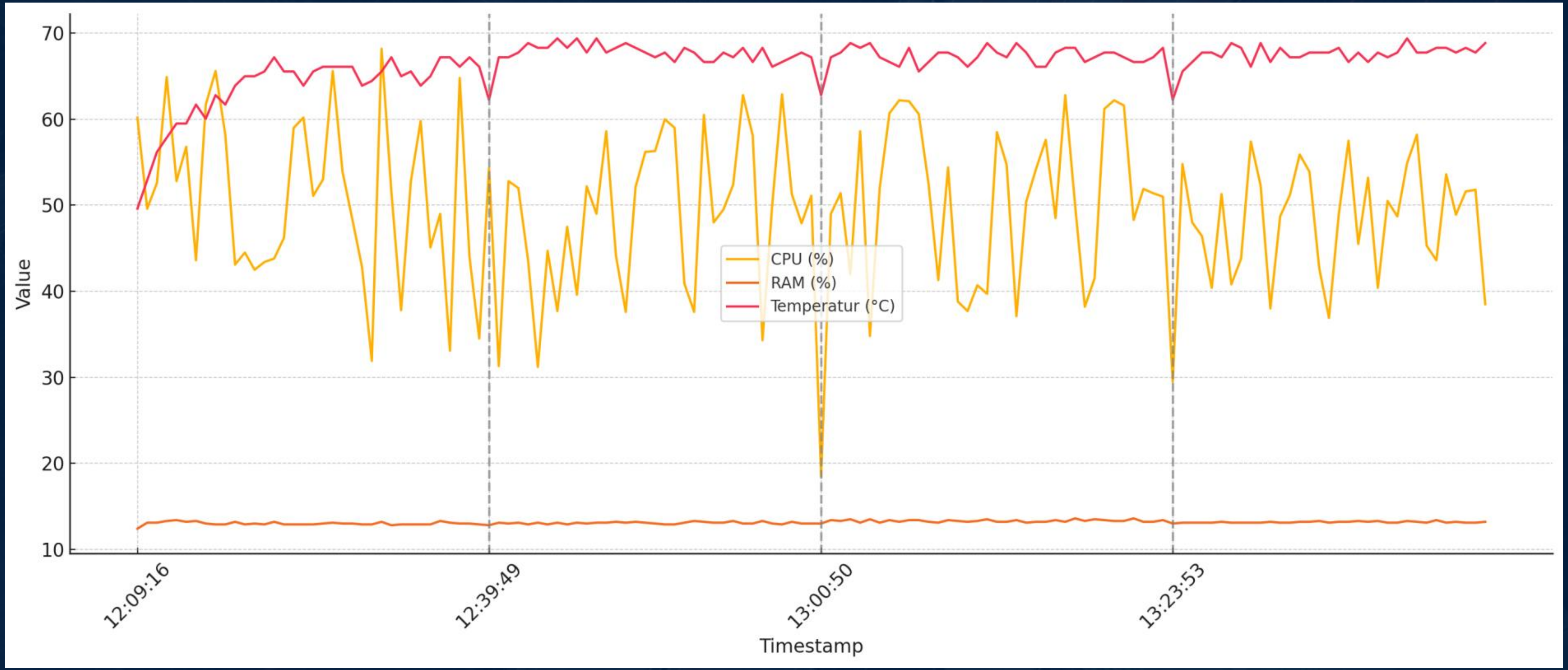
Hardware parts:

- Raspberry Pi5 (8GB RAM)
- GNSS Receiver ublox ZED-F9R
- Active ublox multi-band antenna
- LTE/5G-Transceiver Teltonika RUTX50
- Touchscreen Display
- Mobile Power Supply

VSD System Overview

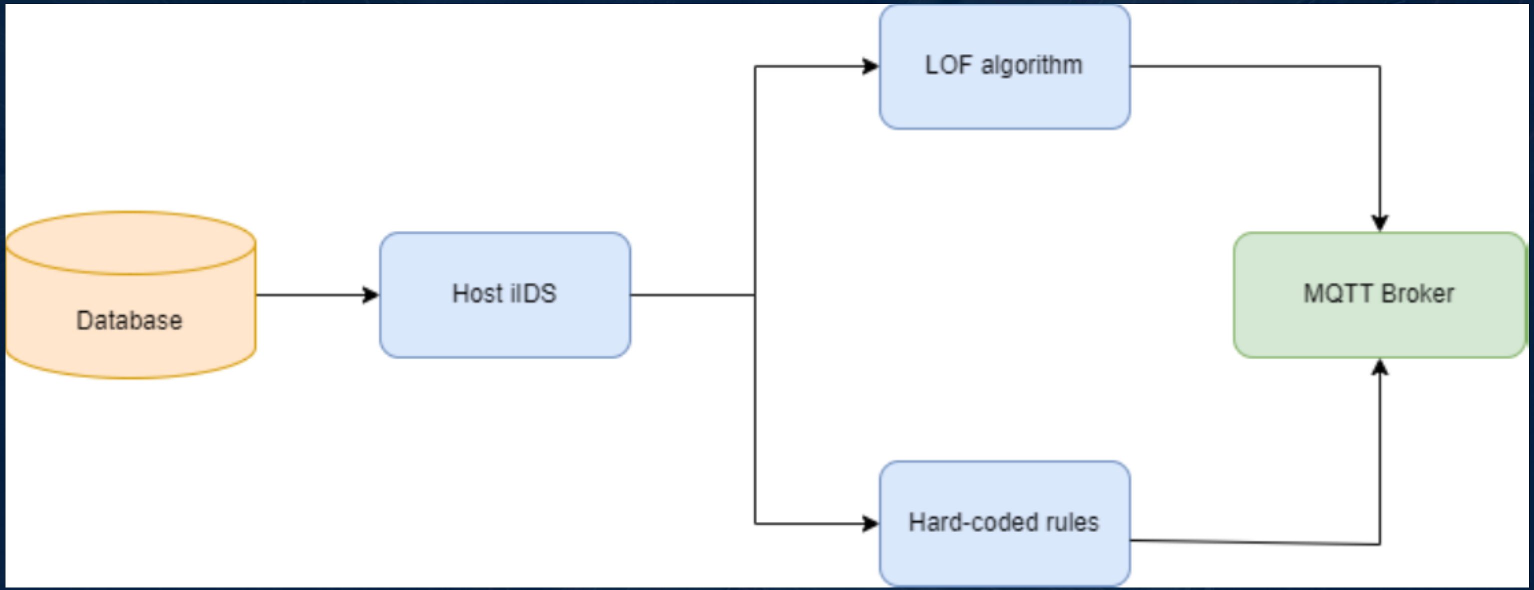


VSD System Monitoring



Long-term test:
System monitors critical parameters and reports threshold violations via MQTT to the MDC

iIDS Architecture



Local Outlier Factor (LOF) Algorithm:

- Anomaly detection method
- Measures local deviation of data points compared to neighbors

Hard-coded rules:

- Use predefined thresholds to identify anomalies
- Compare measured values against fixed limits

