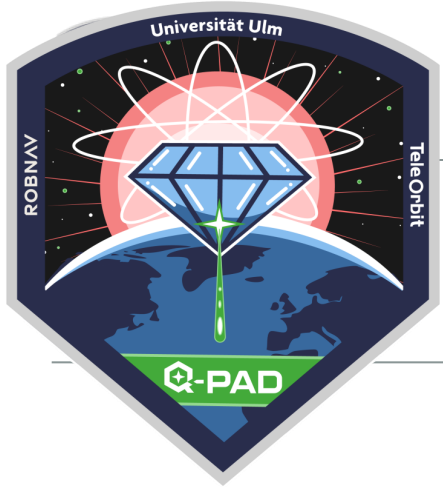




universität
uulm



ROBNAV TeleOrbit

ESA Contract No. 4000148904/25/NL/PS/dg

Q-PAD

AI FOR ANOMALY DETECTION IN MULTI-SENSOR PNT

Final Presentation

Webinar; 20.10.2026

**Daniel Seybold
Jürgen Seybold**

**TeleOrbit GmbH
Nürnberg, Germany**

**Iñigo Cortés
Ross van der Merwe
Marcelo Michael
Andy Marchl**

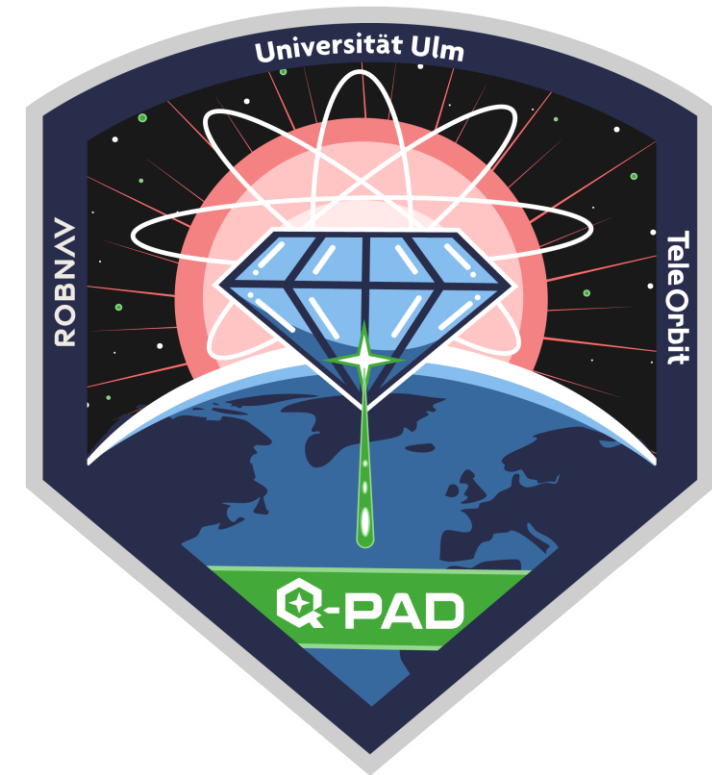
**RobNav GmbH
Nürnberg, Germany**

**Prof. Fedor Jelezko
Rajan Paul**

**Universität Ulm
Ulm, Germany**

Agenda

1. Welcome and introduction (D. Seybold, TOG)
2. Context, Rationale, Overview (D. Seybold, TOG)
3. Q-PAD Outcome (I. Cortes, RN)
4. Conclusion, Exploitation, Feedback (D. Seybold, TOG)
5. Q&A (all)



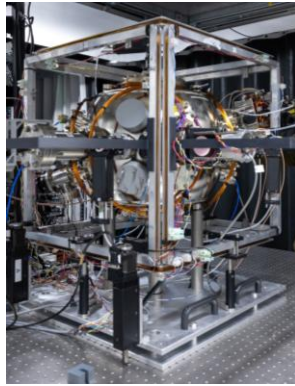
Context and Rationale

“This activity aims to explore and validate how AI can help characterize and detect internal anomalies in quantum sensors, with potential performance exceeding classical anomaly detection algorithms.
(It) synthesizes research exploring *quantum sensing capabilities, AI-driven characterization techniques, and machine learning algorithms for advancing quantum sensor monitoring in PNT applications.*”
(ESA SoW)

Team Experience and Interests

- Years of experience in GNSS and (AI-based) anomaly detection (focus on interference mitigation)
- Keen to explore alternatives to traditional PNT techniques and hardware
- Combine our GNSS knowledge with quantum expertise from University of Ulm and imec

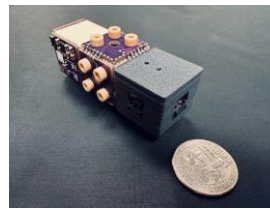
Quantum Sensing in PNT [2]



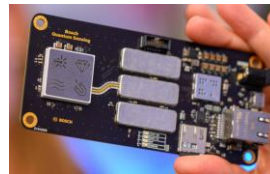
© Thomas Angus / Imperial College London

Quantum accelerometers & gyroscopes

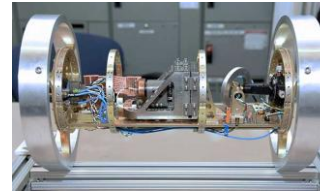
- Measure acceleration and rotation using atom interferometry.
- Full inertial navigation in GPS-denied environments.
- Highly precise and stable over long durations.



© Q-Ctrl



© Bosch quantum sensing



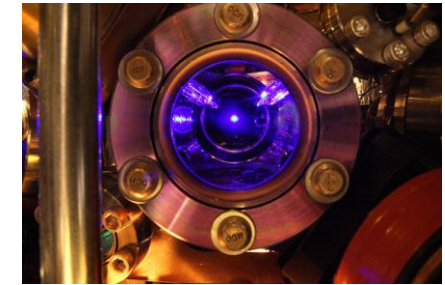
© Lockheed Martin



© IMEC

Quantum magnetometers [3-5]

- Measure magnetic fields with extreme precision ($\sim$ pT)
- Fine heading estimation
- Support magnetic navigation
- Useful in GPS-denied environments



Credit: The Ye group and Brad Baxley, JILA

Quantum clocks

- Next-generation atomic clocks with optical transitions
- Improve synchronization in networks and PNT systems.
- Enhance GNSS resilience and anti-spoofing capabilities.

[2] Degen, C. L., et al. (2017). *Quantum sensing*. *Reviews of Modern Physics*, 89(3), 035002. <https://doi.org/10.1103/RevModPhys.89.035002>

[3] Stürner, F. M., et al. (2019). Compact integrated magnetometer based on nitrogen-vacancy centres in diamond. <https://doi.org/10.1016/j.diamond.2019.01.008>

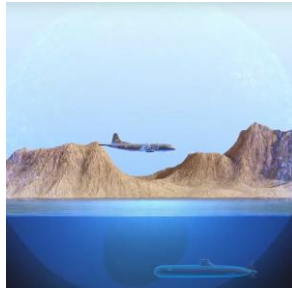
[4] Stürner, F. M., et al. (2021). Integrated and portable magnetometer based on nitrogen-vacancy ensembles in diamond. <https://doi.org/10.1002/qute.202000111>

[5] Hrubý, J., Nesládek, M., et al. (2021). OSCAR-QUBE: Integrated diamond-based quantum magnetic field sensor for space applications, IAC 2021

Quantum Magnetometers for PNT



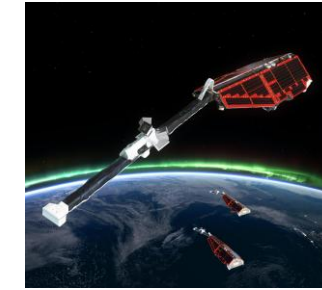
© SPH Engineering



© CAEvideogallery



© Q-CTRL



© ESA/AOES Medialab

Ground & Sea

- Detection of submarines [6]
- Detection of rare materials
- Unexploded ordnance (UXO)

Air

- Magnetic anomaly navigation (MagNav) [7]
- Magnetic SLAM – simultaneous localisation and mapping [8]

Space

- Magnetic field maps
- Geomagnetic storm monitoring
- Alternative orbit determination [7]

[6] Sheinker, A., et al. (2012). Magnetic anomaly detection using high-order crossing method. *IEEE Trans. Geosci. Remote Sens.*, 50(4), 1095-1101.

[7] Quantum Economic Development Consortium (QED-C). *Quantum Sensing for Position, Navigation and Timing Use Cases*. Arlington, VA: SRI International, September 2024. quantumconsortium.org/pnt2024

[8] Lee, T. N., & Canciani, A. J. (2020). MagSLAM: Aerial simultaneous localization and mapping using Earth's magnetic anomaly field. *NAVIGATION: J. Inst. Navigation*, 67(1), 95-107. DOI 10.1002/navi.352

Main Objectives

Simulation environment development

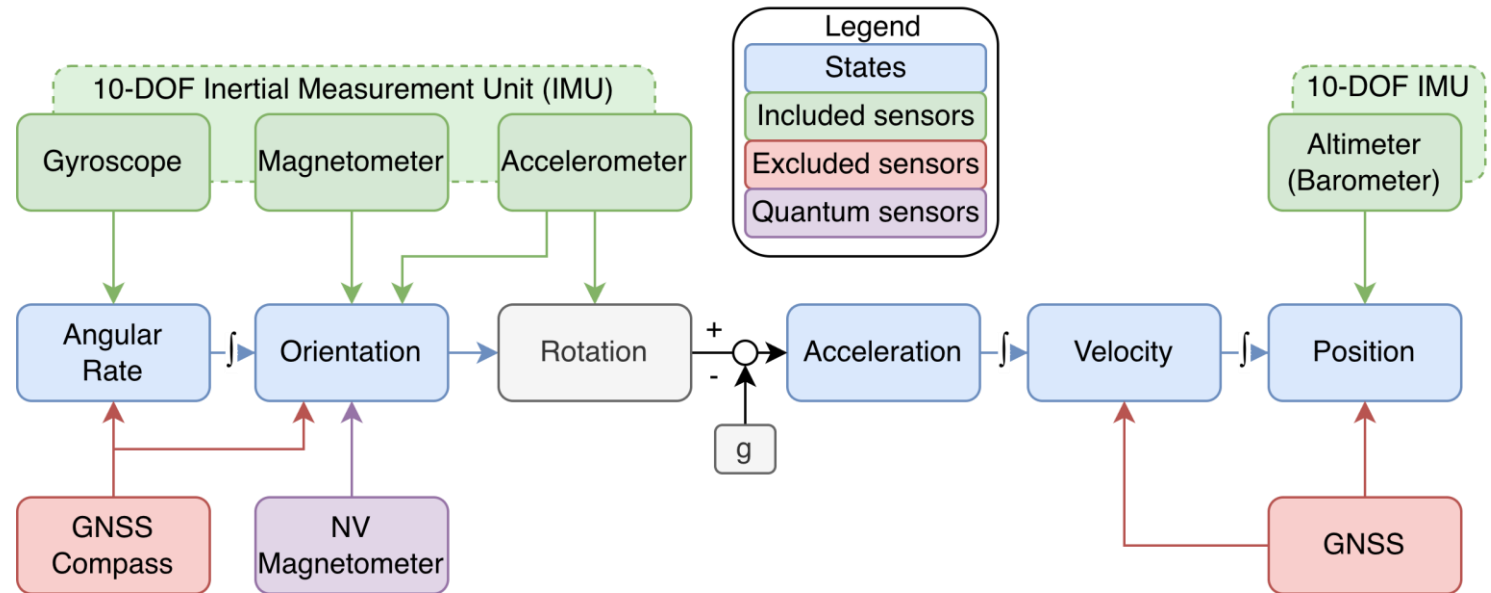
- NV-based quantum magnetometer
- Vapor cell-based quantum magnetometer
- Testbed for AI-based anomaly detection

Hardware integration

- Multi-sensor PNT
 - NV-based magnetometer
 - Classical magnetometer
 - 6-DOF IMU (Accelerometer + Gyroscope)
 - Barometer
- AI-based anomaly detection evaluation

Adaptive sensor fusion

- Anomaly detection extension for variance estimation
- Adaptive control algorithm



Final result:

- TRL 4 breadboard deliverable
- TRL 4 Q-PAD Simulator

Q-PAD Project Team

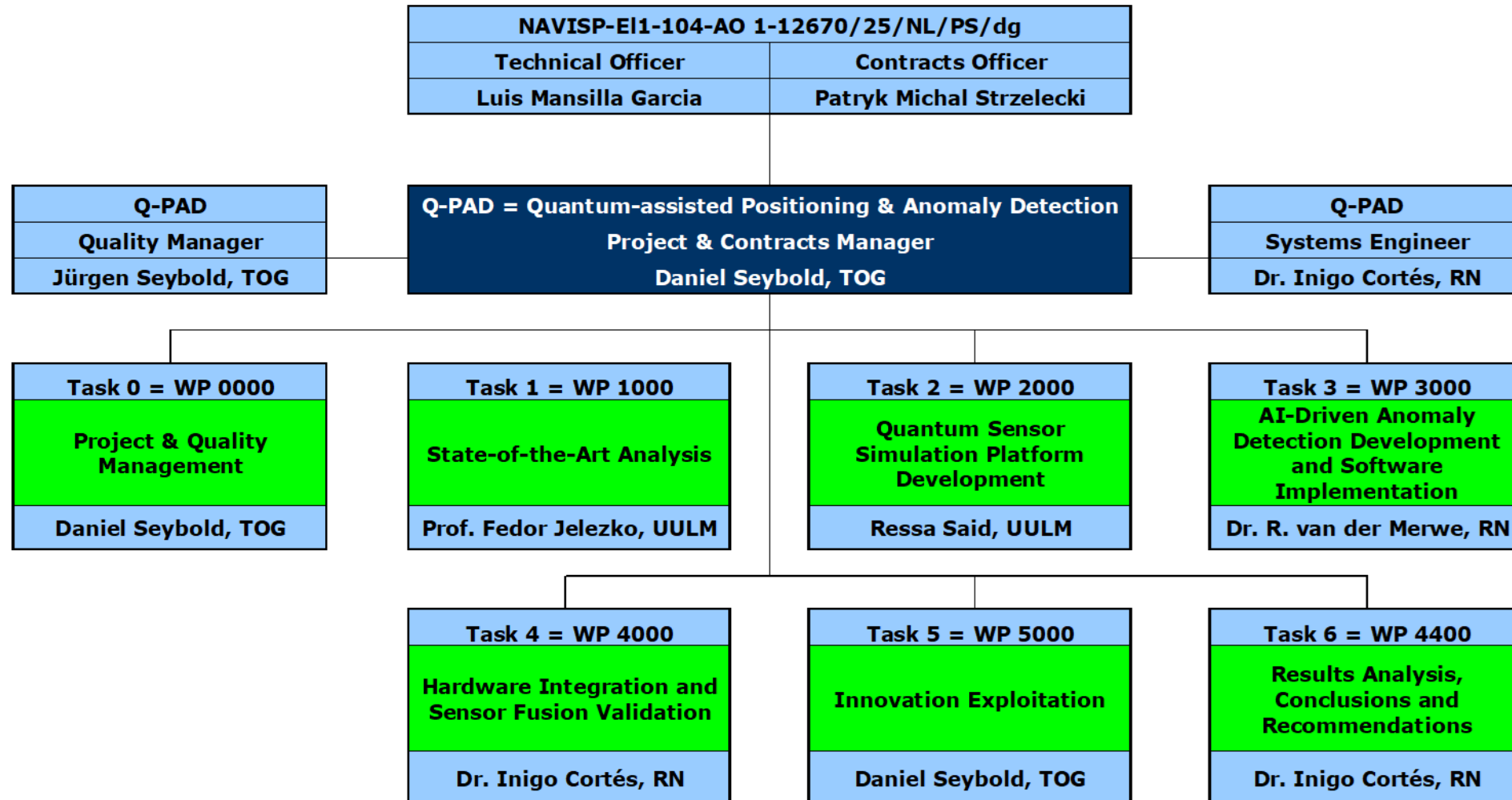
TeleOrbit GmbH is a privately owned engineering, marketing, and sales company providing innovative satellite navigation technologies and solutions incorporating satellite navigation, satellite communication, and geoinformation. The SME company's HQ is located in Nuremberg, Germany. TeleOrbit was the *prime contractor*.

The **University of Ulm** is represented by the Institute of Quantum Optics, which focuses on quantum technologies based on NV centres in diamond, including quantum sensing.

RobNav GmbH is a new, technology-oriented SME founded in July 2024 in Nürnberg, Germany, with a core focus on robust guidance, navigation, and control (GNC) systems. The company is dedicated to advancing high-integrity navigation technologies to meet the demanding requirements of aerospace and defense applications for autonomous systems.

IMEC is the world-leading research and innovation hub in nanoelectronics, digital, and quantum technologies. The institute's cutting-edge research is driving the development of next-generation chips and systems and enabling technologies for ambient intelligence and quantum. IMEC was the *associated partner* who supplied the NV-quantum magnetometer.

Q-PAD Project Organisation



Q-PAD Project Schedule

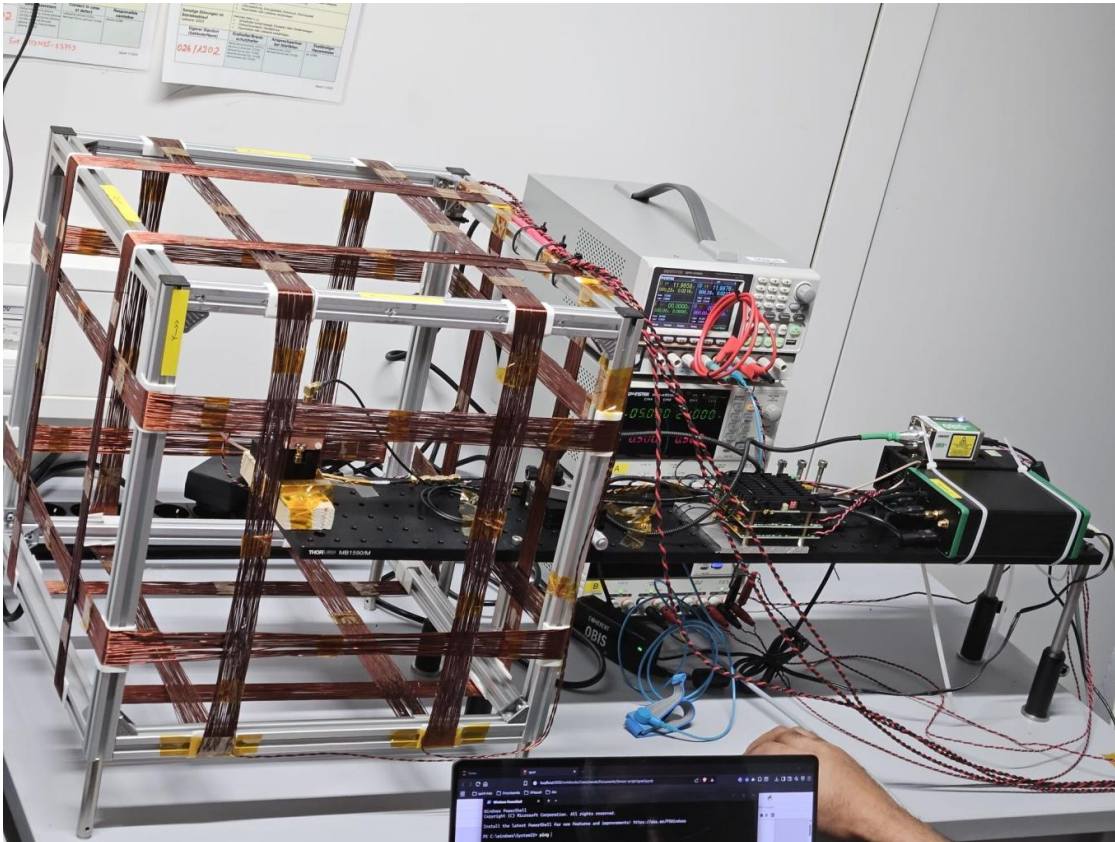
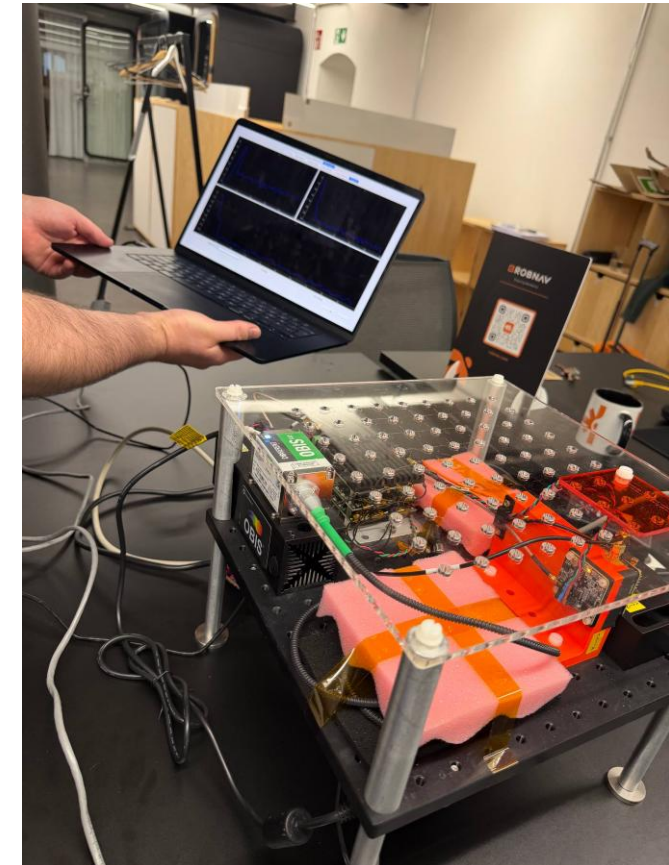
NAVISP EL1-104 Q-PAD Project Schedule			12 Months Overall												
		2025	2025				2026								2026
Workpackages		8	9	10	11	12	1	2	3	4	5	6	7	8	9
WP 0000	Project & Quality Management														
WP 1000	State-of-the-Art Analysis														
WP 2000	Quantum Sensor Simulation Platform Development														
WP 3000	AI-Driven Anomaly Detection Development and Software Implementation														
WP 4000	Hardware Integration and Sensor Fusion Validation														
WP 5000	Innovation Exploitation														
WP 6000	Results Analysis, Conclusions and Recommendations														
Project Milestones:		NM/ KOM					PDR			TRR				FR	Close Out

NM = Negotiation Meeting
 KOM = Kick-Off Meeting
 PDR = Preliminary Design Review

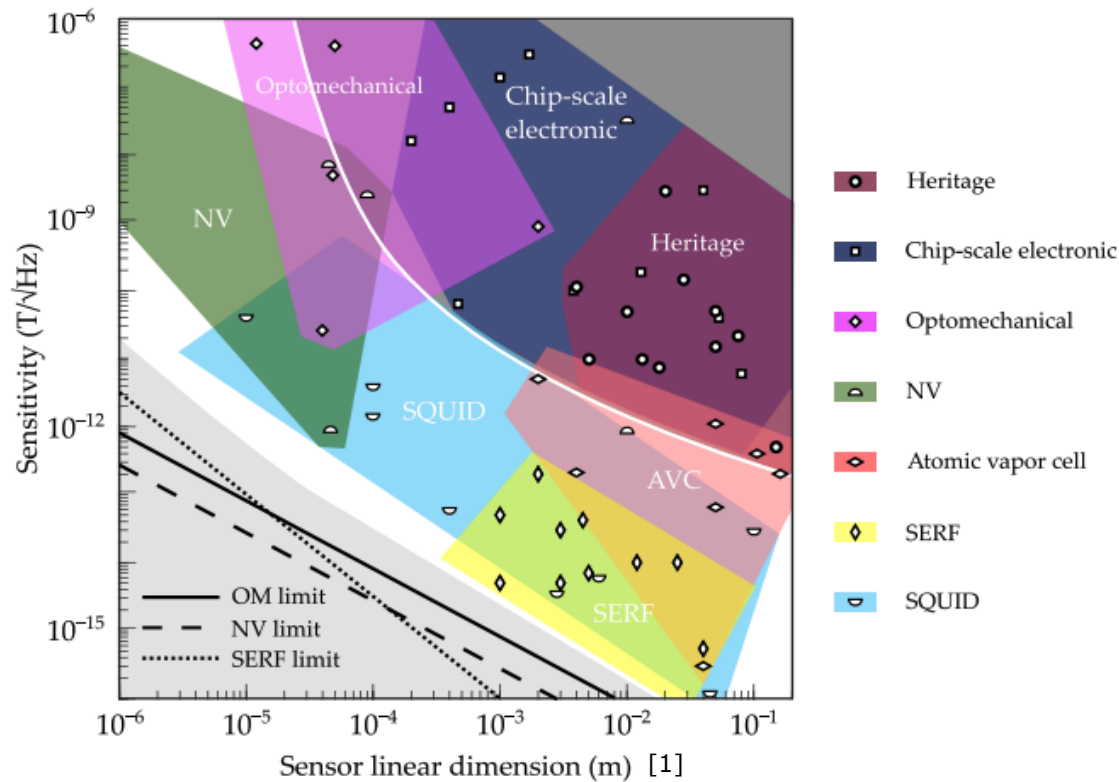
TRR = Technology Readiness Review
 FR/CO = Final Review / Close-Out

Additionally, 7 progress meetings were organised during which the consortium updated ESA on its progress and discussed the coming period and work.

Outcome of the Project



From classical to quantum, and why nitrogen-vacancy (NV)

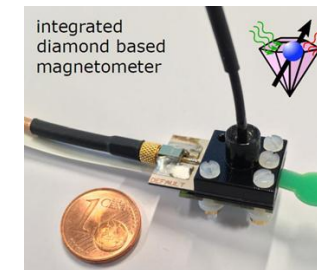
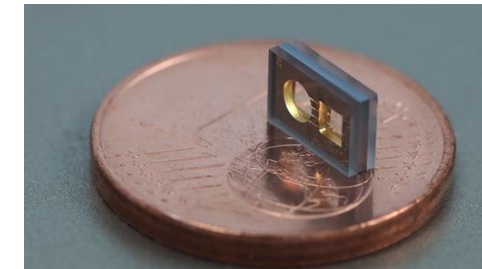


Classical → quantum

- Heritage sensors (e.g., fluxgate) drift.
- They need recalibration. Quantum sensors do not.

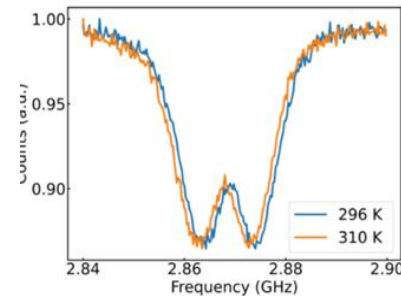
Quantum → NV centres

- Solid state. Room temperature. No cryogenics.
- Wide dynamic range. DC to GHz.
- Vector output. Radiation tolerant.
- Less sensitive than OPM. Far easier to deploy.



Intrinsic Anomalies

NV Magnetometer



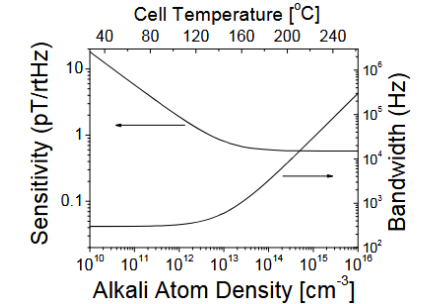
Temperature variations [14]

- Generates a bias in the resonance frequencies
- If not compensated, leads to an observation bias

Dynamic range vs. sensitivity

- If narrow dynamic range:
 - High sensitivity & limited coverage
- Wide dynamic range:
 - Low sensitivity & Large Id coverage

VC Magnetometer [15]



Temperature effects

- Bandwidth limited by the transverse spin relaxation rate
- Higher bandwidth by shortening relaxation time
- Temperature influences the sensitivity

Magnetic field effects

- High-sensitivity operation of the magnetometer in unshielded environments: by the active compensation of stray static and oscillating magnetic fields.

Other physical factors that degrade sensitivity

- Photon shot noise
- Laser AM and FM noise
- Magnetic field gradients

[14] Zhang, N., et al. (2022). Temperature fluctuations compensation with multi-frequency synchronous manipulation for an NV magnetometer in fiber-optic scheme. Sensors, 22(14), Article 5218.

[15] Kitching, J., et al. (2008). Microfabricated atomic magnetometers and applications. In 2008 IEEE International Frequency Control Symposium.

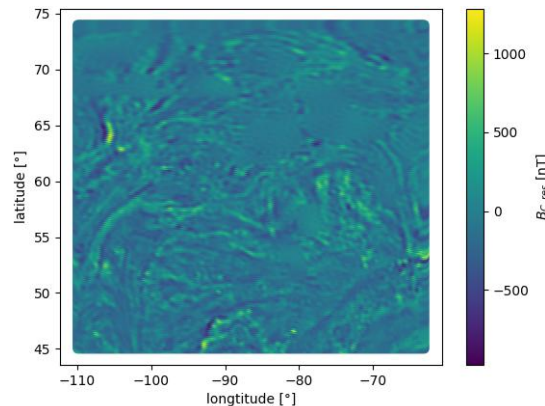
Environmental Anomalies

UAV & Airplane

Regional and geological anomalies

- From iron rich soils, rocks and local magnetization
- Models used: EMAG2 and EMM2017 [16]

Different hard iron & soft iron effects



EMM2017 Residuals at Canadian Shield (100 m)

LEO

Temperature

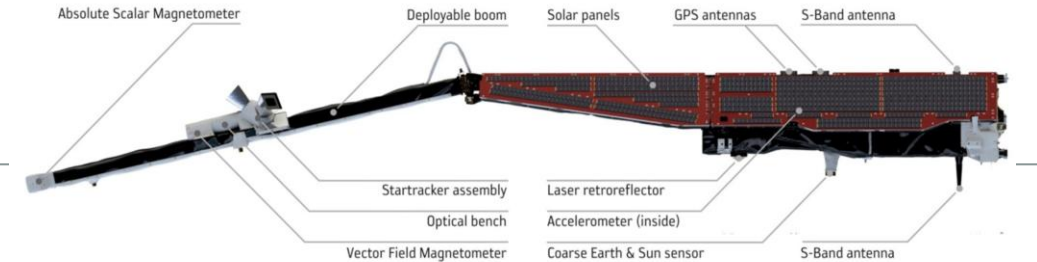
- 1 °C per minute during sun-lit to eclipse transients
- 0.25 °C per minute during slower transitions

Magnetic moments of external components

- μAm^2 due to a star trackers
- Magnetorquers magnetic interference

Geomagnetic storms [17] [18] [19]

- From minor ($\sim 2\text{-}100\text{nT}$, $0.1\text{-}2\text{nT/s}$) to moderate ($\sim 100\text{-}300\text{nT}$, $5\text{-}20\text{nT/s}$) to strong ($\sim 300\text{-}1000\text{nT}$, $50\text{-}500\text{nT/s}$)
- Rapid change during minutes to hours. After that, it takes days until the magnetosphere slowly recovers.
- More intense in the polar region, less near the equator.
- Solar winds causes geomagnetic storms, which in turn can generate ionospheric currents.



[16] National Centers for Environmental Information, National Oceanic and Atmospheric Administration (NOAA), <https://www.ncei.noaa.gov/products/earth-magnetic-model-anomaly-grid-2>

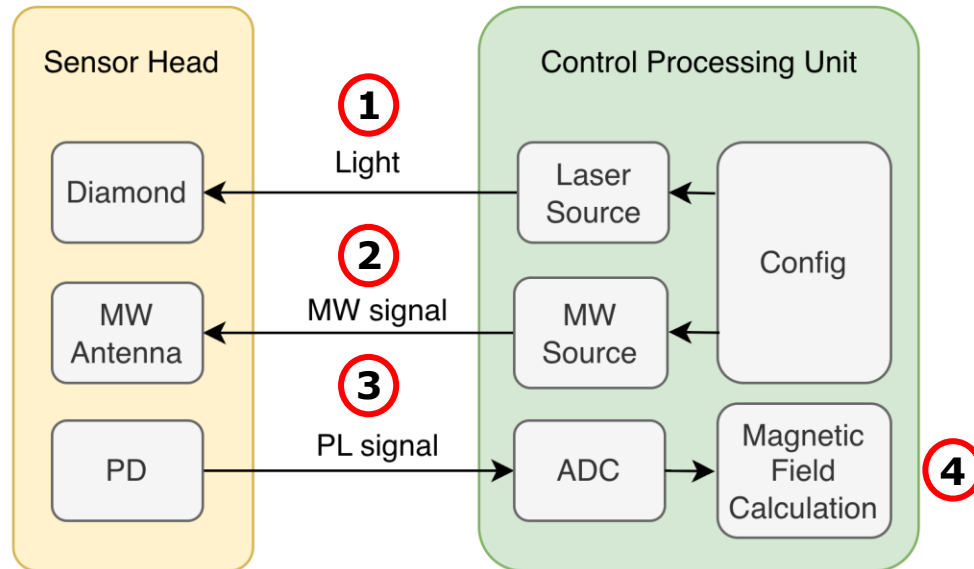
[17] Open database of Swarm satellite <https://swarm-diss.eo.esa.int/>

[18] Virtual research environment: <https://earth.esa.int/eogateway/tools/swarm-vre>

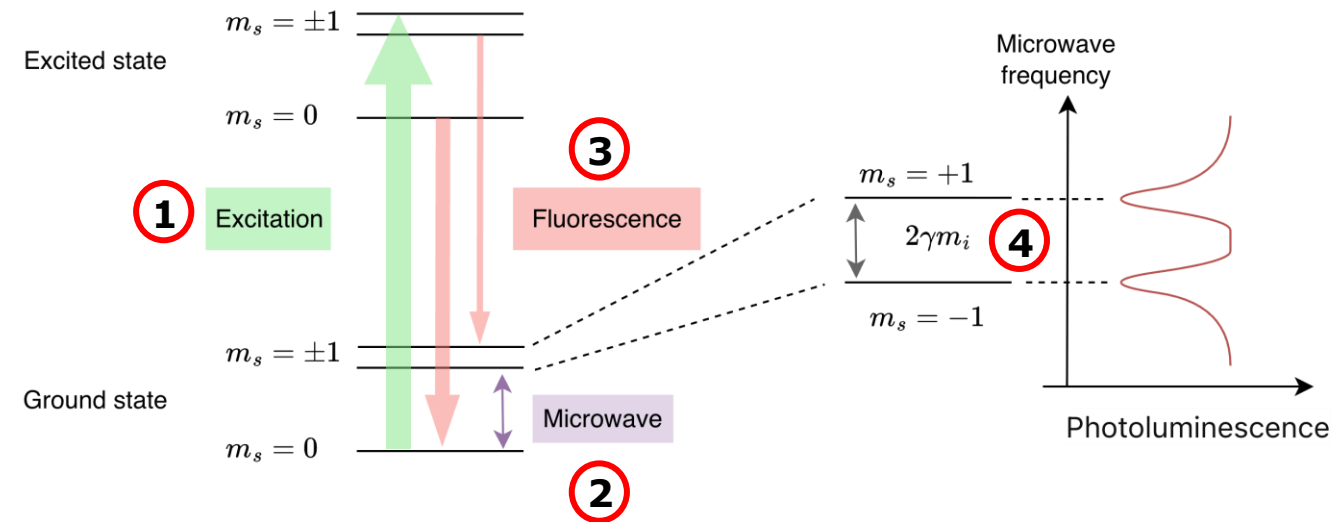
[19] WMMHR: <https://www.ncei.noaa.gov/products/world-magnetic-model-high-resolution>

NV-based Quantum Magnetometer

Main architecture



Optically detected magnetic resonance (ODMR)



- 1** **Excitation:** green laser pumps the NV centres.
- 2** **Microwave (MW) drive:** antenna sweeps the spin transitions.
- 3** **Readout:** photodiode measures photoluminescence.
- 4** **Field estimate:** the resonance splitting gives the field value.

Q-PAD Simulator: Overview

1. Trajectory Designer

- Reference flight path
- Environmental anomaly injection

2. Quantum Sensor Simulation Platform (QSSP)

- Models the NV magnetometer

3. Classical Sensor Simulation Platform (CSSP)

- 10 DoF inertial measurement unit (IMU)

4. Anomaly Detection

- Autoencoder, XGBoost or Mahalanobis
- Outputs a soft anomaly score

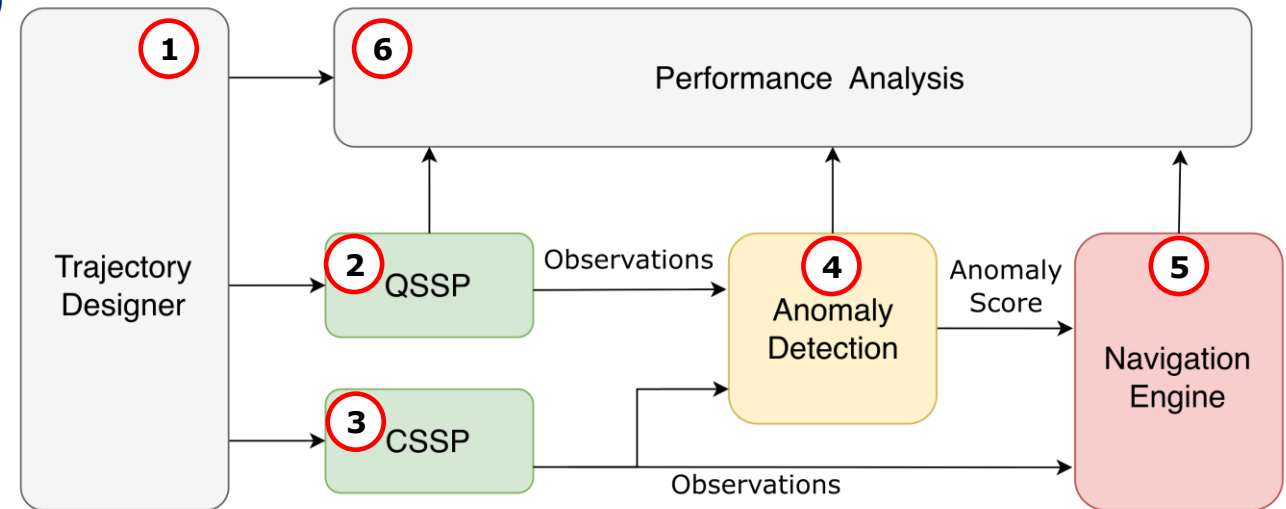
5. Navigation Engine

- Fuses quantum and classical observations into the solution.