GNSS Values and Thresholds

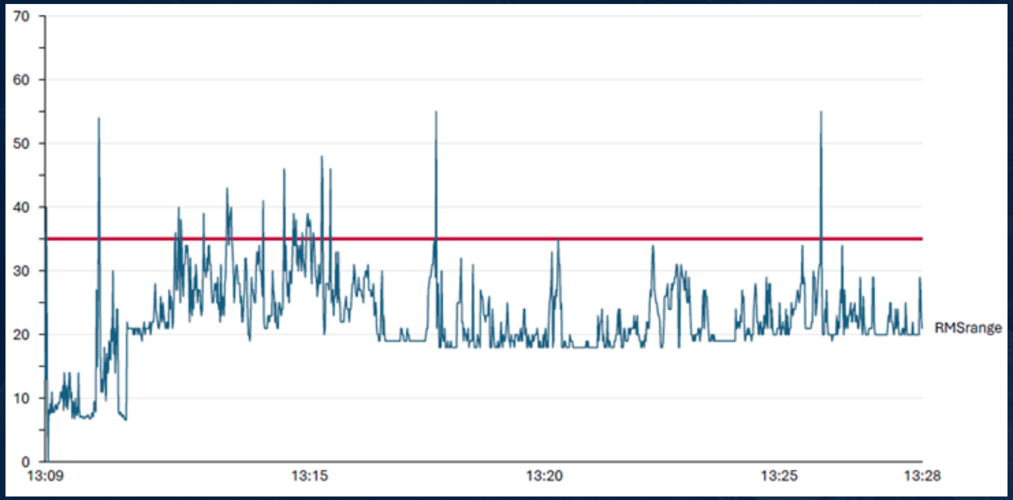
Index	Value	Threshold	Measurement	Sentence	Index in Sentence
0	Timestamp	>1 sec		GNRMC	1
1	Speed	Variable (ML)	Variable (ML)	GNRMC	7
2	Latitude	Variable (ML)	Variable (ML)	GNGGA	2
3	Latitude Hemisphere	-	-	GNGGA	3
4	Longitude	Variable (ML)	Variable (ML)	GNGGA	4
5	Longitude Hemisphere	-	-	GNGGA	5
6	Altitude	Variable (ML)	Variable (ML)	GNGGA	9
7	PDOP	>6.0	10.0 - 25.0	GNGSA	15
8	HDOP	>4.0	0.75 - 1.52	GNGSA	16
9	VDOP	>4.0	0.42 - 0.93	GNGSA	17
10	Num Sats GPS	<4	1 - 14	GPGSV	3
11	Num Sats Galileo	<3	1 - 10	GAGSV	3
12	RMS Range	>10.0	6.2 - 68.0	GNGST	2
13	Std Major	>3.0	1.4 - 5.3	GNGST	3
14	Std Minor	>2.0	0.97 - 3.3	GNGST	4
15	Angle Major	-	1.2 – 180.0	GNGST	5
16	Std Lat	>1.5	0.53 - 1.6	GNGST	6
17	Std Lon	>2.0	0.43 - 2.0	GNGST	7
18	Std Alt	>3.0	1.0 - 2.0	GNGST	8

Simulating a Jamming Attack

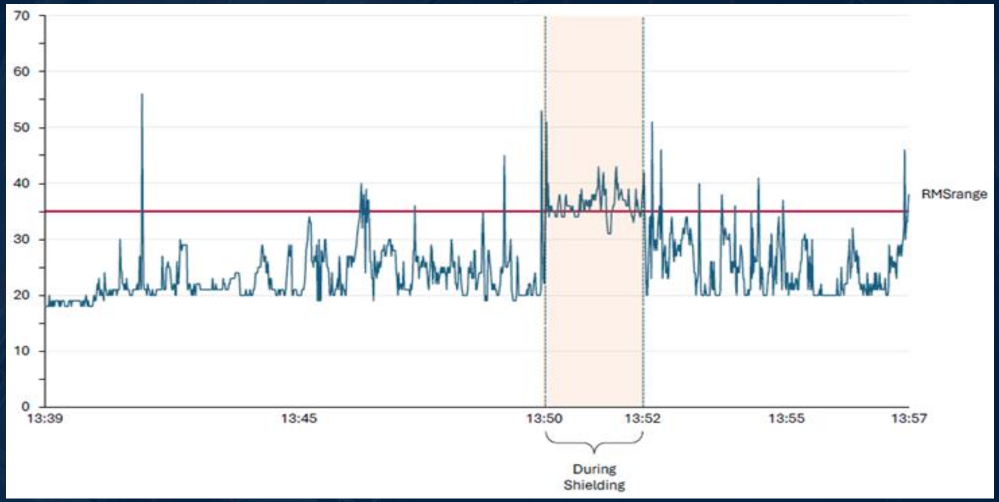
- GNSS receiver was shielded for 2 minutes
- Satellite signals were temporarily weakend

Results of the Hard-coded rules

Drive 1



Drive 2



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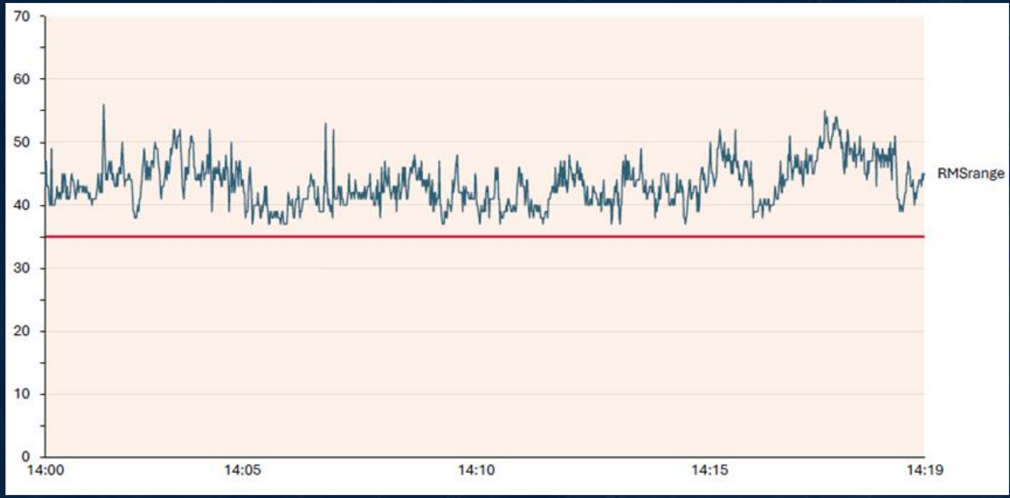

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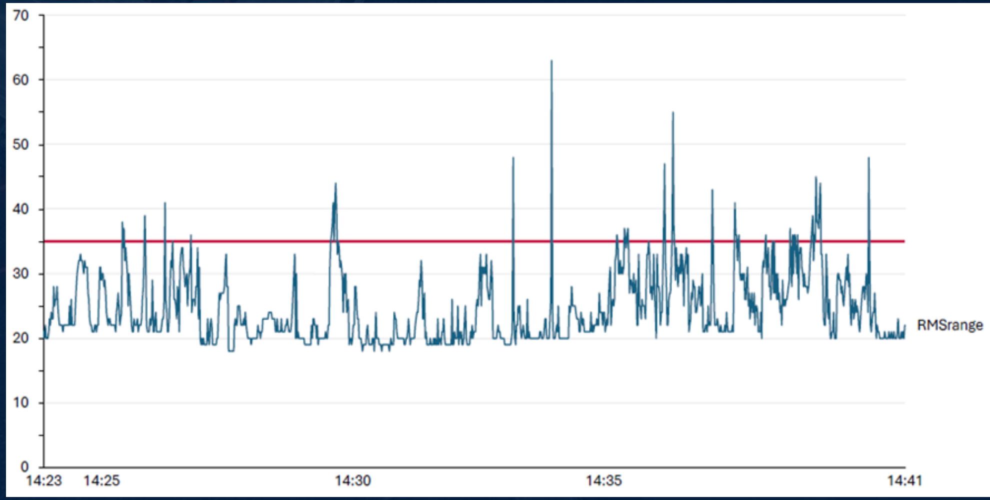
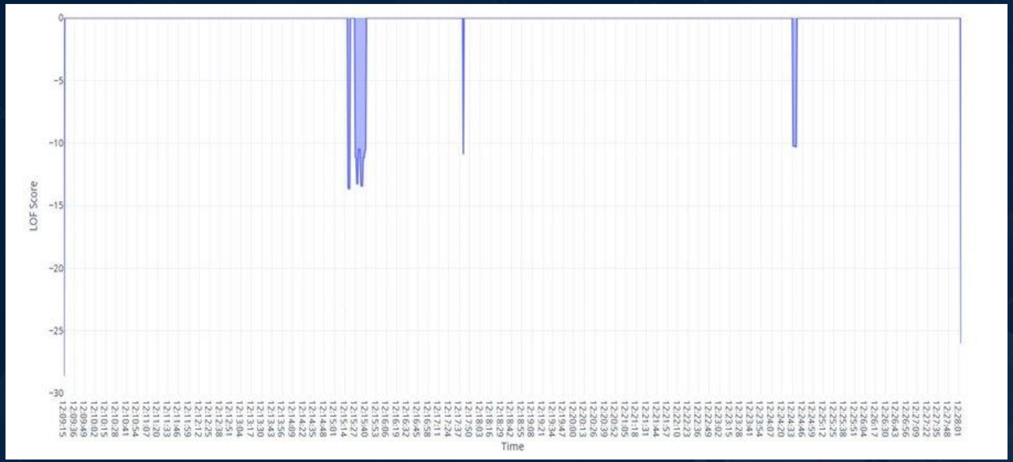


Results of the LOF Algorithm

Drive 1



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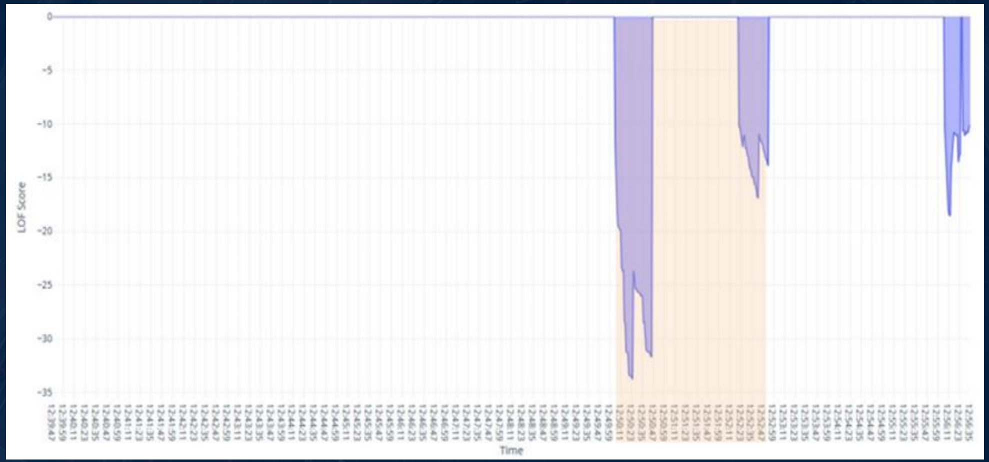

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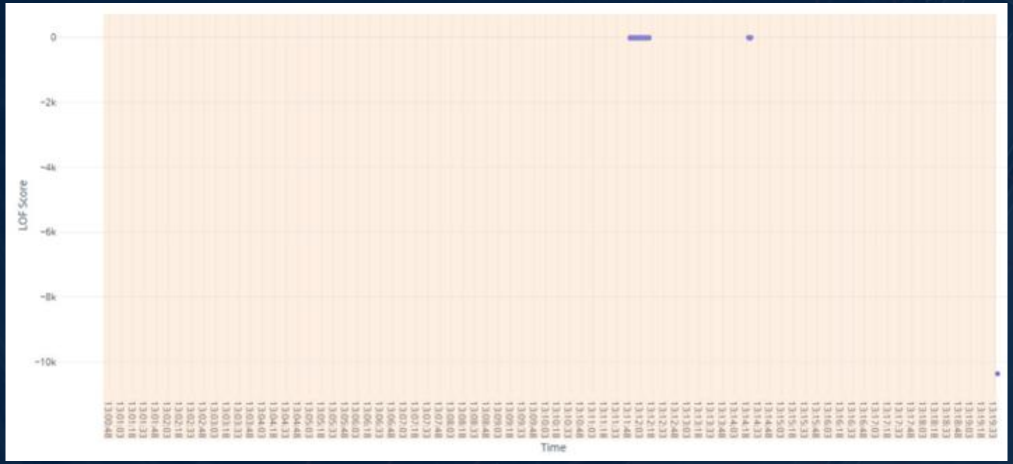

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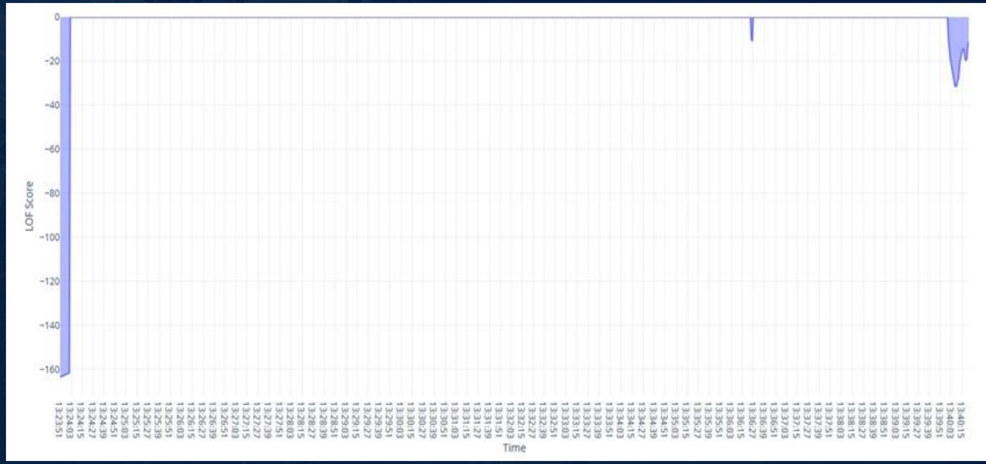
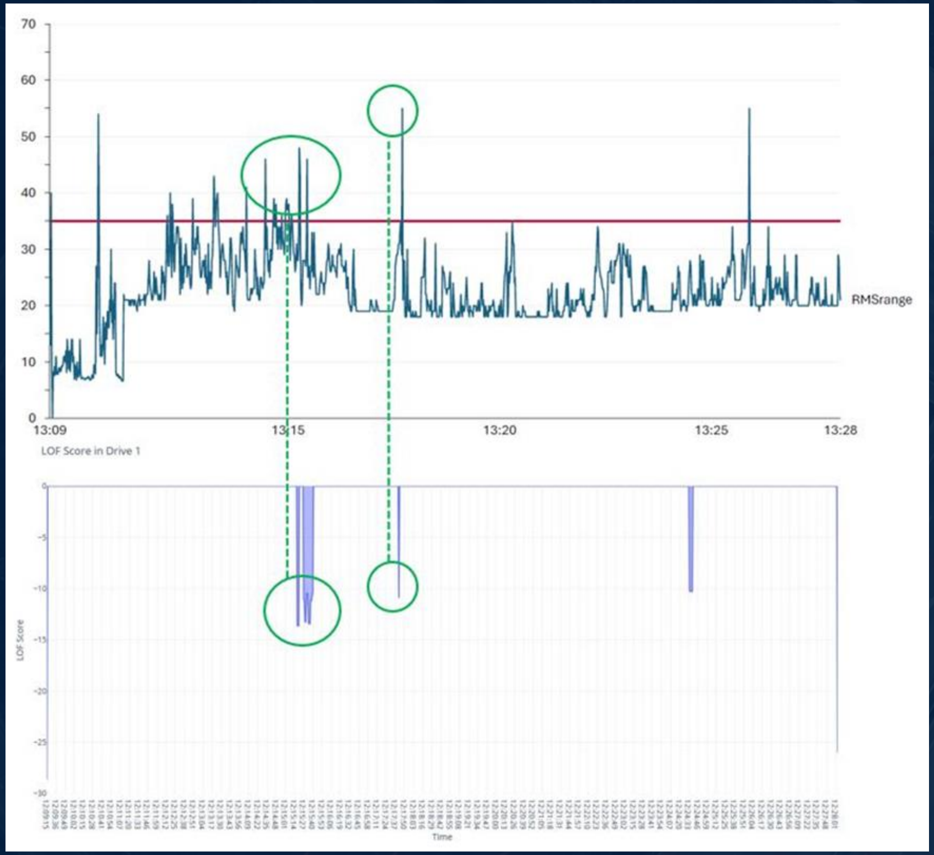
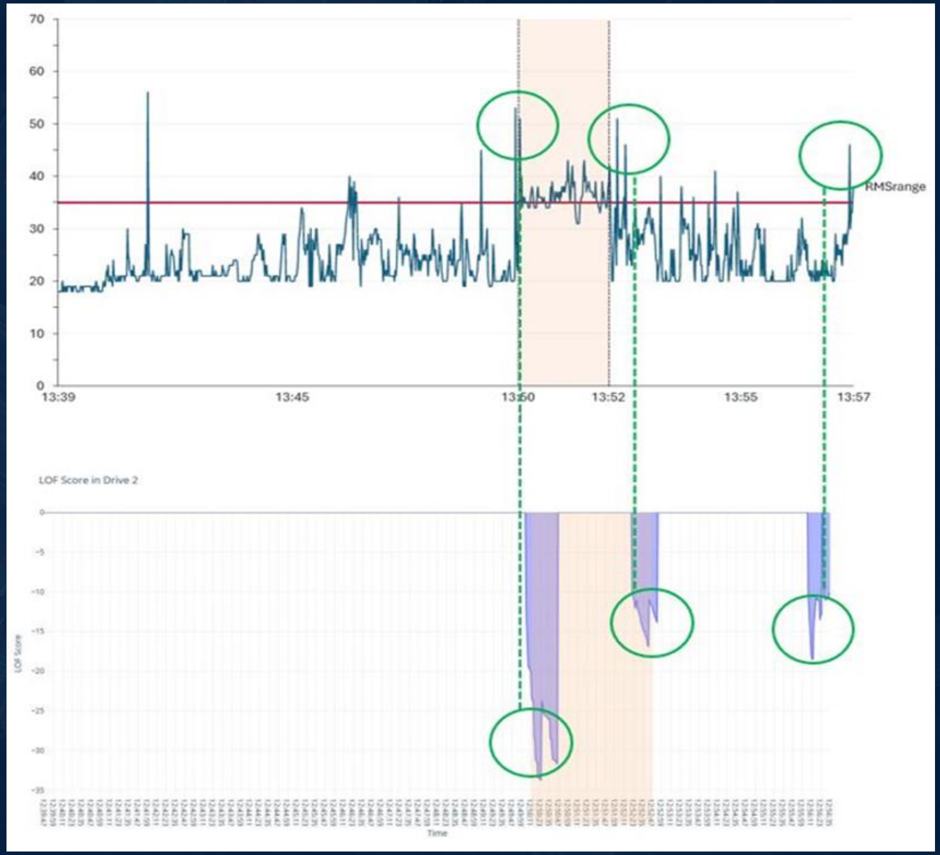