6. Performance Analysis

- Scores every stage against the reference trajectory.

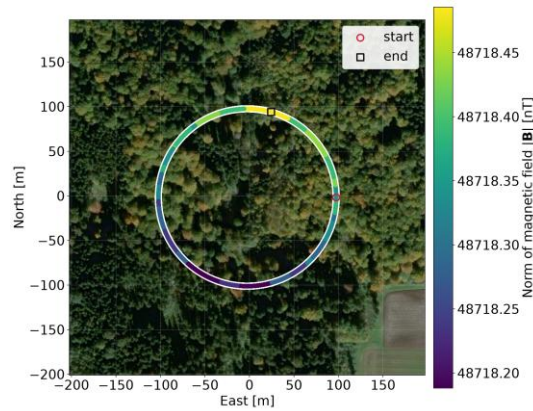
An end-to-end simulation chain



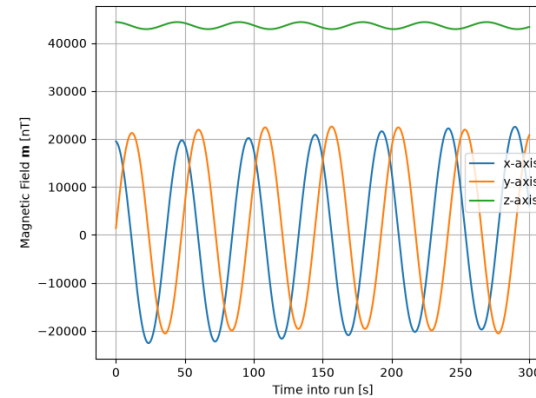
Q-PAD Simulator: Trajectory Designer & Anomaly Injection

UAV

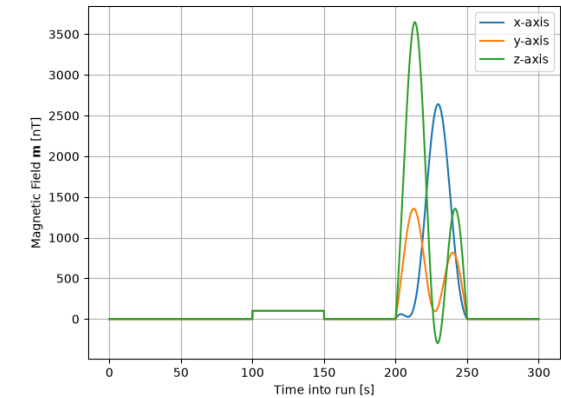
Trajectory



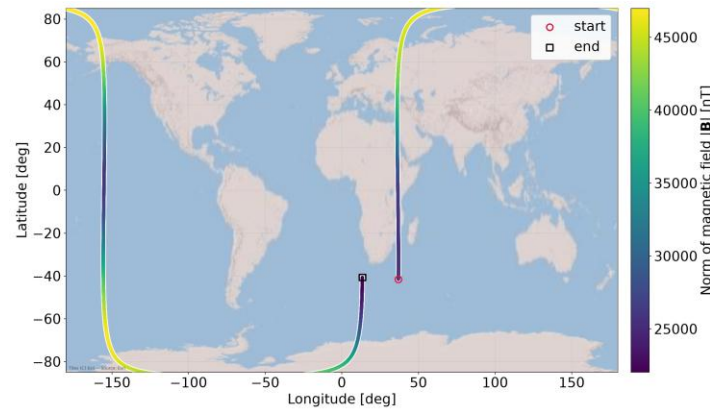
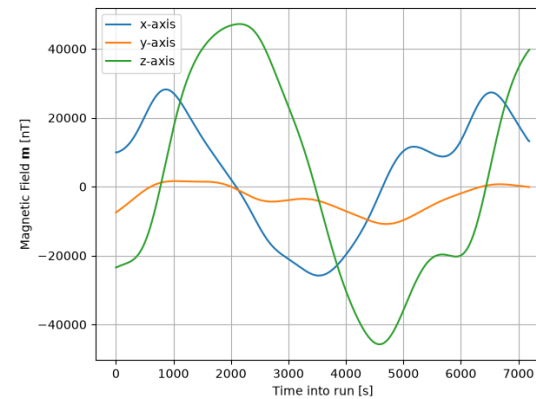
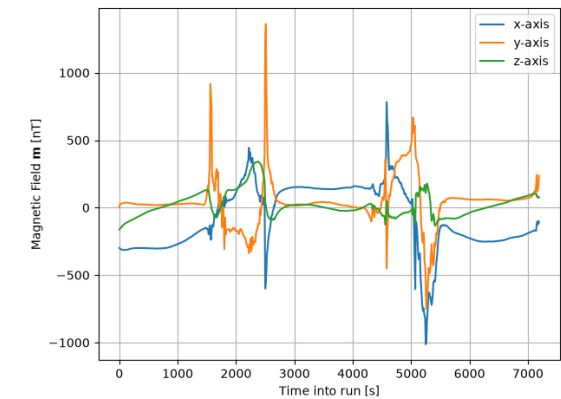
Magnetic observations



Injected anomalies



LEO



Q-PAD Simulator: QSSP

Two-step sensor model

Configuration inputs

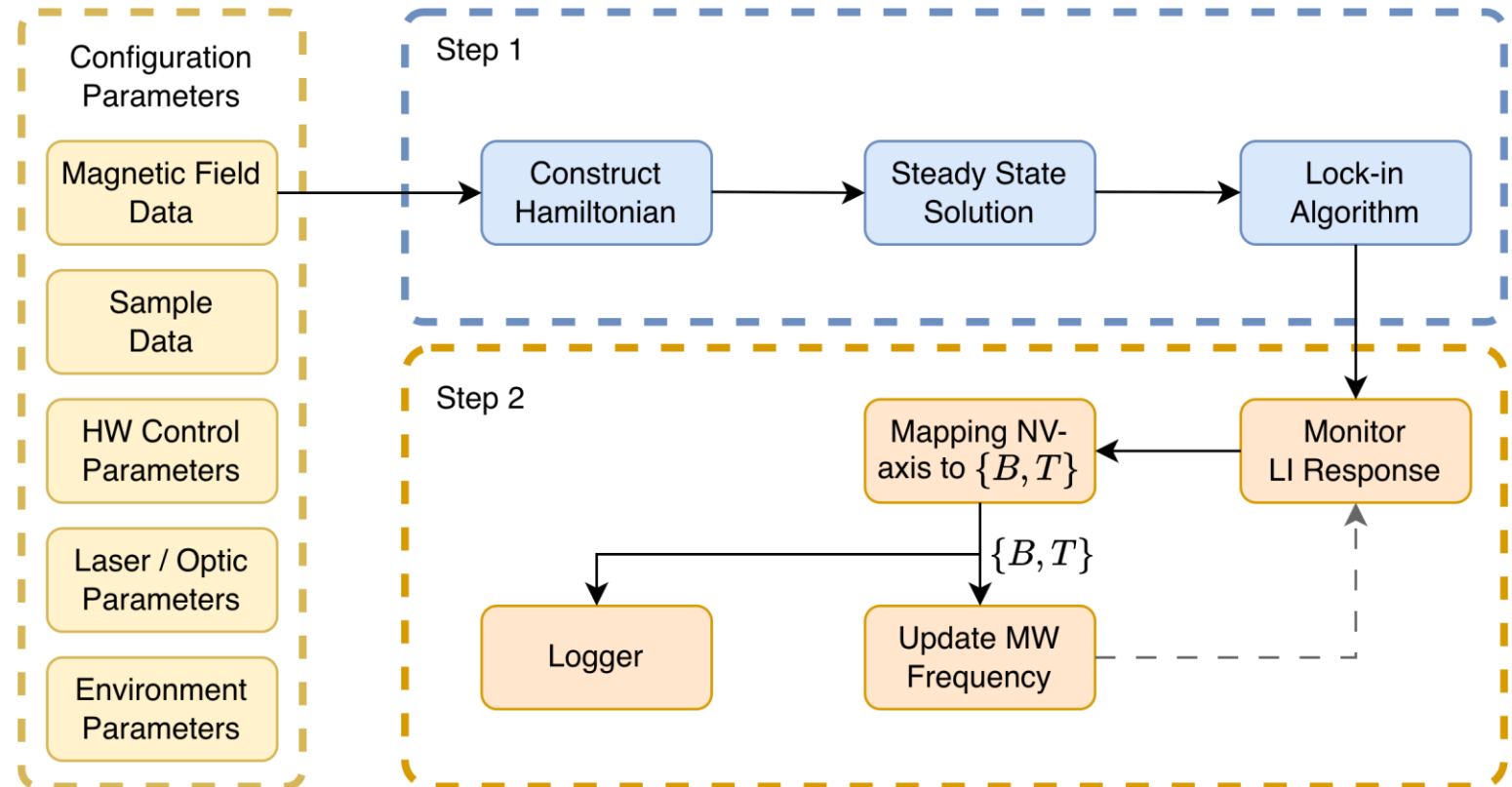
- Magnetic field and sample data
- Hardware, laser/optics, environment

Step 1: Physics

- Construct the NV Hamiltonian
- Solve for the steady state
- Apply the lock-in (LI) algorithm

Step 2: Closed loop

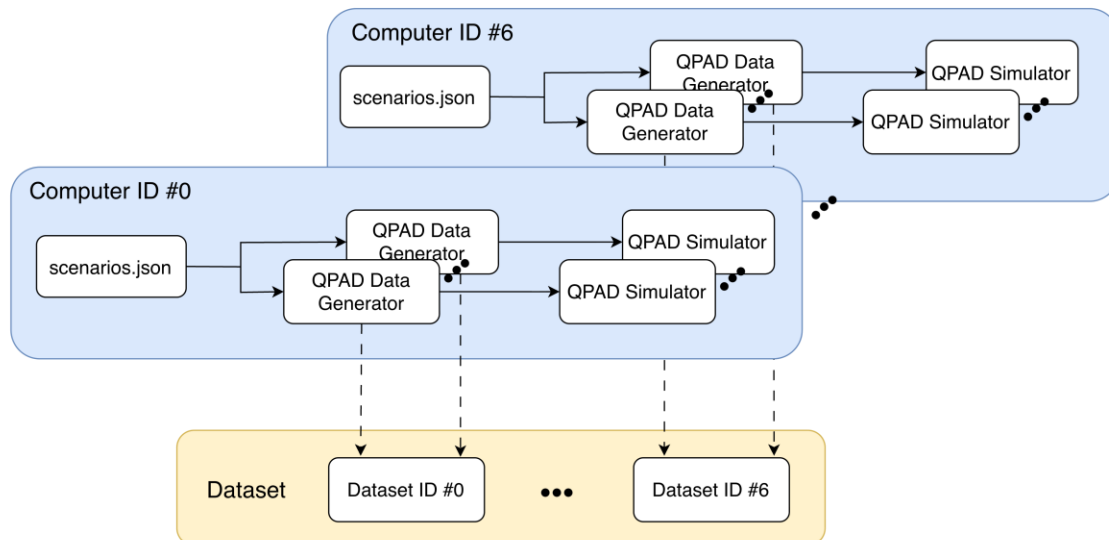
- Monitor the LI response
- Map NV axes to field B and temperature T
- Retune the microwave (MW) frequency to stay on resonance



Q-PAD Simulator: Data Generation

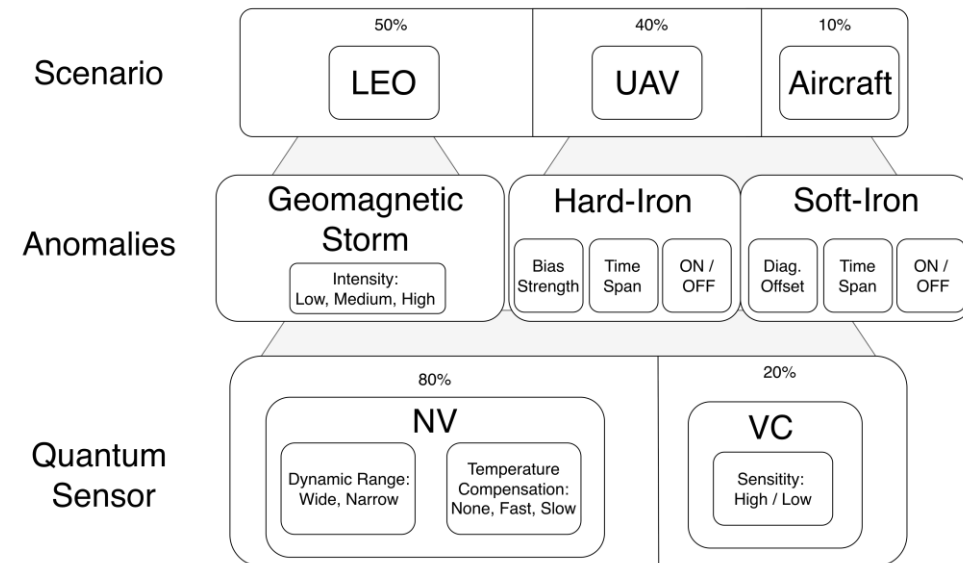
Workflow

- Many computers running many processes
- One run = one configuration, 300 s at 100 Hz
- One dataset per run



Configuration distribution

- 3 scenarios × 3 anomaly types × 2 quantum magnetometers
- LEO 50%, UAV 40%, aircraft 10%; NV 80%, VC 20%
- Temperature changes and UAV attitude variation



Q-PAD Simulator – ML Framework

1. Data Generation

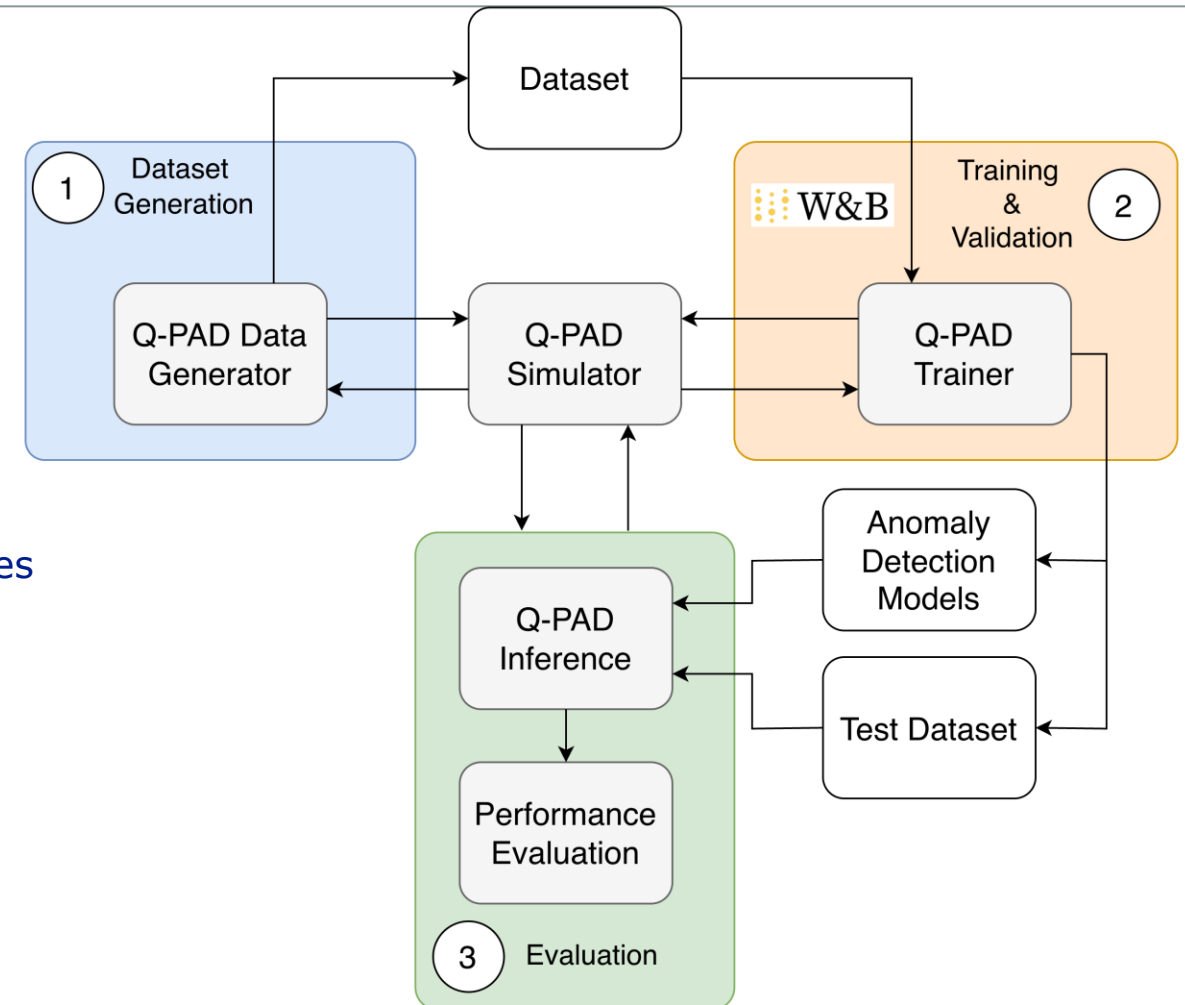
- Run trajectory designer, QSSP & CSSP
- Randomizing between:
 - Scenarios
 - Quantum sensor configurations
 - Anomaly injections

2. Training & Validation

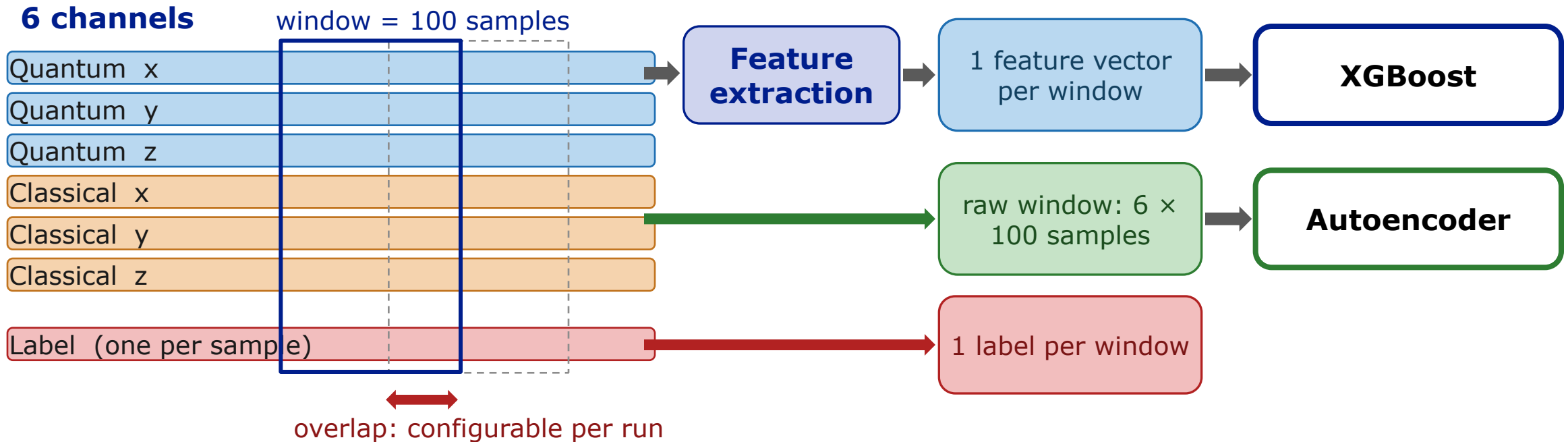
- Read entire dataset
- Divide dataset into training, validation & test dataset
- Train and validate AI-based anomaly detection techniques
- Store models and test dataset

3. Evaluation

- Evaluate trained models using test dataset
- Performance metrics
- Study impact in navigation



Anomaly Detection: Windowing, Features and Labels



$$L[n] = \min\left(1, \frac{|m_q[n] - m_r[n]|}{T_\epsilon}\right)$$

$T_\epsilon = 500 \text{ nT (wide), } 200 \text{ nT (narrow)}$

Symbols

$L[n]$ – label of sample n
 m_q – quantum magnetometer field
 m_r – reference magnetic field
 T_ϵ – anomaly threshold

Anomaly Detection: XGBoost

1) + 2) Training & validation

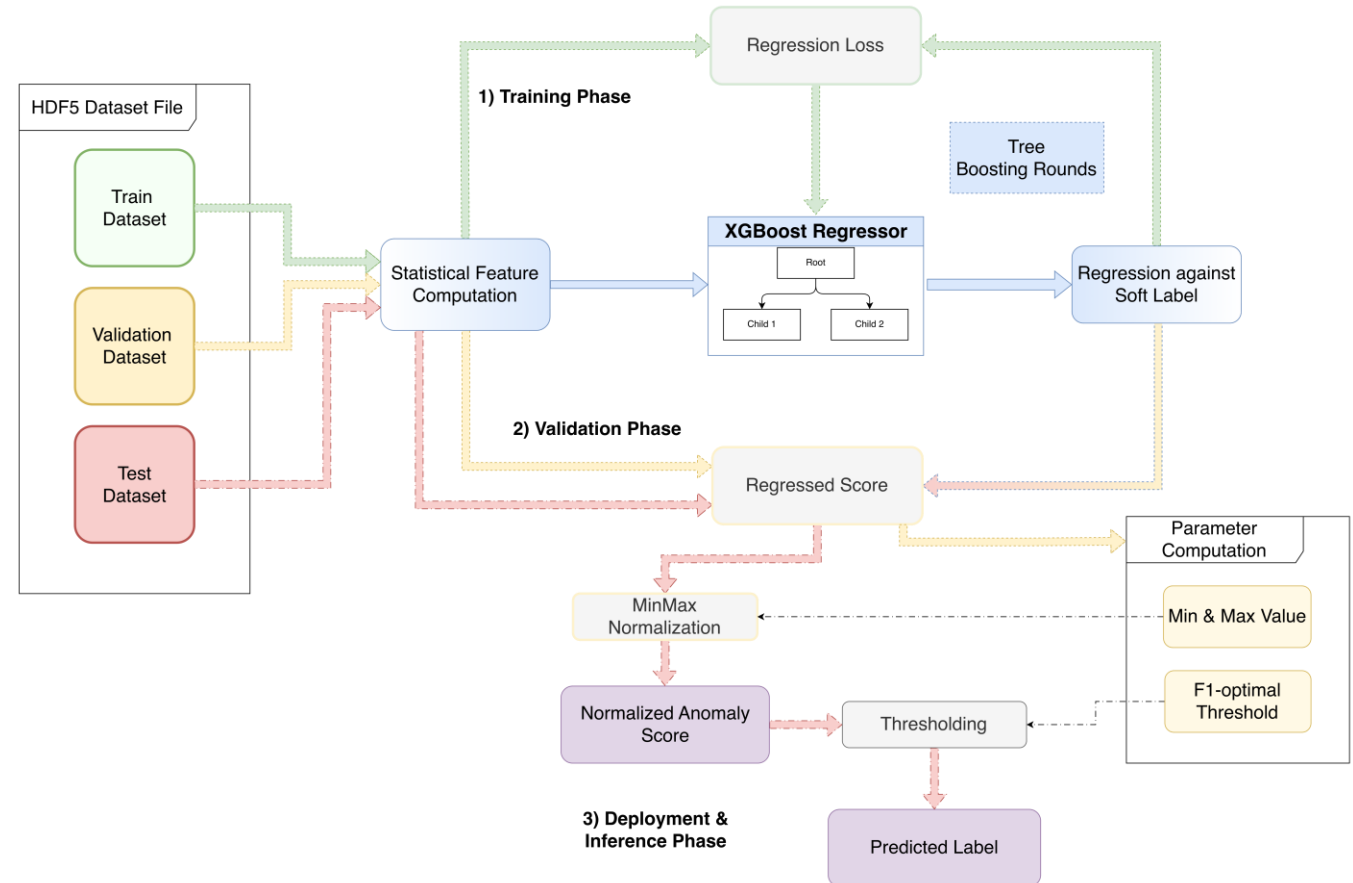
- Optuna hyperparameter optimisation loop
- Regression against the soft label
- Objectives: AUC-PR, latency, model size
- Validation fixes min/max and the F1-optimal threshold

3) Deployment & inference

- Normalised anomaly score → threshold → label

We report a label. We use the soft score.

- Anomaly is not binary.
- Evaluation → F1-optimal threshold used
- In operation → Continuous score feeds navigation engine.



AUC-PR: area under the precision-recall curve

Anomaly Detection: Autoencoder

1) + 2) Training & validation

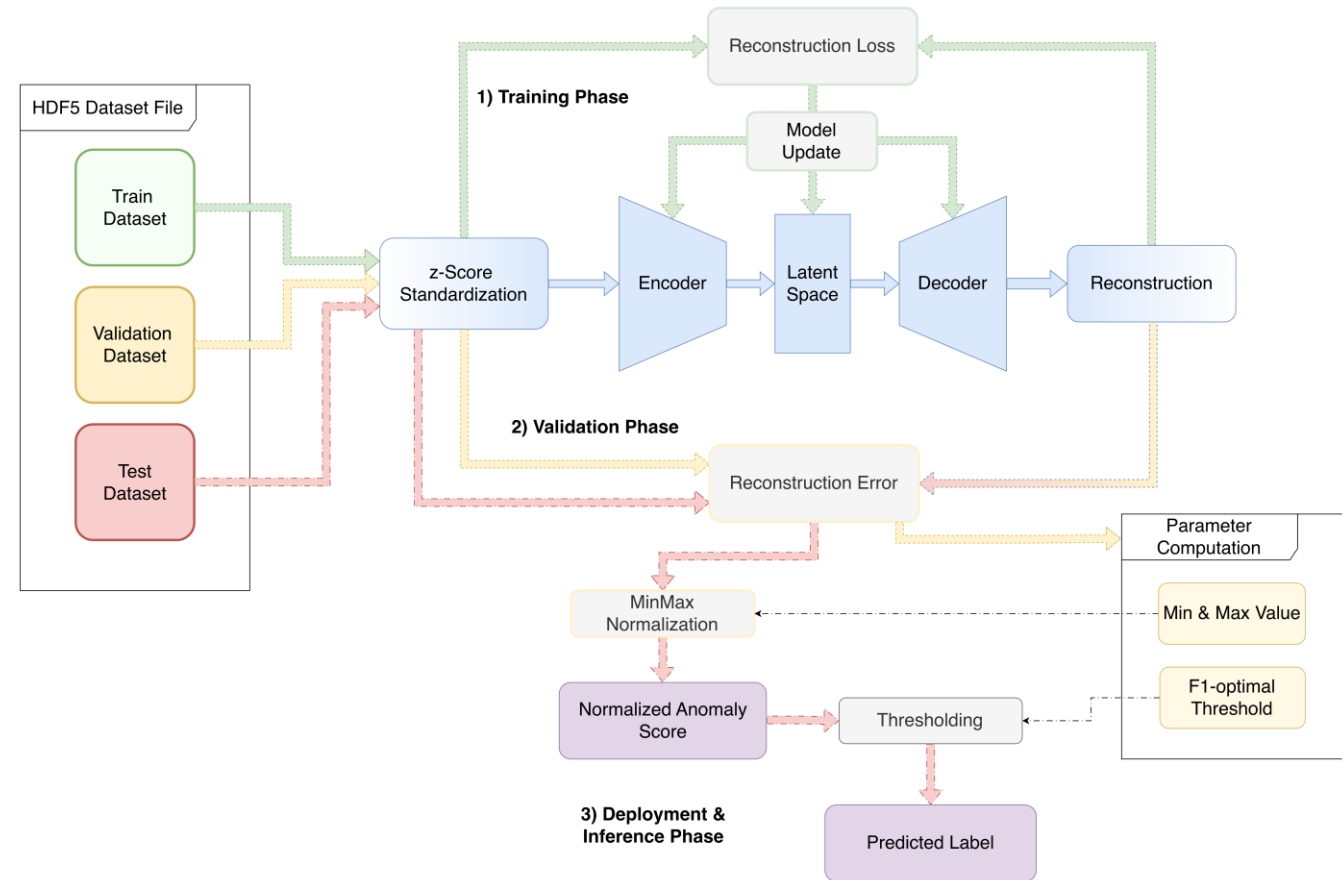
- Optuna hyperparameter optimisation
- z-score standardisation
- Encoder → latent space → decoder, trained on reconstruction loss
- Objectives: AUC-PR, latency, model size
- Validation fixes min/max and the F1-optimal threshold

3) Deployment & inference

- Reconstruction error → normalised score → threshold → label

We report a label. We use the soft score.

- Anomaly is not binary.
- Evaluation → F1-optimal threshold used
- In operation → Continuous score feeds navigation engine.



AUC-PR: area under the precision-recall curve

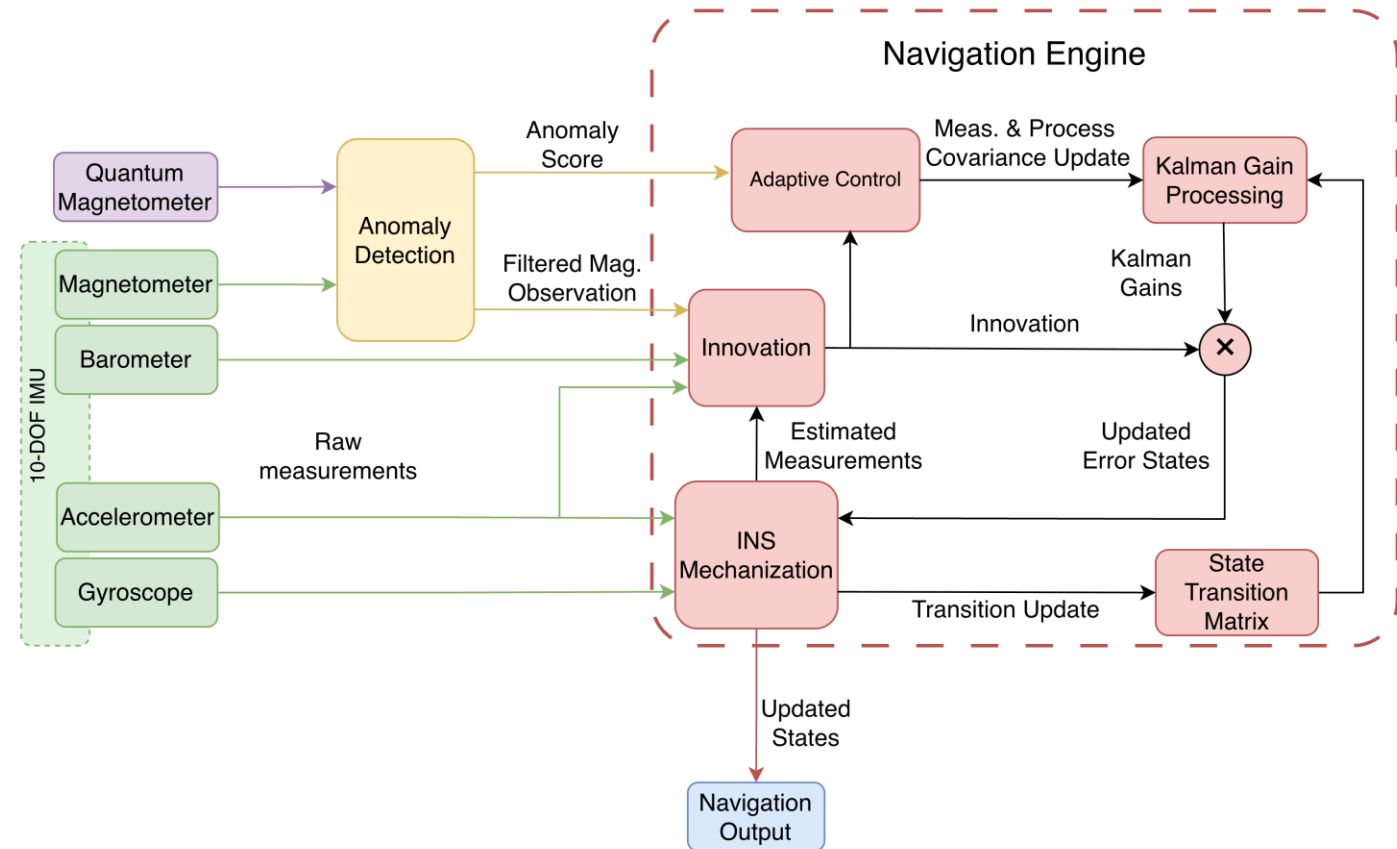
Navigation Engine: UAV and Airplane

Assumptions

- Near-surface: gravity treated as constant
- East-North-Up (ENU) reference frame
- Heading from magnetometer, levelling from accelerometer

Sensors

- 10-DOF inertial measurement unit (IMU): accelerometer, gyroscope, barometer, magnetometer
- Quantum magnetometer field observations



ENU: East-North-Up · IMU: inertial measurement unit · DOF: degrees of freedom · INS: inertial navigation system

Navigation Engine: LEO

What changes in orbit

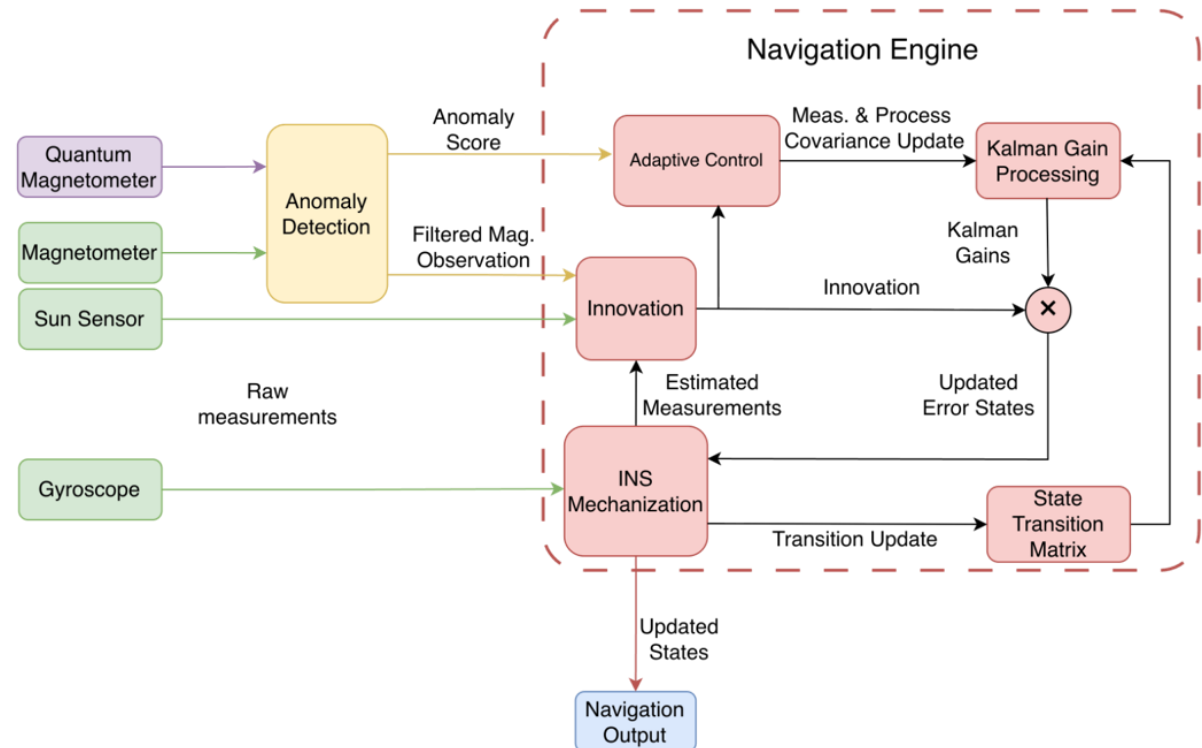
- Near-surface assumptions (constant gravity, flat local frame) no longer hold
- Free fall: no accelerometer needed
- Gravity varies with position over thousands of km

Consequences

- Position and velocity mechanised in ECEF, not ENU
- Gravity model applied
- Dynamics decoupled from attitude (free fall)

Sensors

- Sun sensor, gyroscope, quantum magnetometer field observations



ECEF: Earth-Centred, Earth-Fixed · ENU: East-North-Up · INS: inertial navigation system