Combining Hard-coded rules and LOF Algorithm

Drive 1



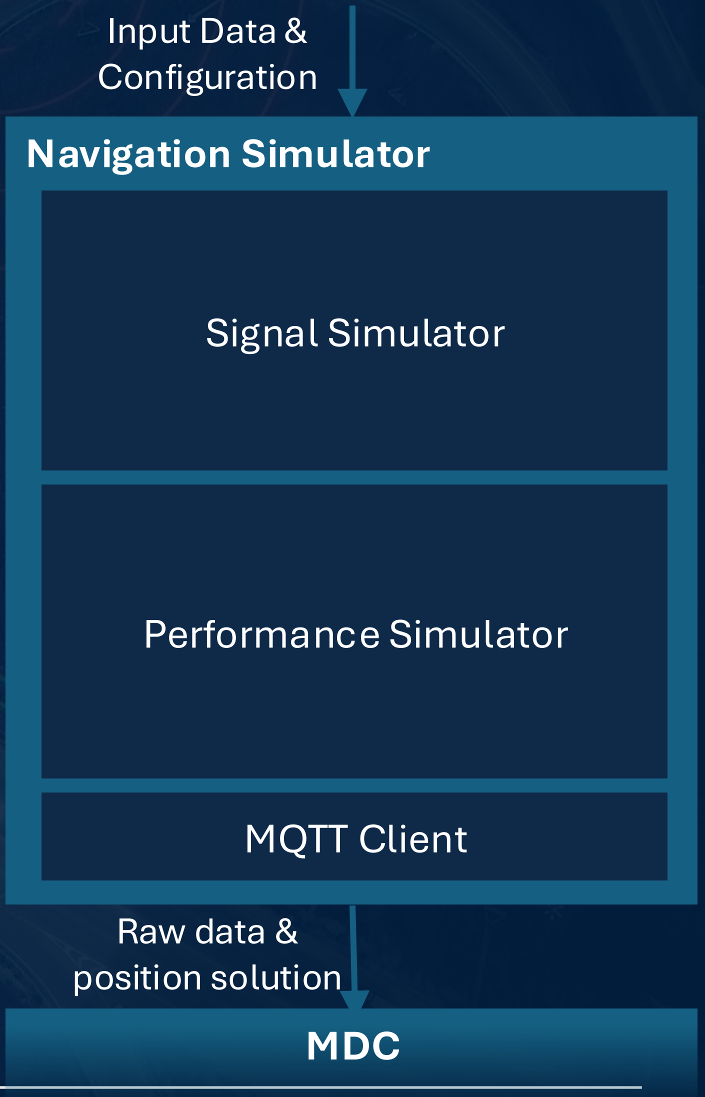
Drive 2



Navigation Simulator by ANavS

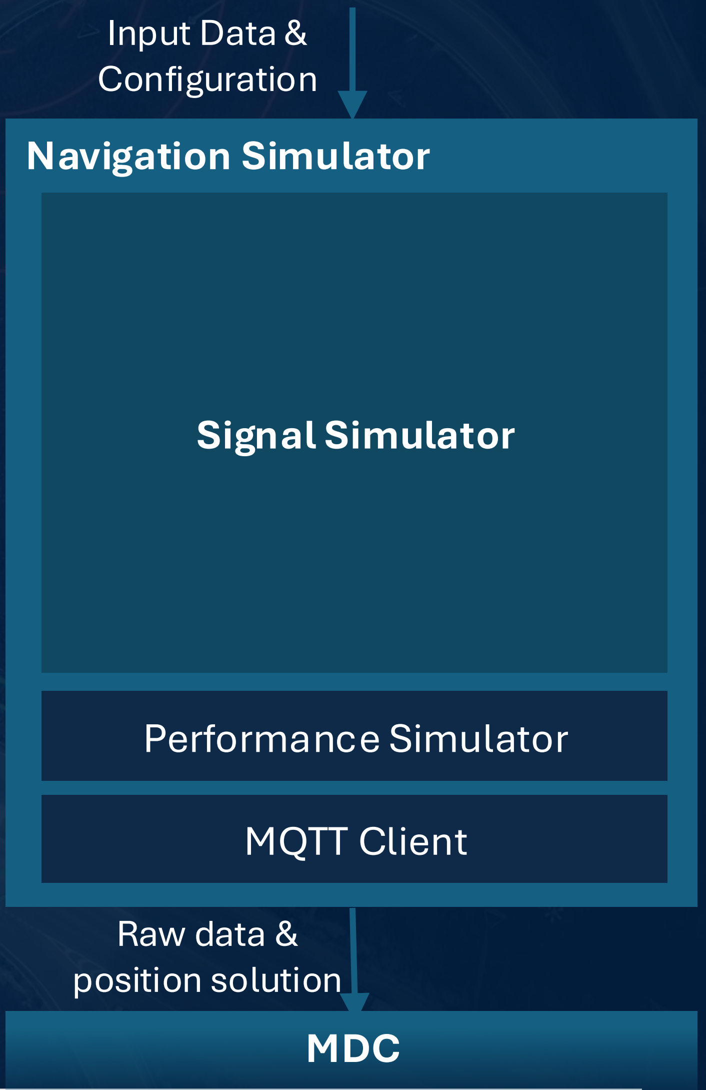
- Objective:
  The Navigation-Simulator was developed to ***generate high-fidelity simulated navigation data*** *to enhance testing capabilities for autonomous driving applications within the N4FM project. It enables* ***controlled, repeatable, and configurable test scenarios*** *in corporation with real-world data.*