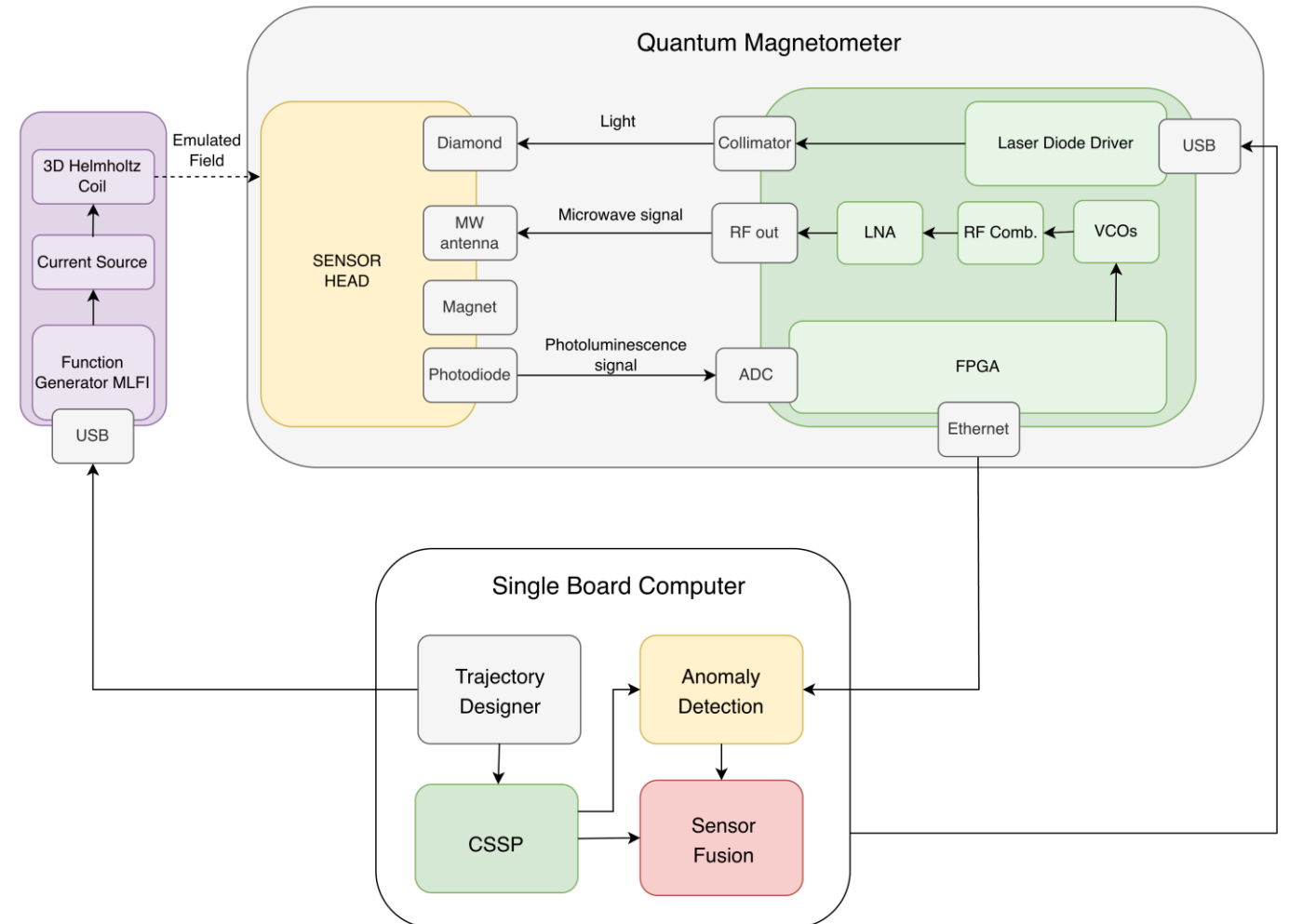
HIL Framework

Single board computer:

1. Generate trajectory
2. Control laser diode driver and MLFI
3. Receive photoluminescence signal
4. Calculate 3-D magnetic field observations
5. Run anomaly detection
6. Perform sensor fusion

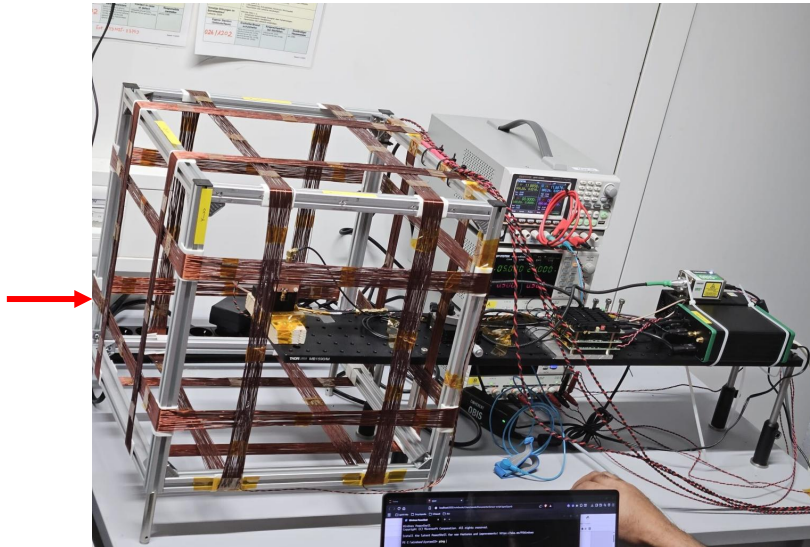
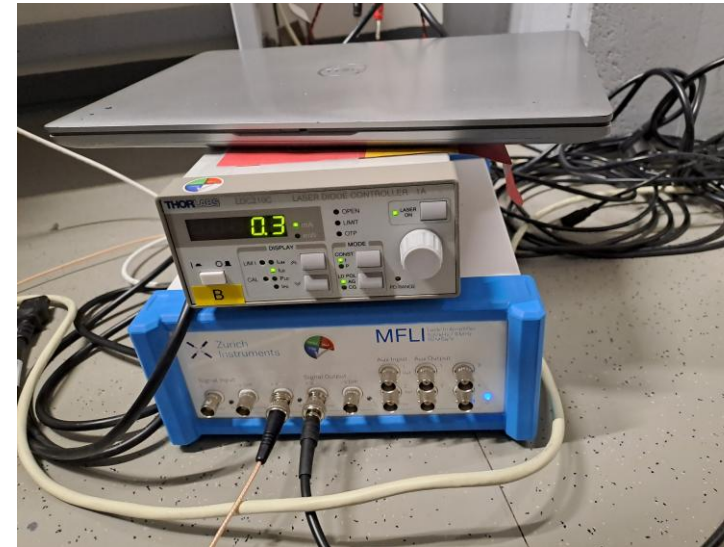
3D Helmholtz coil:

1. Receive programmed voltages
2. Output voltages to current source
3. Reproduce 3D magnetic field based on current sources



HIL Framework

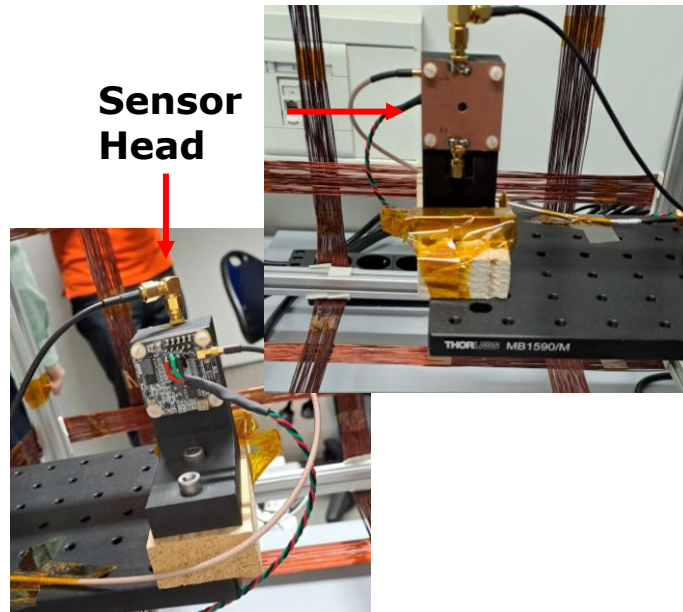
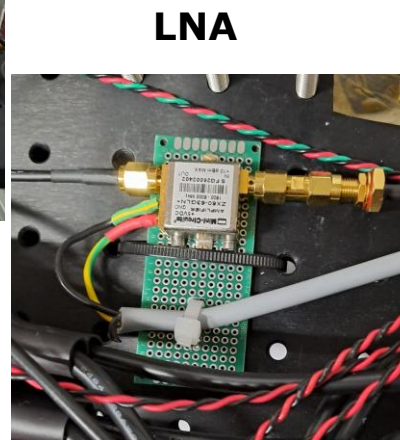
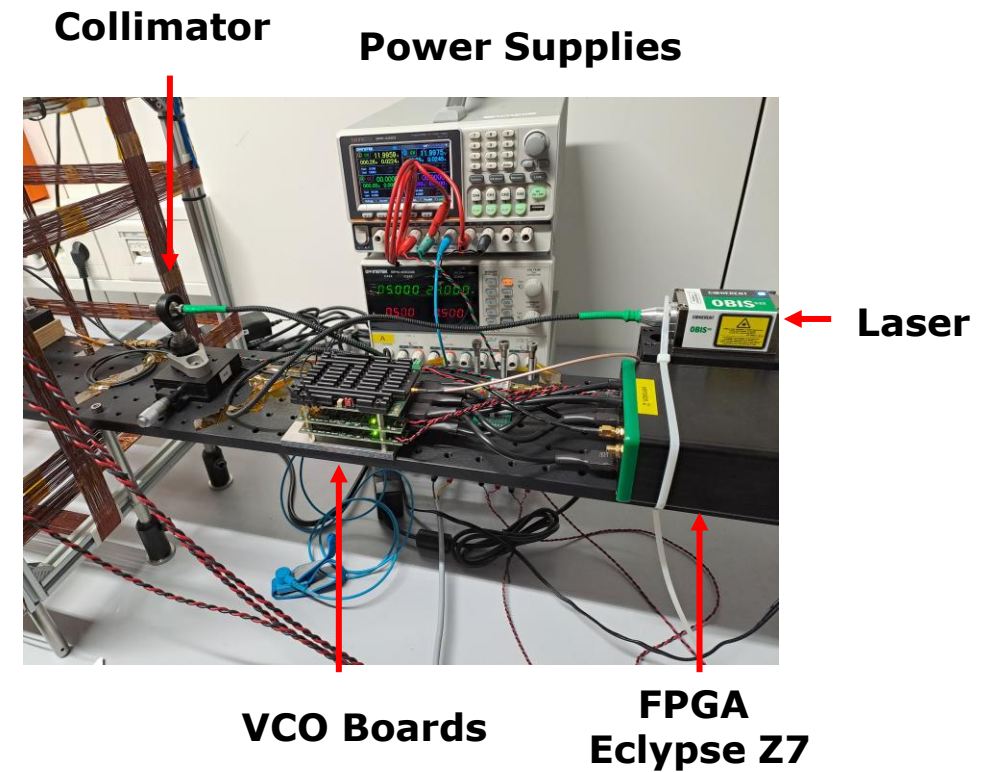
**3D
Helmholtz
Coil**



**3 Current
source
Thorlabs
LDC210C**

**Function
Generator
ZI MFLI**

HIL Framework



HIL Framework: Main Findings

Electrical devices in the lab are adding magnetic field interferences

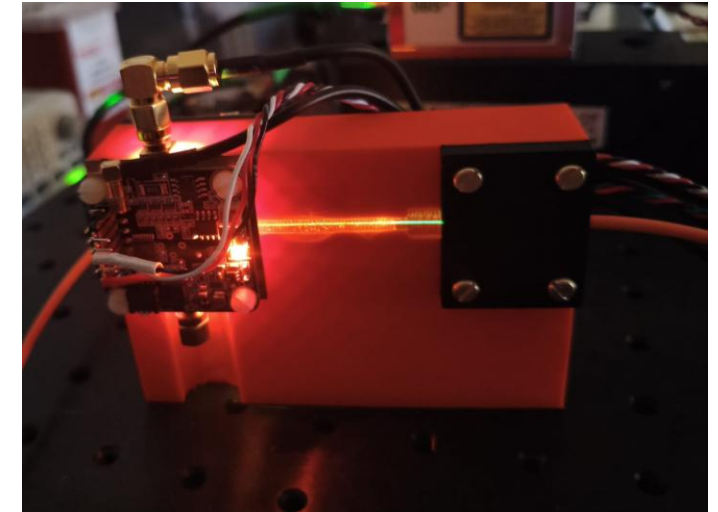
- ✓ Improvements with a second photodiode, fibre coupling to the sensor head and smoothing with integration time

Current source control is slower than expected

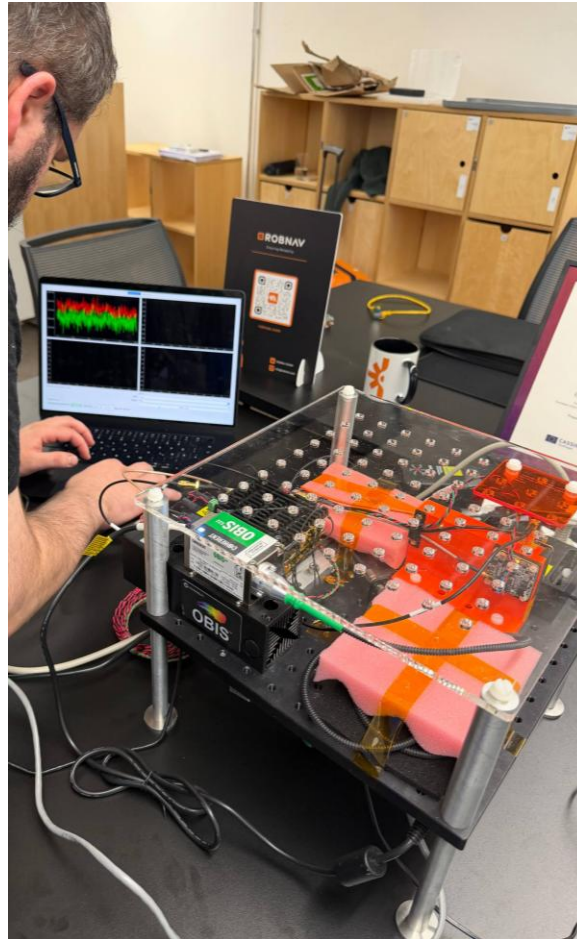
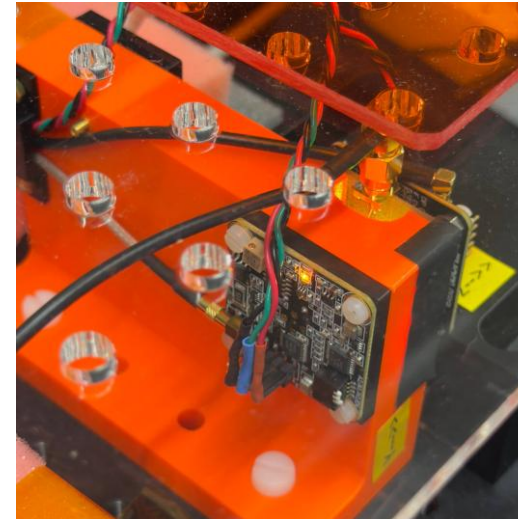
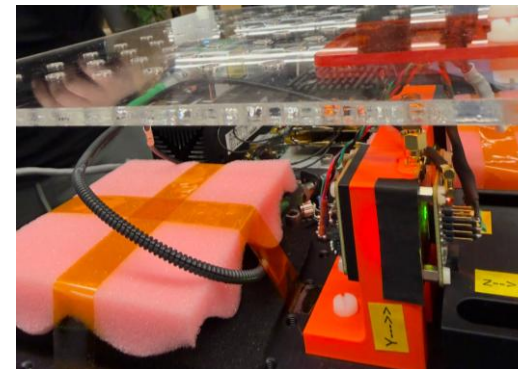
- ✓ The quantum magnetometer runs in real time; emulating the field takes some time, but this is totally fine.

Bias and drift over time

- ✓ Coil calibration and temperature extraction
- ✓ Future work: Thermal calibration in the sensor head's magnet

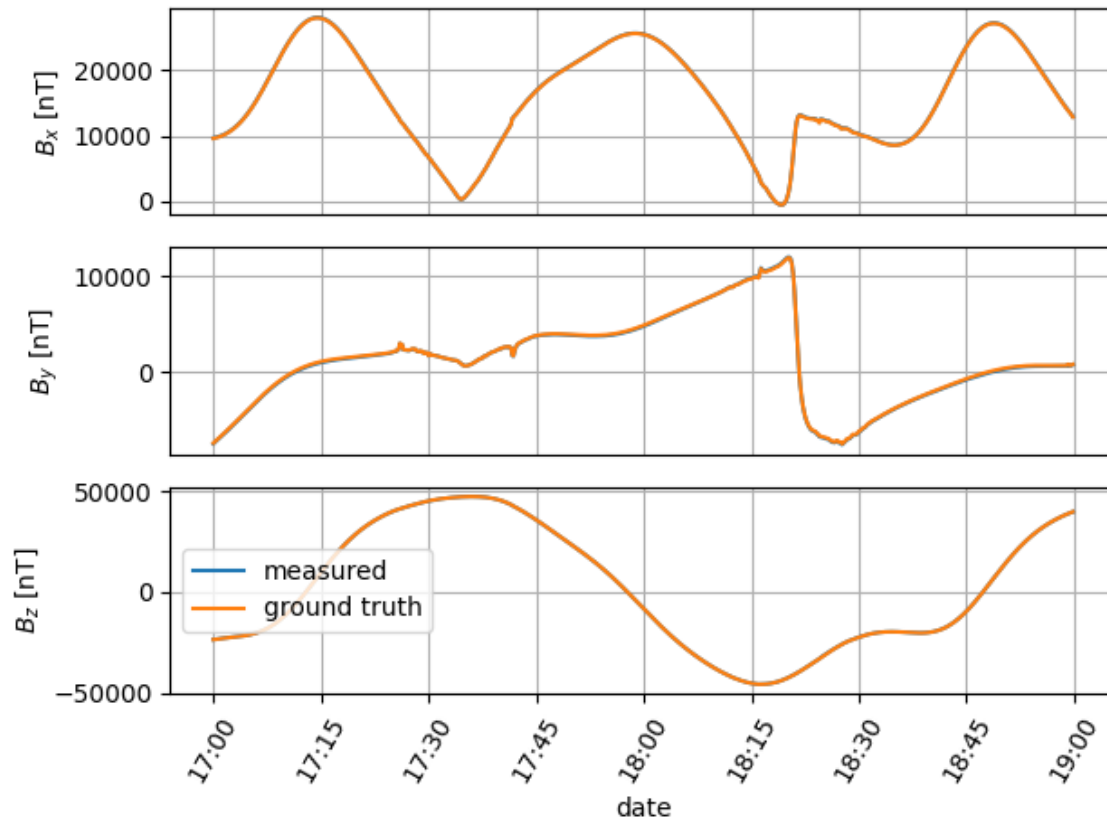
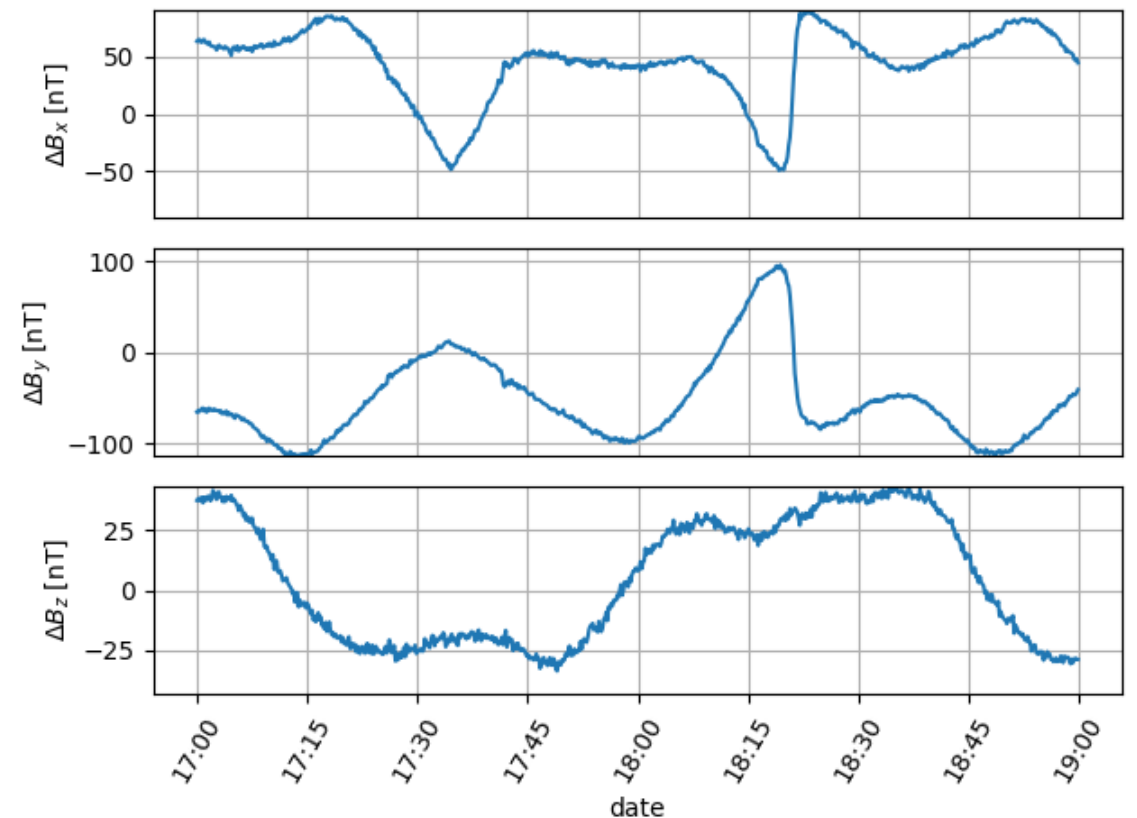


Compact HW Prototype



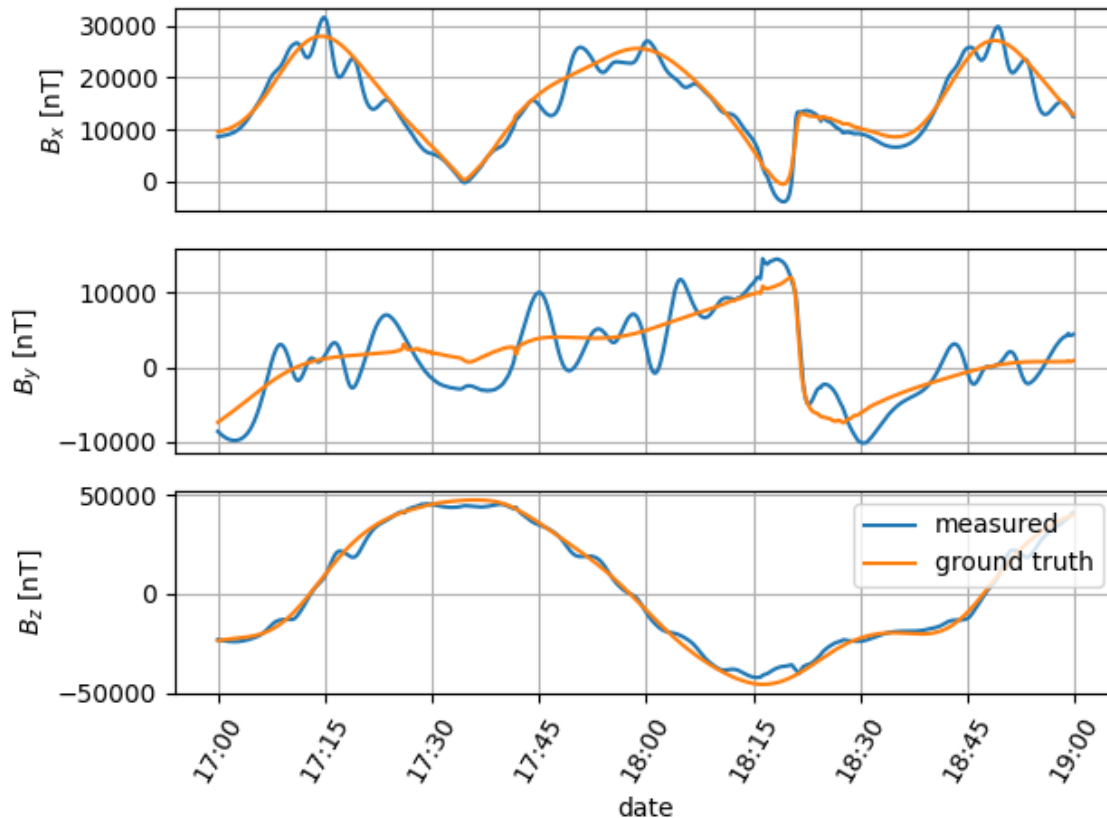
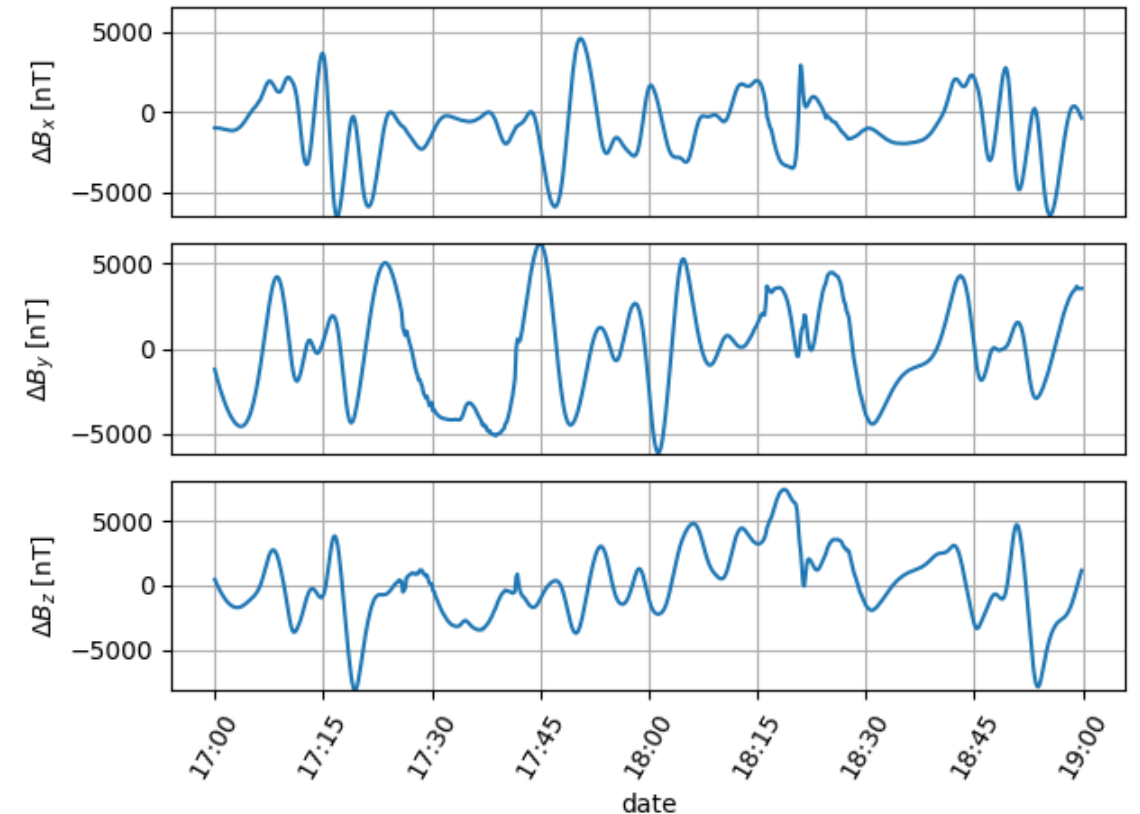
Quantum sensor simulation platform – NV results

LEO scenario: NV-based magnetometer with wide dynamic range



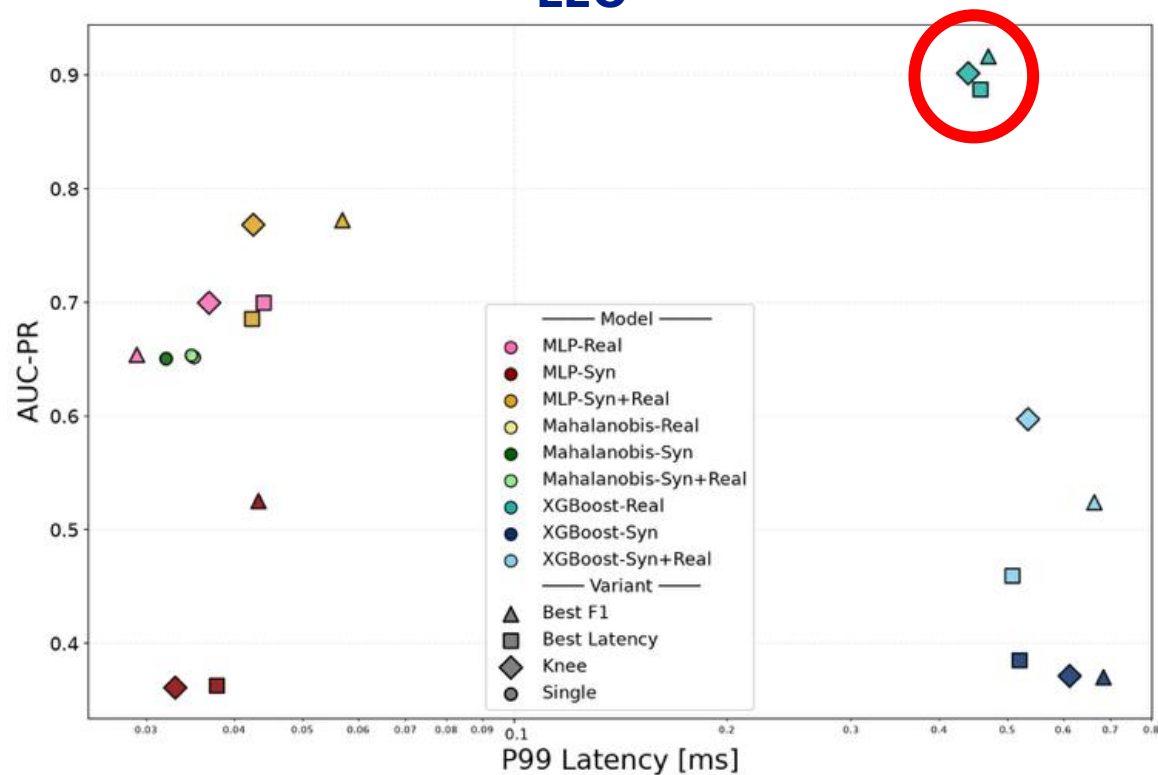
Quantum sensor simulation platform – NV results