- Key Features
  - Simulate **Galileo**, **GPS** and **LEO-PNT** constellations and respective GNSS observations
  - Optional **multipath simulation** using real recorded GNSS signals
  - Simulation of **irregular faults**, **signal delays** and **receiver noise** for all constellations
  - Seamless **integration with the Mobility Data Center (MDC)** for combined performance analysis



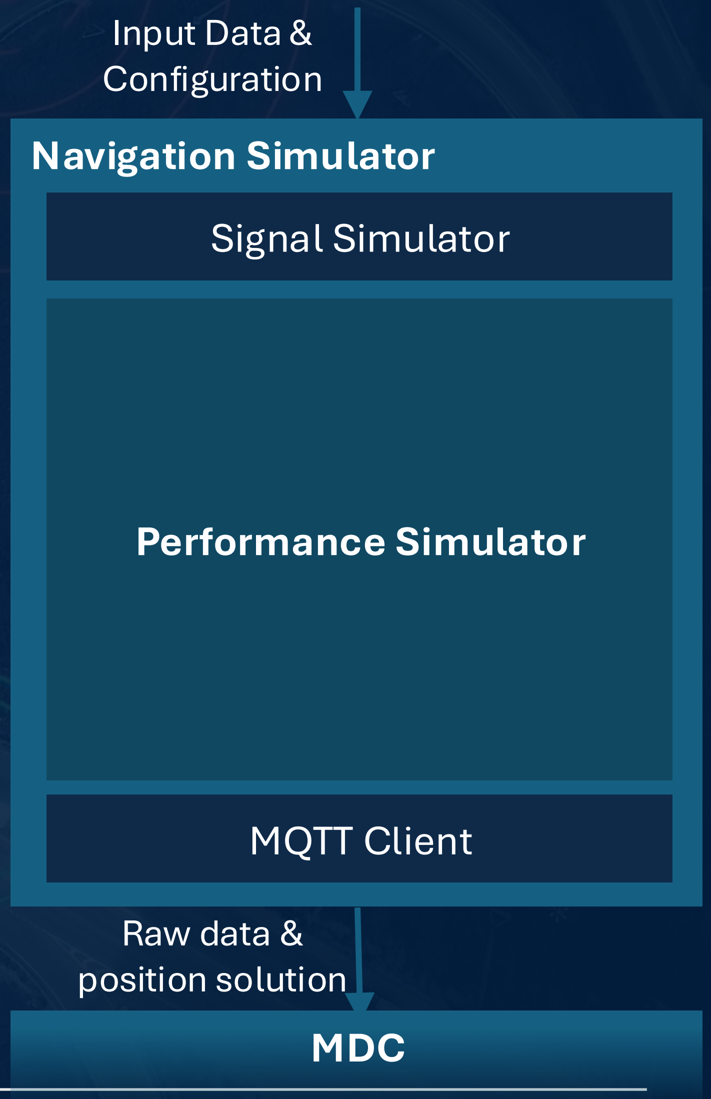
Navigation Simulator by ANavS

- **Signal Simulator**
  - Generates GNSS (GPS, Galileo) and LEO-PNT observations for:
    - Static or dynamic receiver
    - Simulated RTK reference station for correction data generation
  - Models diverse signal effects to replicate real-world conditions:
    - Atmospheric delays (ionospheric and tropospheric propagation effects)
    - Multipath effects using both analytical models and extracted from recorded GNSS measurements
    - Receiver noise and irregular signal faults
  - Offering high degree of configurability
  - Encodes all simulated observations into data streams for MDC ingestion and Performance Simulator



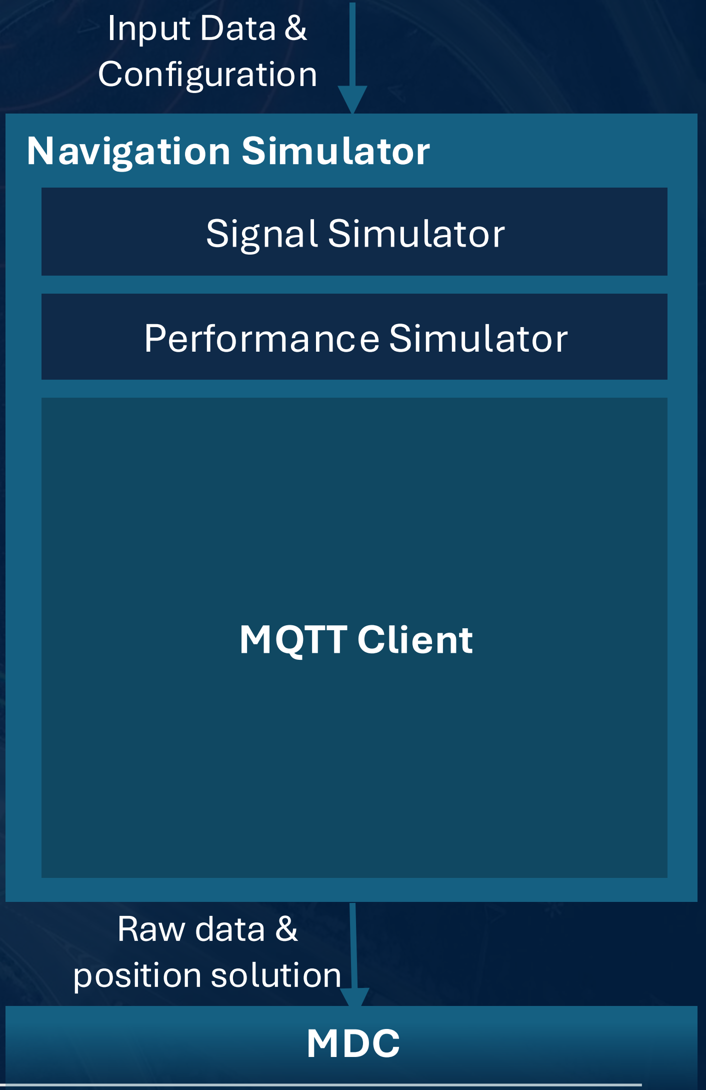
Navigation Simulator by ANavS

- **Performance Simulator**
  - Processes simulated GNSS and LEO-PNT observations to perform **state estimation** of position, velocity and further estimates
  - Implements **fault detection and exclusion (FDE)** algorithms and **Protection Level (PL)** calculations for navigation integrity monitoring
  - Can run both in Real-Time Kinematik (RTK) and "Precise-Point-Positioning (PPP)" Mode
  - Enables verification that system performance meets **autonomous driving operational limits** under normal and degraded conditions



Navigation Simulator by ANavS

- **MQTT Client**
  - Responsible for data transfer to the Mobility Data Center (MDC) via MQTT:
    - Raw GNSS & LEO-PNT observation data from the Signal Simulator
    - Position solutions with associated integrity metrics from the Performance Simulator



Navigation Simulator by ANavS

- **Simulator enables great support to analyze reaction to various faults and to e.g., compare the robustness with and without LEO-PNT**
- **Results**
  - Consistent accuracy improvement across all test runs when LEO-PNT are included
  - Improvements are especially pronounced in situations with simulated irregular

With LEO-PNT / Without LEO-PNT	Median Horizontal position error [m]	Median vertical position error [m]
run 1 & 2	0.34 / 0.52	0.29 / 0.42
run 3 & 4	0.39 / 0.54	0.39 / 0.61
run 5 & 6	0.52 / 0.79	0.62 / 2.00
run 7 & 8	0.46 / 0.57	0.38 / 0.66