LEO scenario: NV-based magnetometer with narrow dynamic range

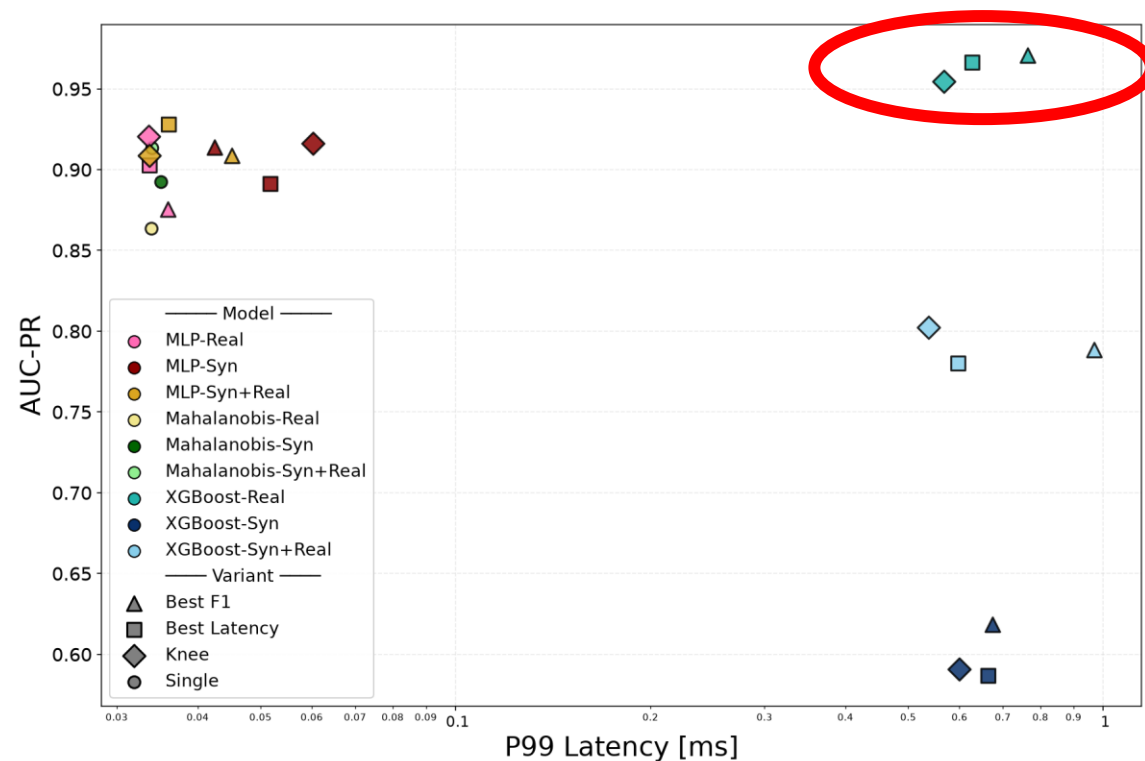


Pareto Front of Inference Results

LEO

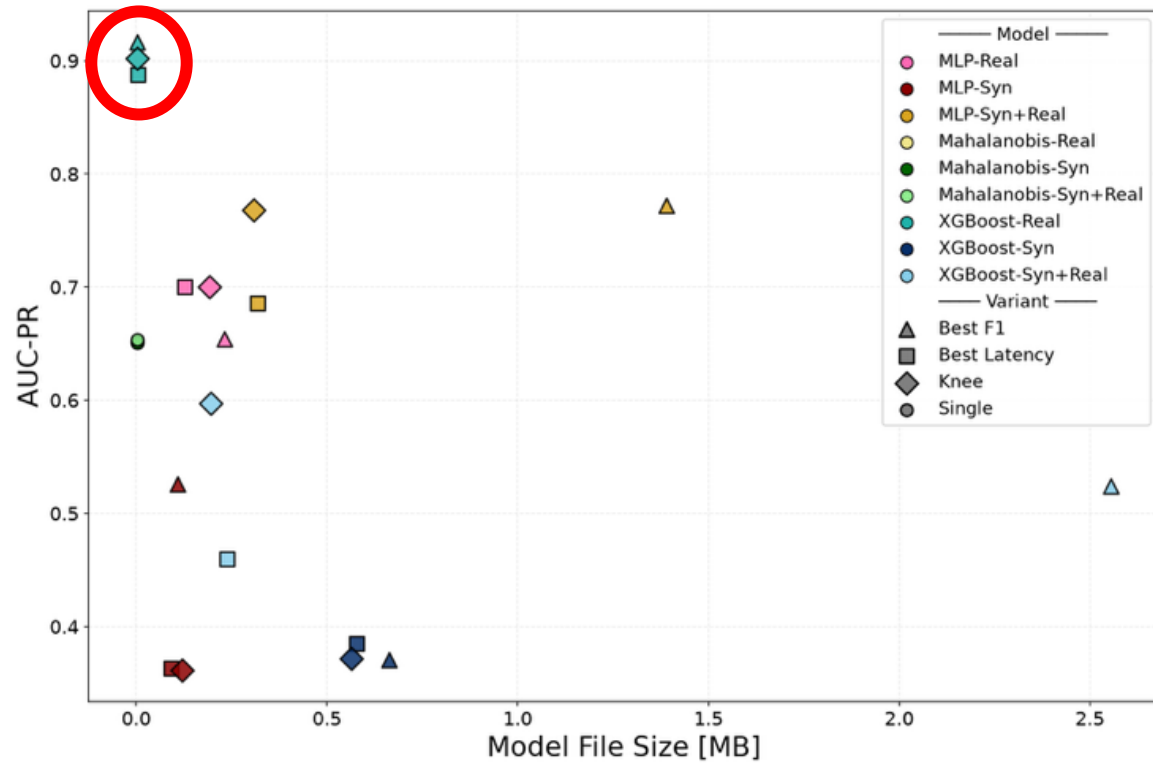


UAV

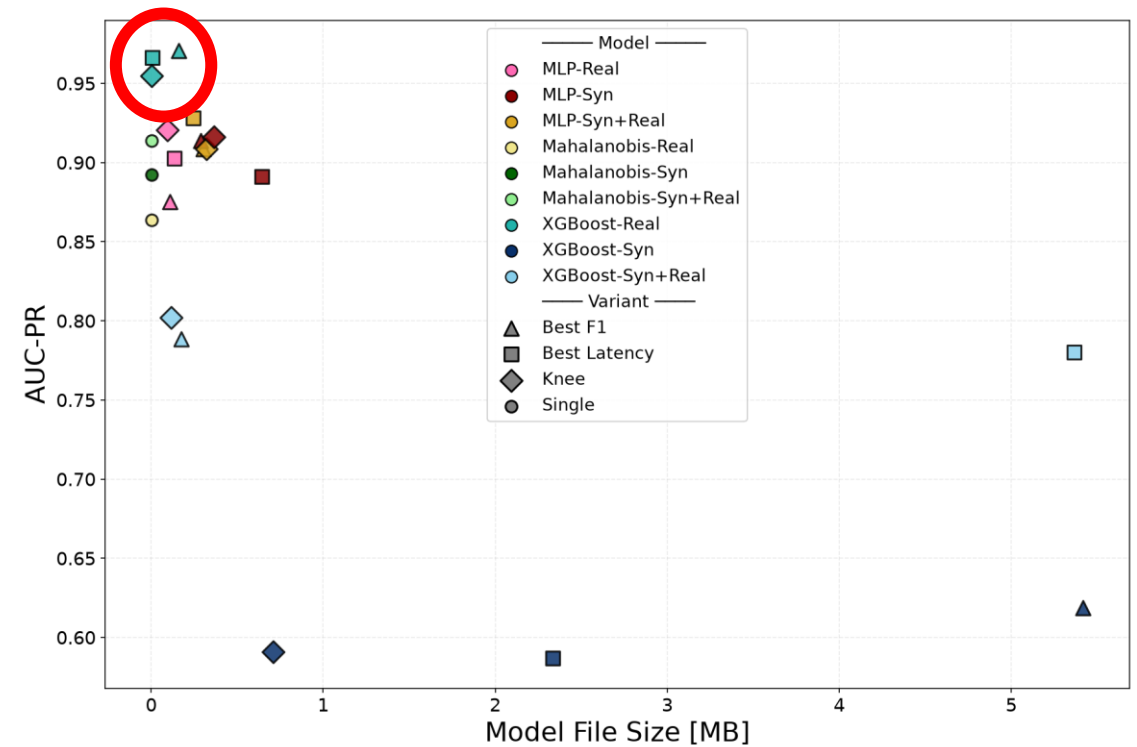


Pareto Front of Inference Results

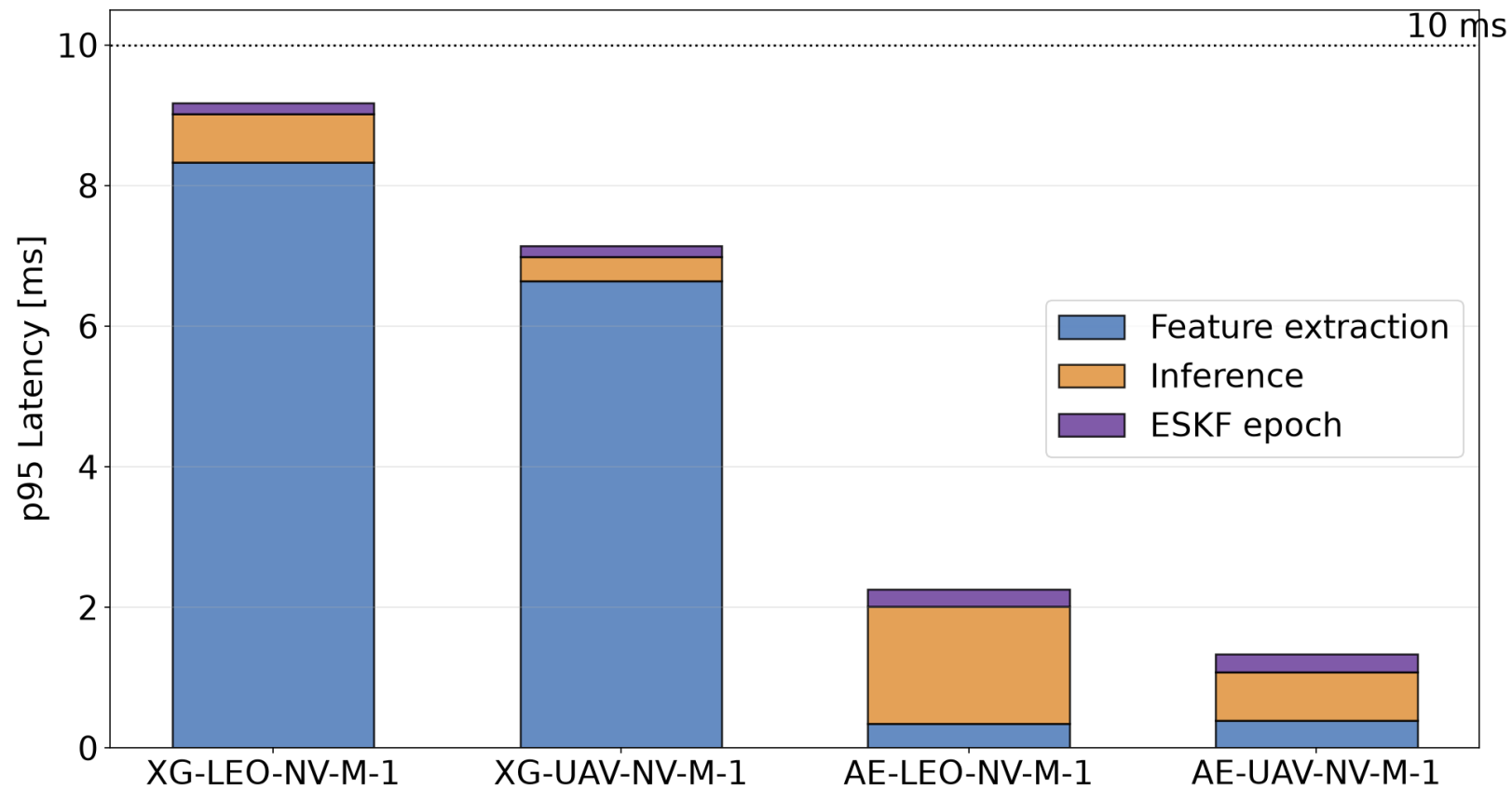
LEO



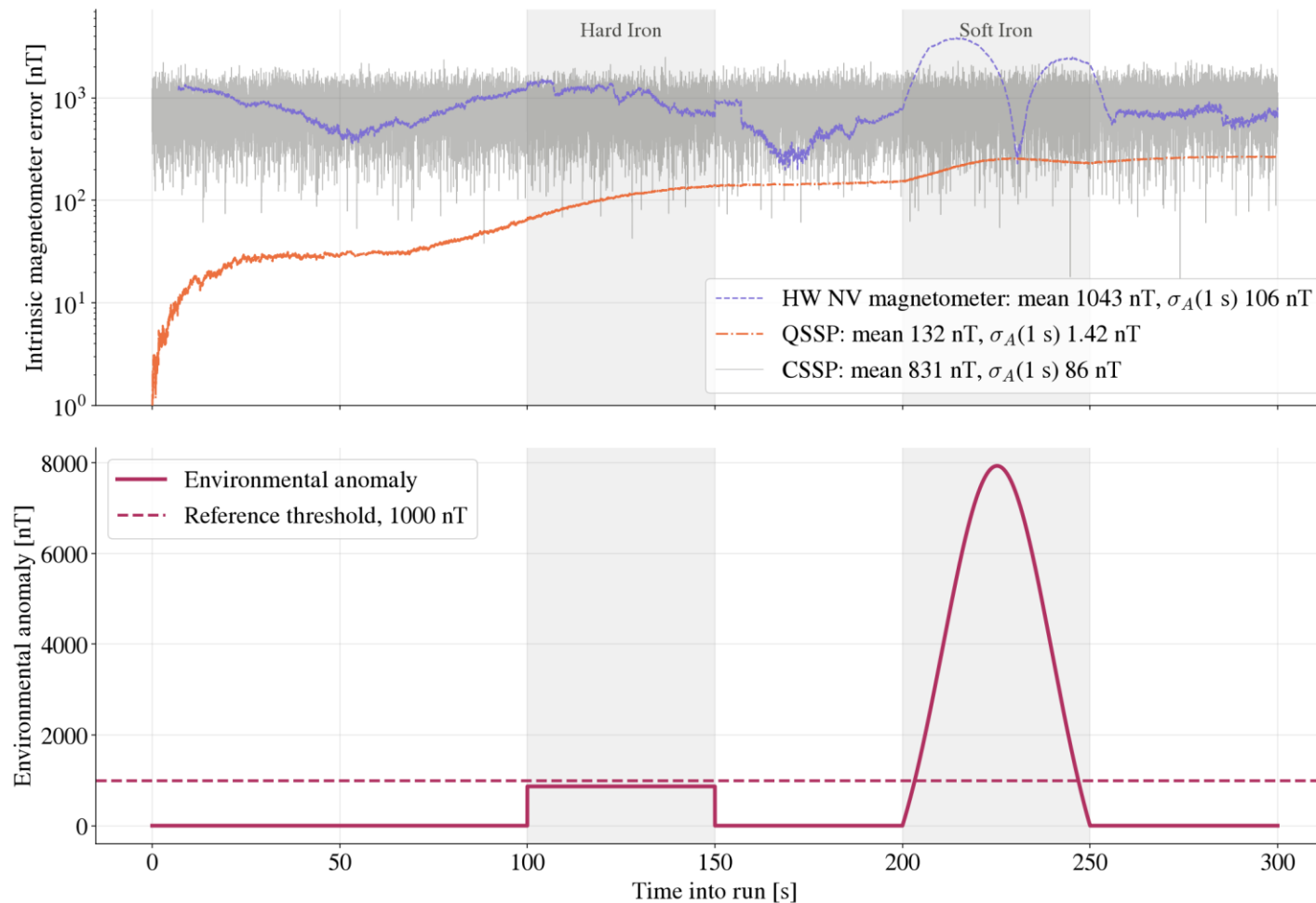
UAV



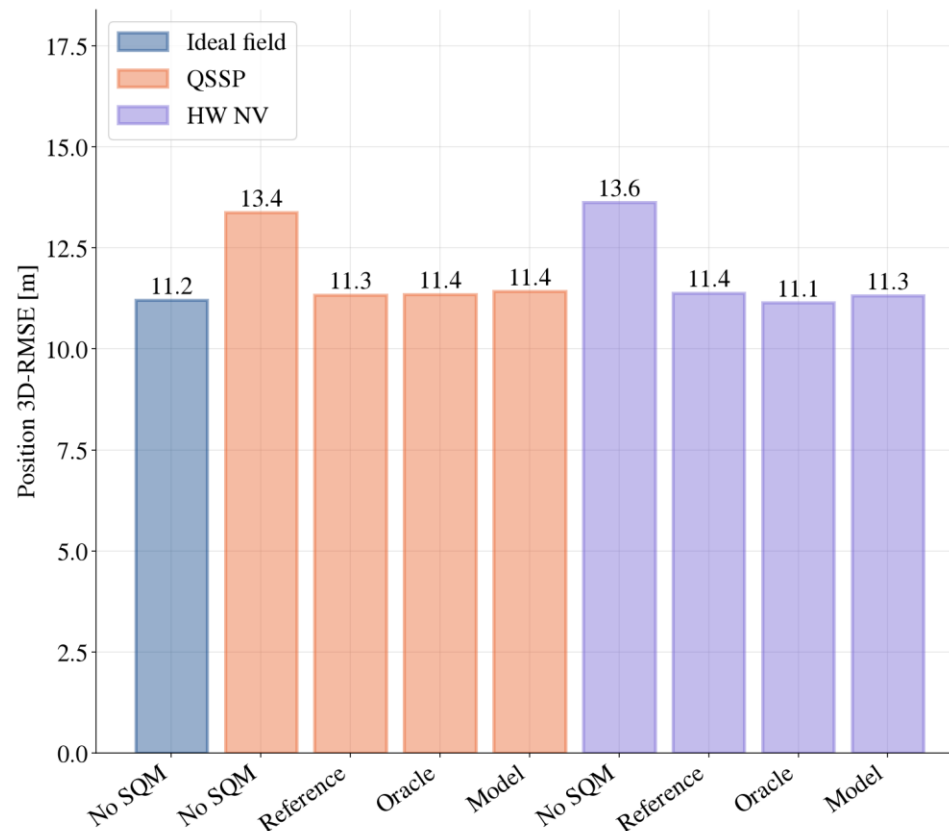
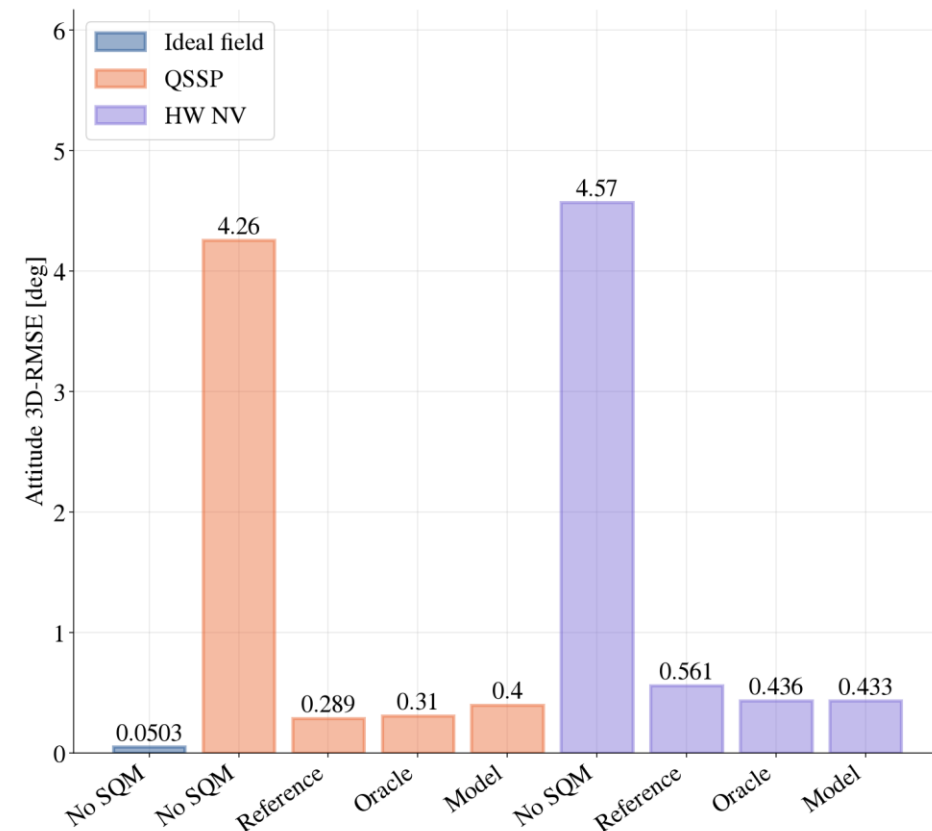
Real time feasibility using Raspberry Pi 4



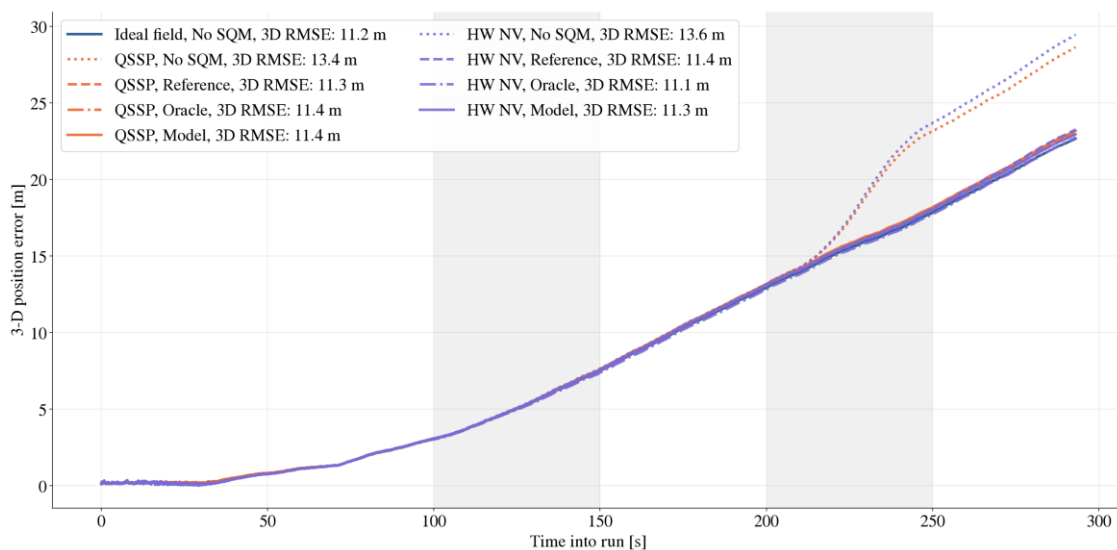
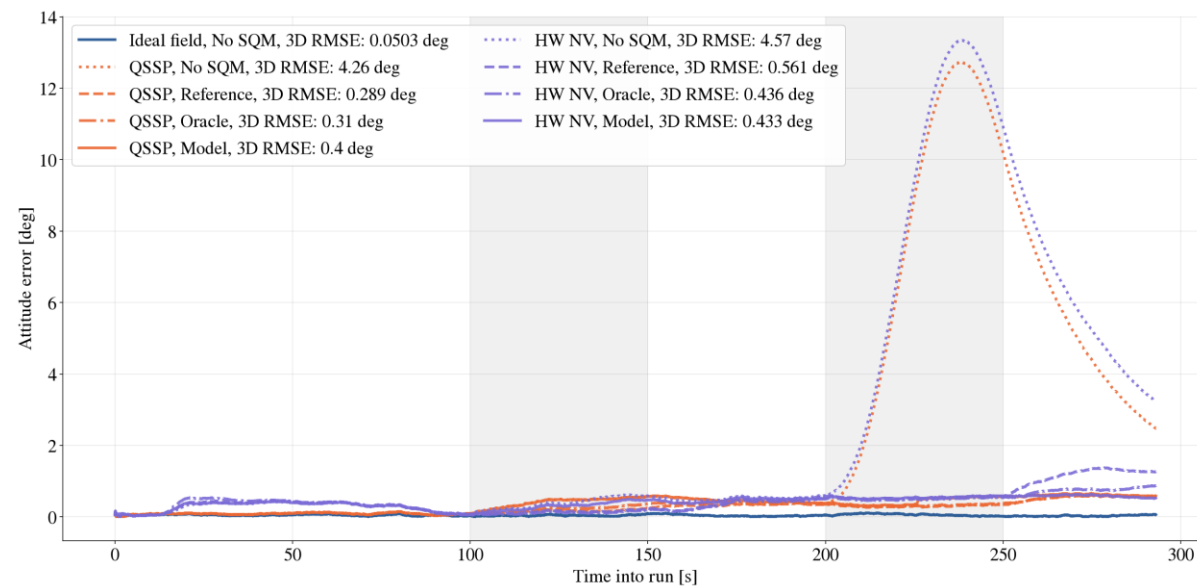
Sensor fusion test campaign, UAV