Table: Position error over all testruns

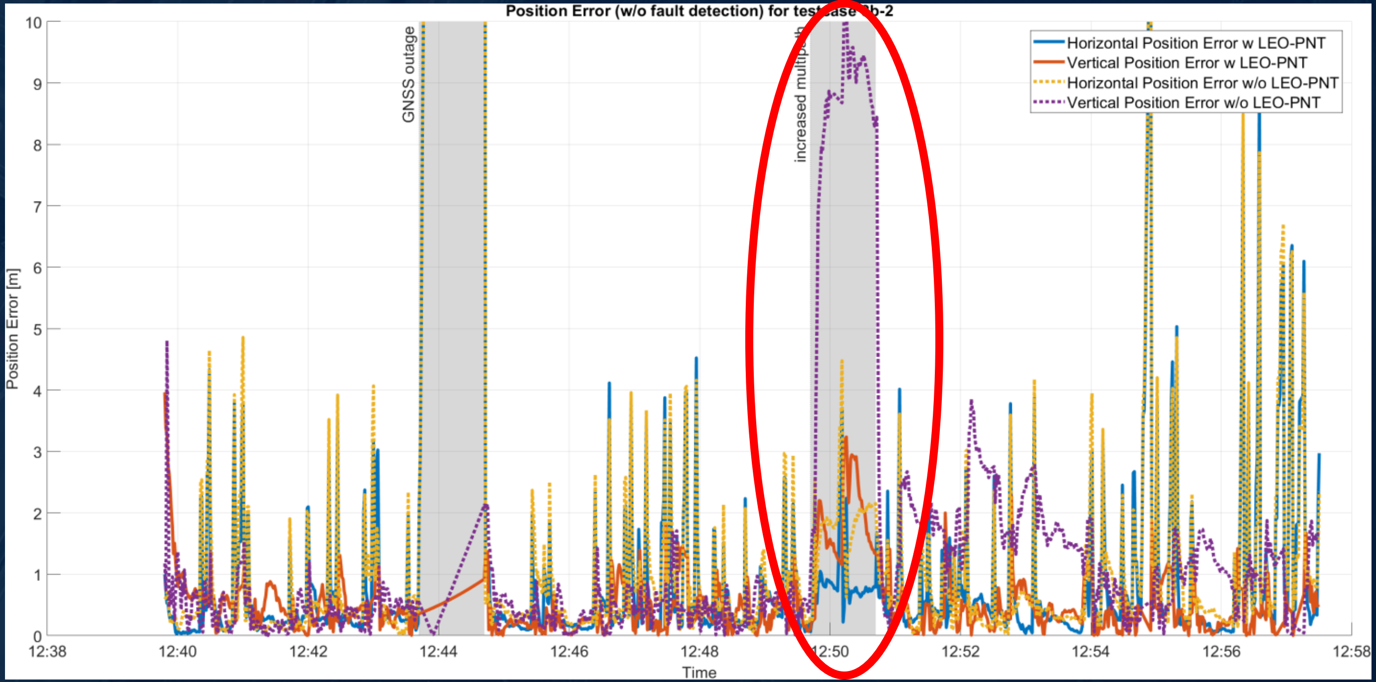
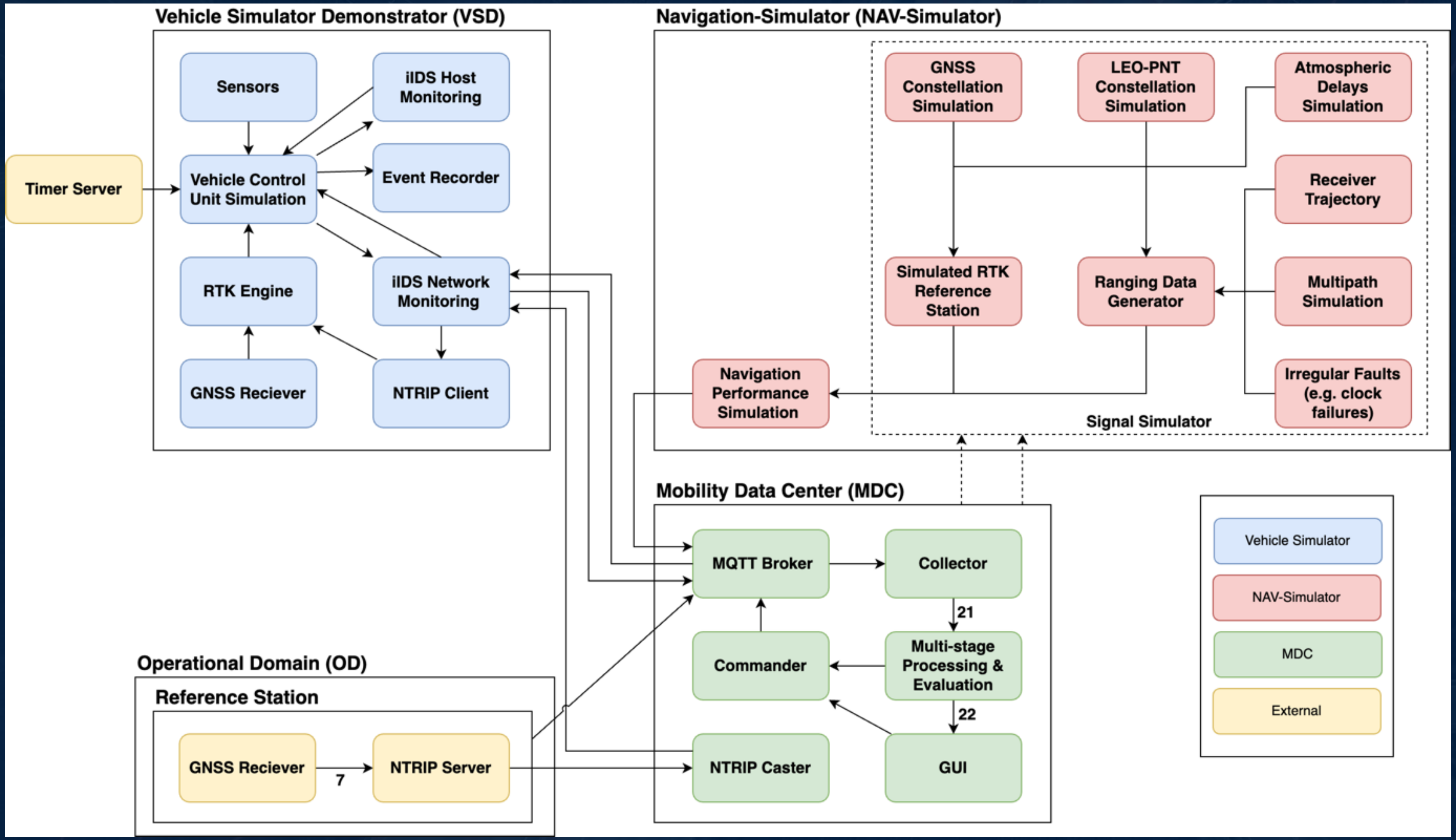


Figure: Position error for Testcase 3B, run 1 & 2
Note: Testcase is based on realGNSS data and contains an increased number of signal outages

Navigation Simulator by ANavS

- **Purpose**: Provide a realistic, configurable, and repeatable test environment for evaluating autonomous navigation solutions with GNSS and LEO-PNT integration.
- **Core Components**:
  - **Signal Simulator** – Generates realistic GNSS/LEO observations under controlled conditions, including atmospheric, multipath, irregular fault and noise effects.
  - **Performance Simulator** – Processes observations to estimate position and perform integrity checks.
- **Key Capabilities**:
  - Simulation of Galileo, GPS, and LEO-PNT constellations
  - Configurable multipath and irregular fault injection
  - Seamless integration with MDC for real-time monitoring and analysis
- **Impact on N4FM**: Enabled safe, cost-efficient testing of challenging scenarios, validated algorithms before field trials, and supported direct comparison between GNSS-only and GNSS+LEO-PNT performance.

System Architecture - Nav4FutureMobility



Mobility Data Center - Nav4FutureMobility

The Mobility Data Center (MDC) features:

- MQTT-Broker (EMQX) for managing communication between system components
- Multi-stage Processing & Evaluation for data analysis and validation, including L4 Conformance and Performance Monitoring functionality to ensure adherence to operational standards
- Collector for gathering and organizing incoming data streams
- NTRIP Caster for distributing RTK corrections
- Commander/Notificator for sending operational commands to vehicles

- GUI for Technical Supervision operators to monitor and interact with the

Mobility Data Center - Nav4FutureMobility

- **GNSS Receiver:** u-blox NEO-F9P-15B-00 paired with Quectel YEGT000W8A antenna
- **GNSS Signals:** GPS & Galileo (L1/E1 and L5/E5a frequencies)
- **Operation Parameters:** Min. satellite elevation 15°, measurement rate 1 Hz
- **Cellular Connectivity:** Quectel RM520NGLAA-M20-SGASA modem + Smarteq TM-710677 antenna
- **Network Access:** Digital-Sim for full German cellular network coverage (Test Case 2)
- **Purpose:** Provides stable GNSS reference points for data validation

Test Results: Overview - Nav4FutureMobility

- Conducted four test cases in simulated and real-world settings to validate navigation system performance

- Used simulations, hardware-in-the-loop, and field tests, progressing from basic checks to complex scenarios for reliability improvement

- Applied structured protocols with clear criteria, ensuring reproducibility and balancing lab control with real-world challenges

- Evaluated navigation performance using metrics critical for autonomous driving - accuracy, availability, continuity, and integrity - while also testing security resilience against signal interference and spoofing

Test Results: Overview - Nav4FutureMobility

- Compared traditional GNSS-only with integrated GNSS/LEO to quantify performance gains

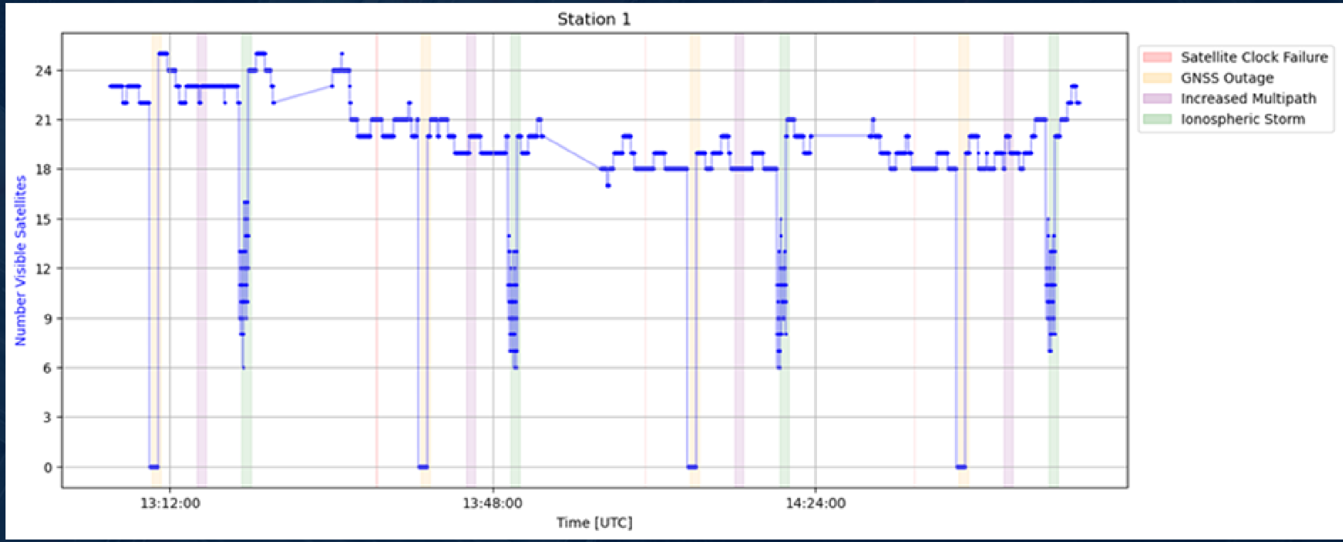
- Collected data from multiple system interfaces, including raw and processed outputs, enabling detailed analysis, troubleshooting, and root cause identification with validated corrective actions

- Findings confirmed current capabilities, highlighted strengths and limitations, and guided future improvements, laying a foundation for advancing positioning technologies in autonomous mobility

Test Case 1 Results:

Test configuration:

- 4 static stations were simulated
- 4 runs each

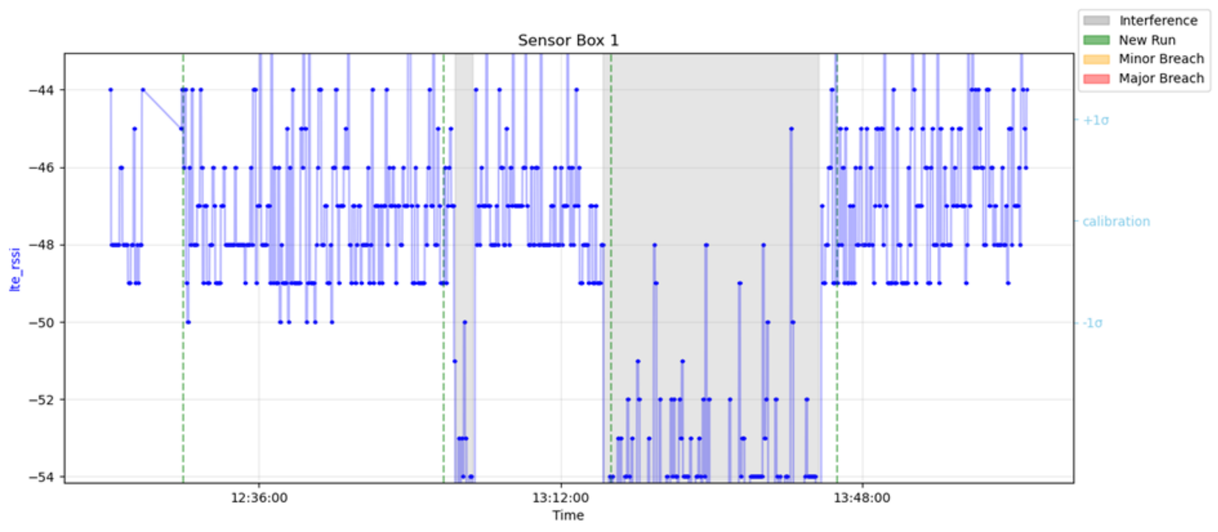


Test objectives:

- Calibration of positioning algorithms
- Verification of system responses
- Validation of message processing
- Establish baseline accuracy

Test Case 2 Results:

Test configuration:
- 4 stations, 6-8 km apart
- 1 VSD, driving at ~80 km/h



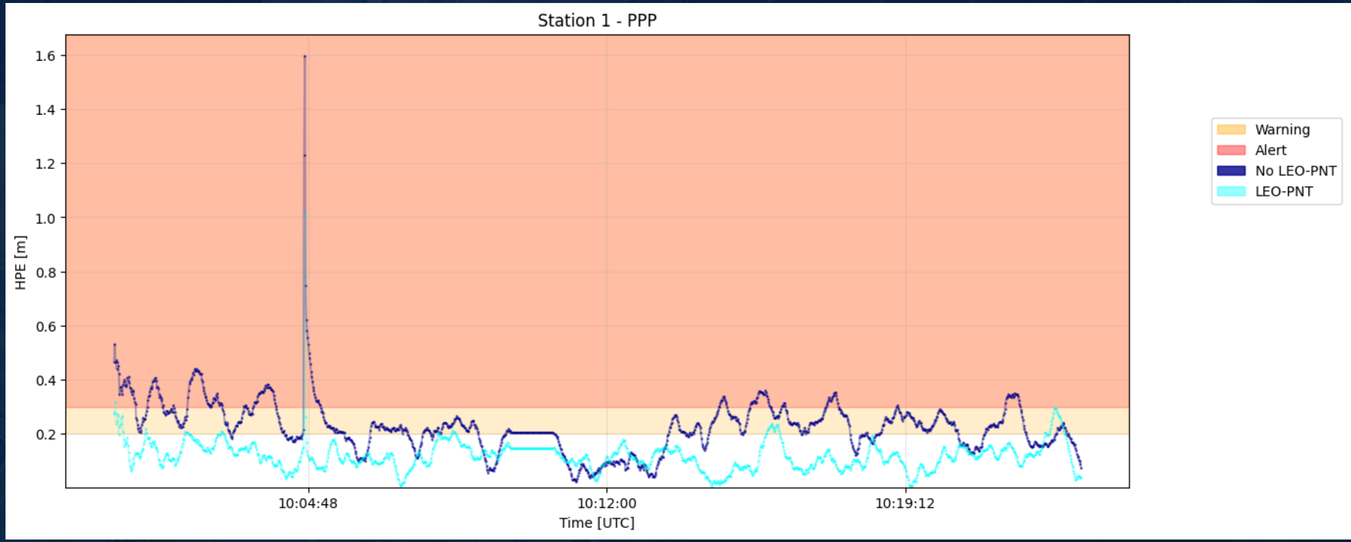
Test objectives:

- Validate hardware prototypes in real-world conditions
- Validate alignment between simulation and real-world

Test Case 3A Results:

Test configuration:

- 4 stations and 1 vehicle were simulated
- 8 runs: 4 without LEO-PNT, 4 with LEO-PNT
- 120 LEO-PNT satellites were simulated



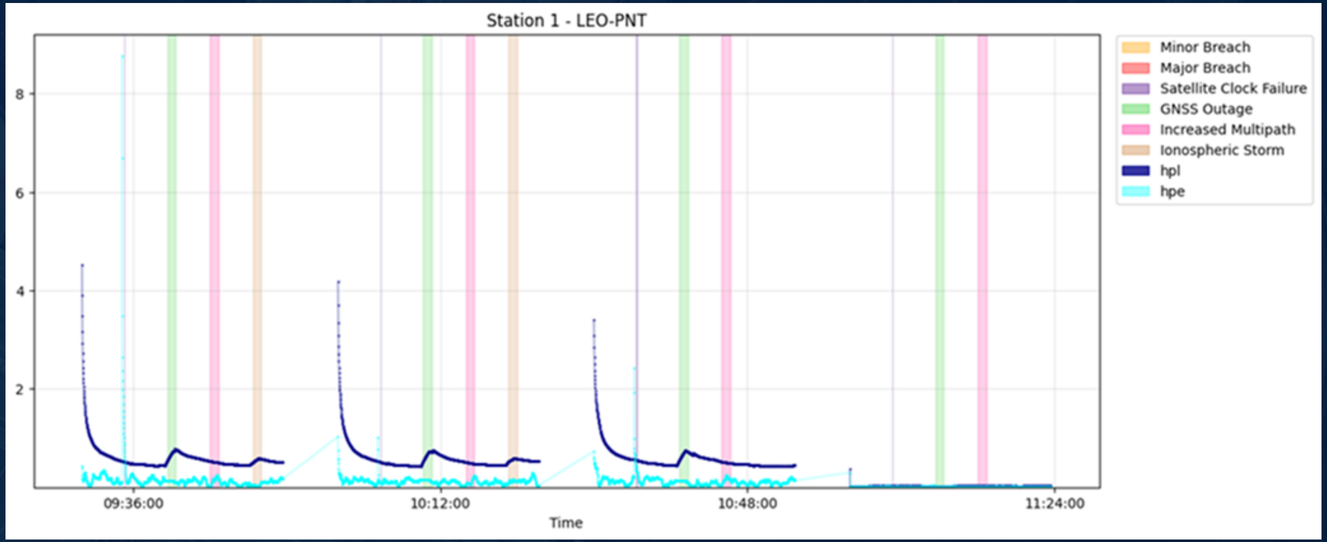
Test objectives:

- Asses performance benefit for LEO-PNT integration

Test Case 3B Results:

Test configuration:

- 4 stations and 1 vehicle were simulated
- 8 runs: 4 without LEO-PNT, 4 with LEO-PNT
- 120 LEO-PNT satellites were simulated
- Simulation used TC2 data as basis



Test objectives:

- Asses overall performance by combining real-world and simulated data

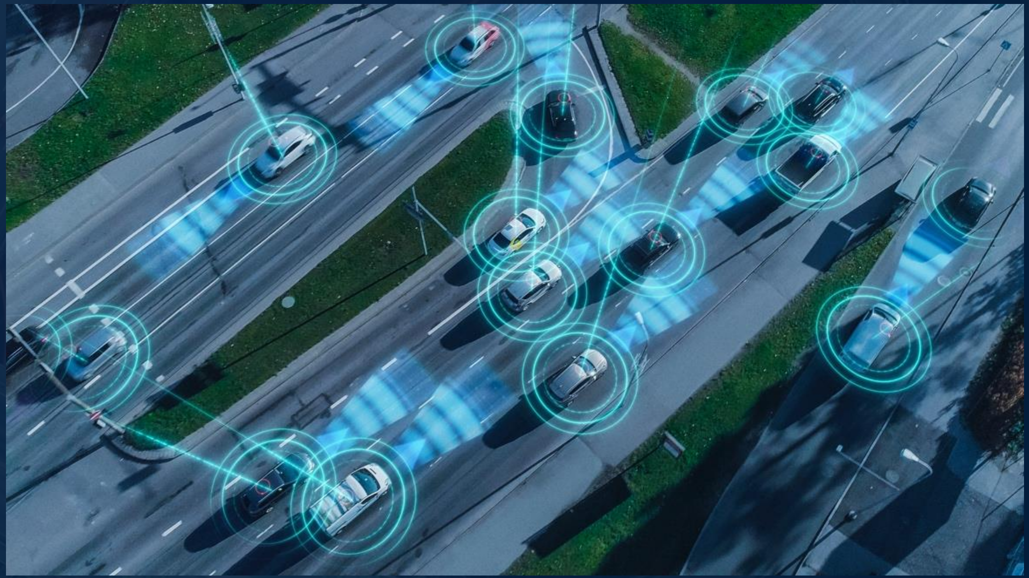
Overall Test Highlights:

- Validated system in simulated and real-world scenarios
- Consistent performance gains from LEO-PNT
- Proofed resilience against various environmental challenges
- Strong simulation-field alignment
- Scalable platform, ready for the future

Multilayer PNT (MEO+LEO) as Enabler for automated Mobility

Additional Benefits of LEO-PNT for Autonomous Driving

- **Augments GNSS** in urban canyons, dense foliage, and contested environments
- **Faster updates**: seconds to first fix, minimal latency for split-second decisions
- **Stronger signals** & **reduced multipath errors** from lower orbit
- **High resilience and Safety**: planned integrity monitoring and early warning service for PNT degradations (jamming/spoofing)



Conclusions

- N4FM has laid the technical groundwork for remote supervision of automated vehicles, a key enabler for SAE-Level 4 operations on public roads.
- Combining GNSS MEO with LEO satellite signals (“Multilayer GNSS”) will significantly improve positioning and timing performance, especially under challenging conditions.
- To scale future mobility solutions, commercial space services must be user-driven: Automotive industry requirements for Positioning, Navigation and Timing (PNT) must shape future LEO-based navigation infrastructures.

Next Steps: NAVISP EL2-245 Project SoLPOINT

DIMOS

The SoLPOINT project focuses on Safety of Life Positioning and Operational Integrity for automated trucks in partnership with MAN Truck & Bus.

- Regulatory Alignment: Supporting national and European regulations (AFGBV, upcoming EU frameworks) for Level-4 automated driving.
- Safety Management System for Safety of Life PNT: Establishing a rigorous safety management framework, adapted from aviation practices, to ensure resilience and reliability.
- Operational Deployment: Transition from concept to real-world validation with trial operations on highways.
- Scalability & Commercial Viability: Preparing for extension from trucks to broader mobility applications (public transport, passenger vehicles, rail, UAS, maritime).

Q&A

Any Questions?

Addendum: Answer for question from audience regarding Protection Levels in simulation

Protection Level		Probability of false alarm	0.01 %
		Probability of missed detection	1e-5 %