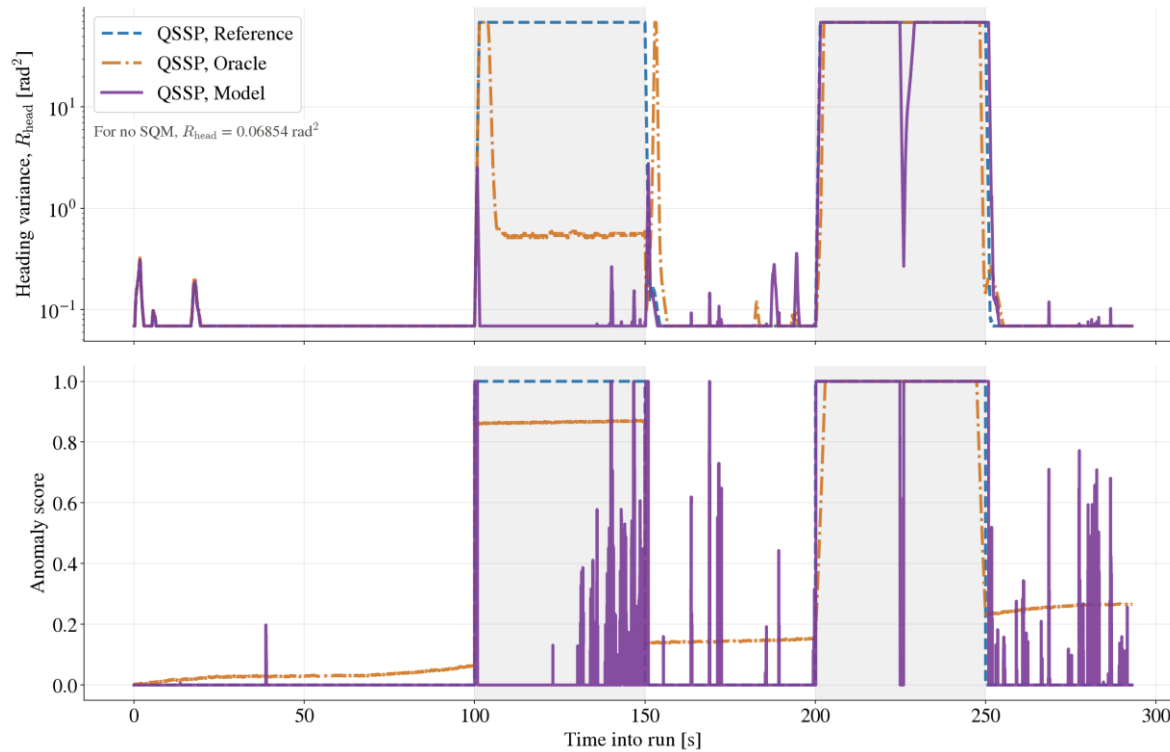
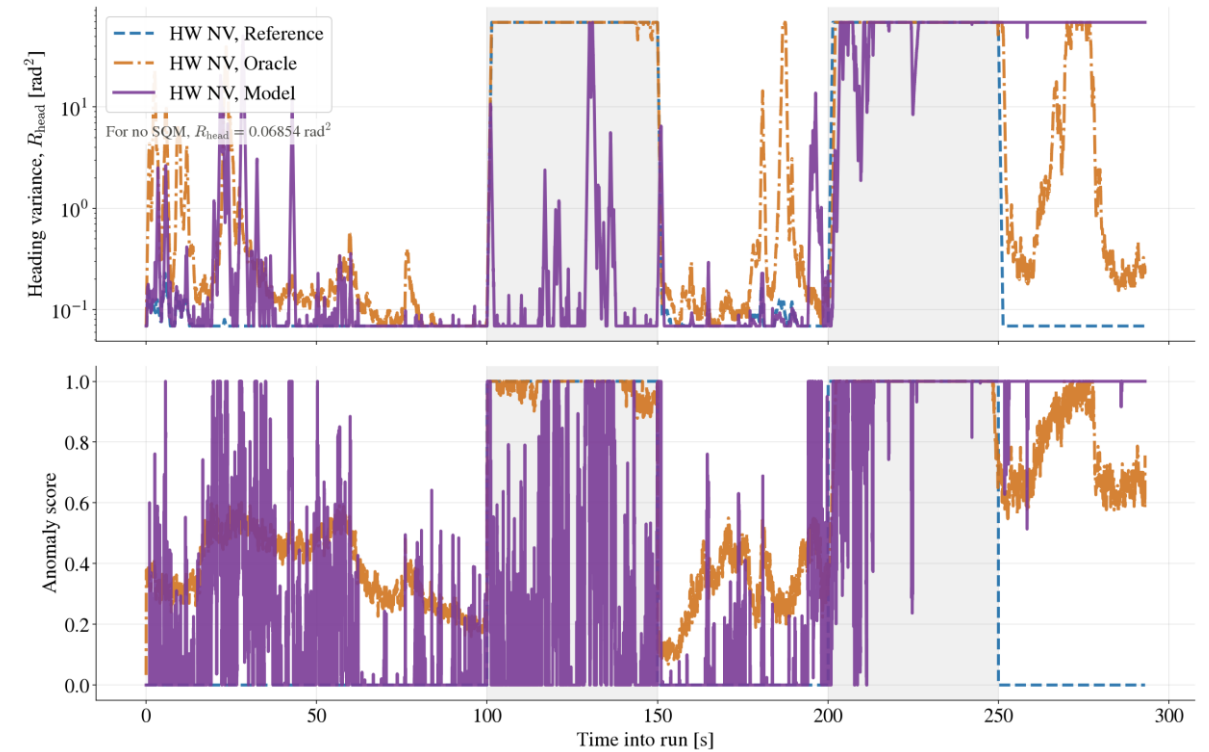
Sensor fusion test campaign, UAV



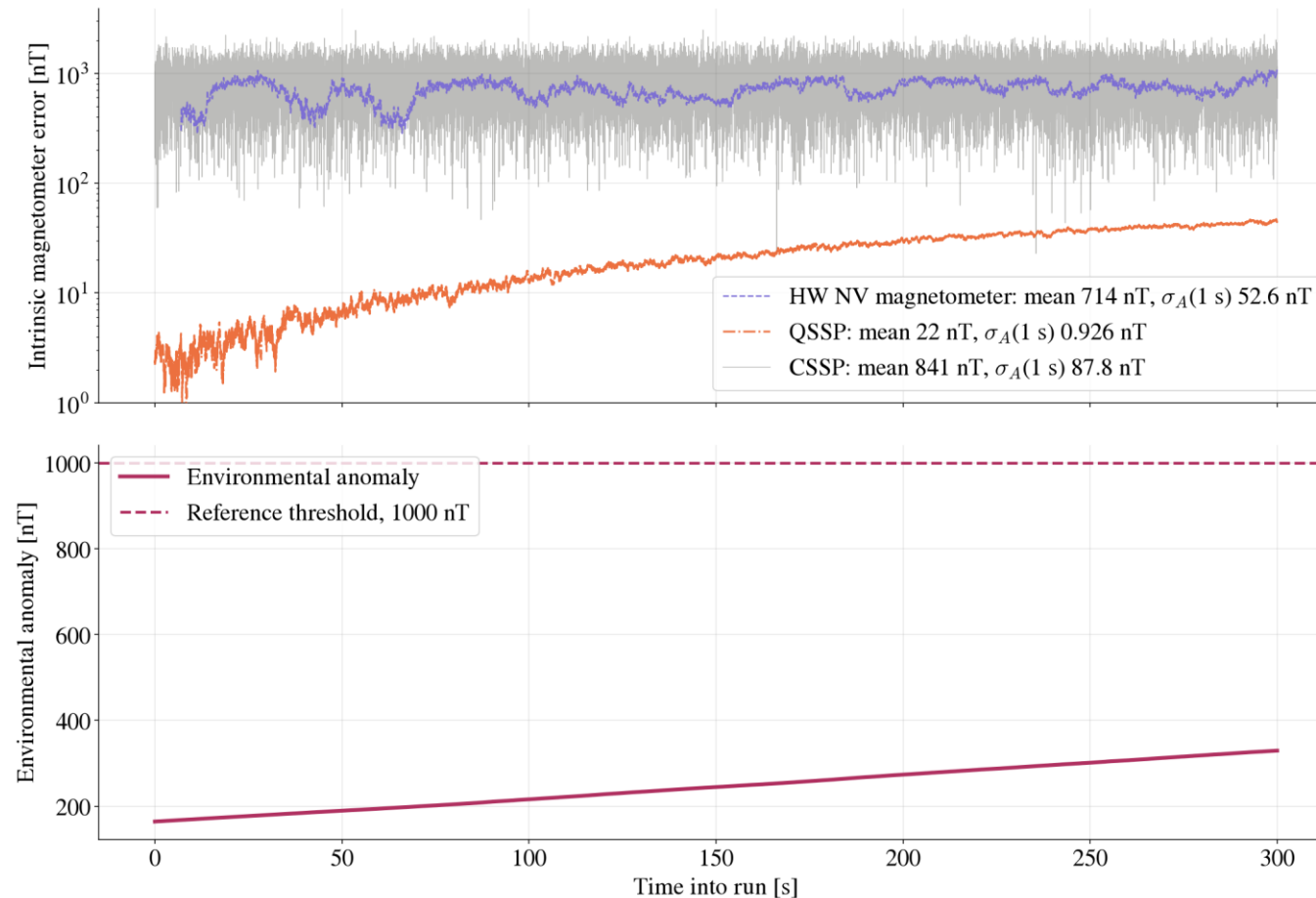
Sensor fusion test campaign, UAV



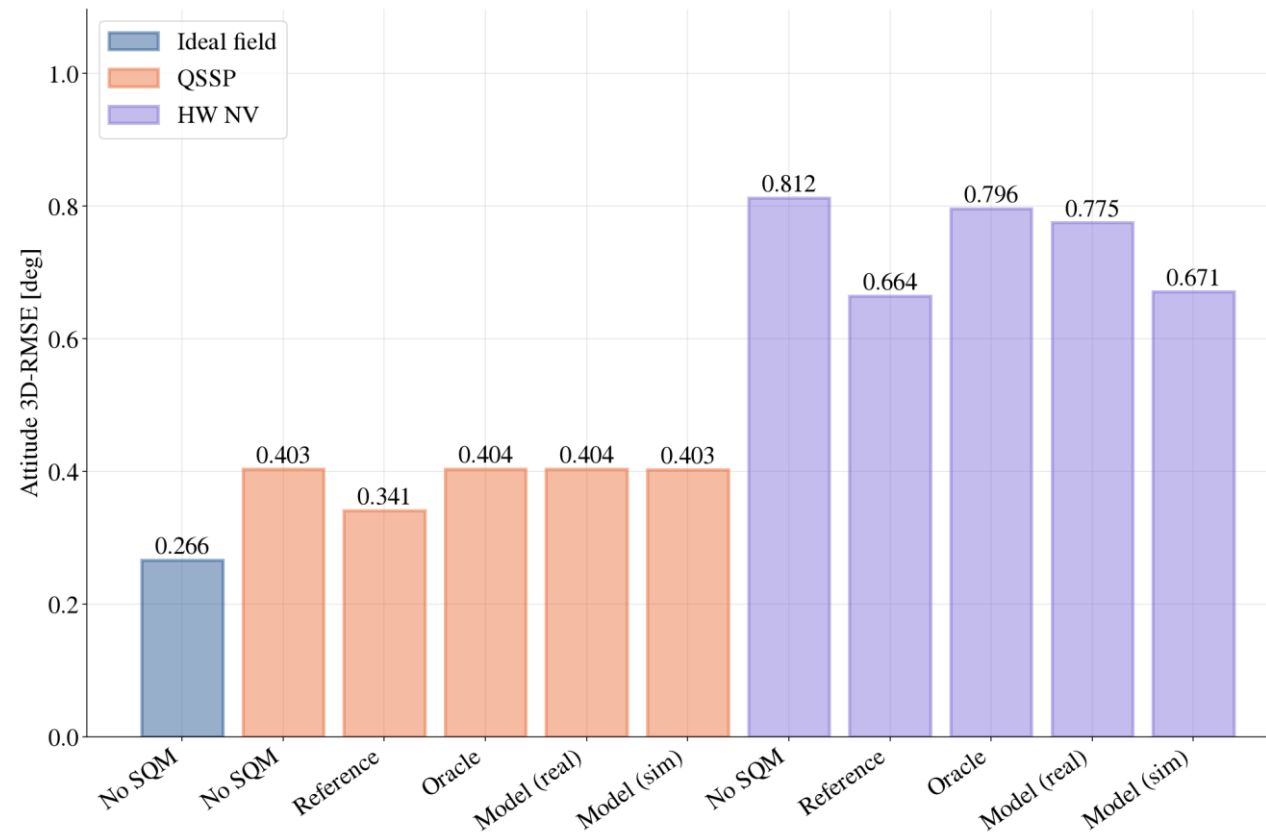
Sensor fusion test campaign, UAV



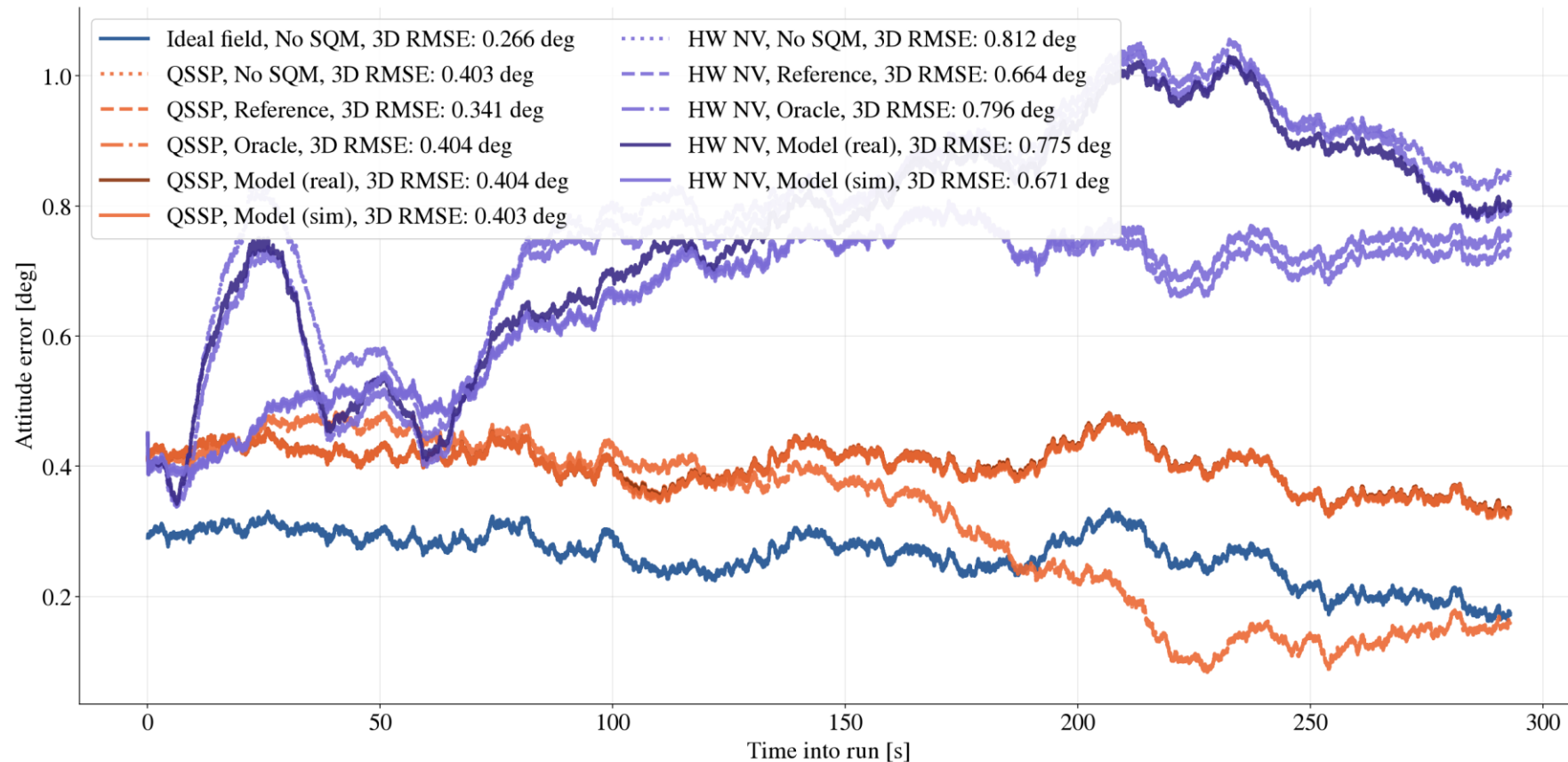
Sensor fusion test campaign, LEO



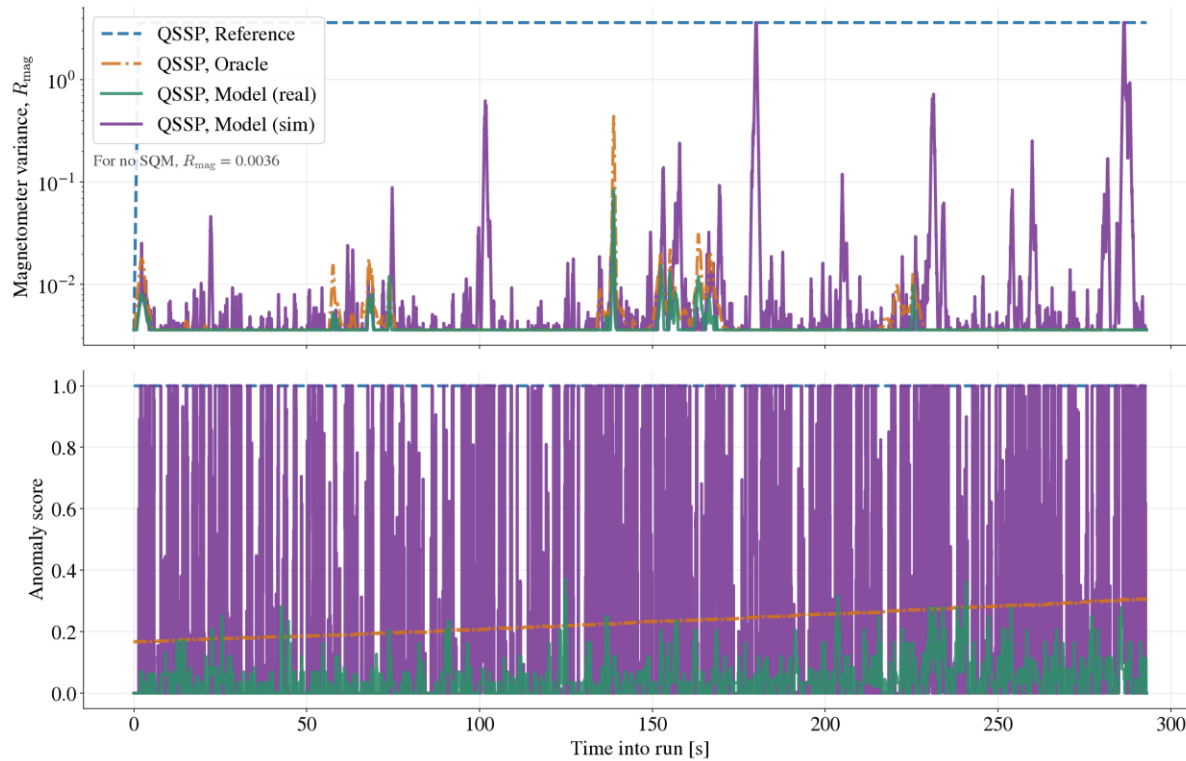
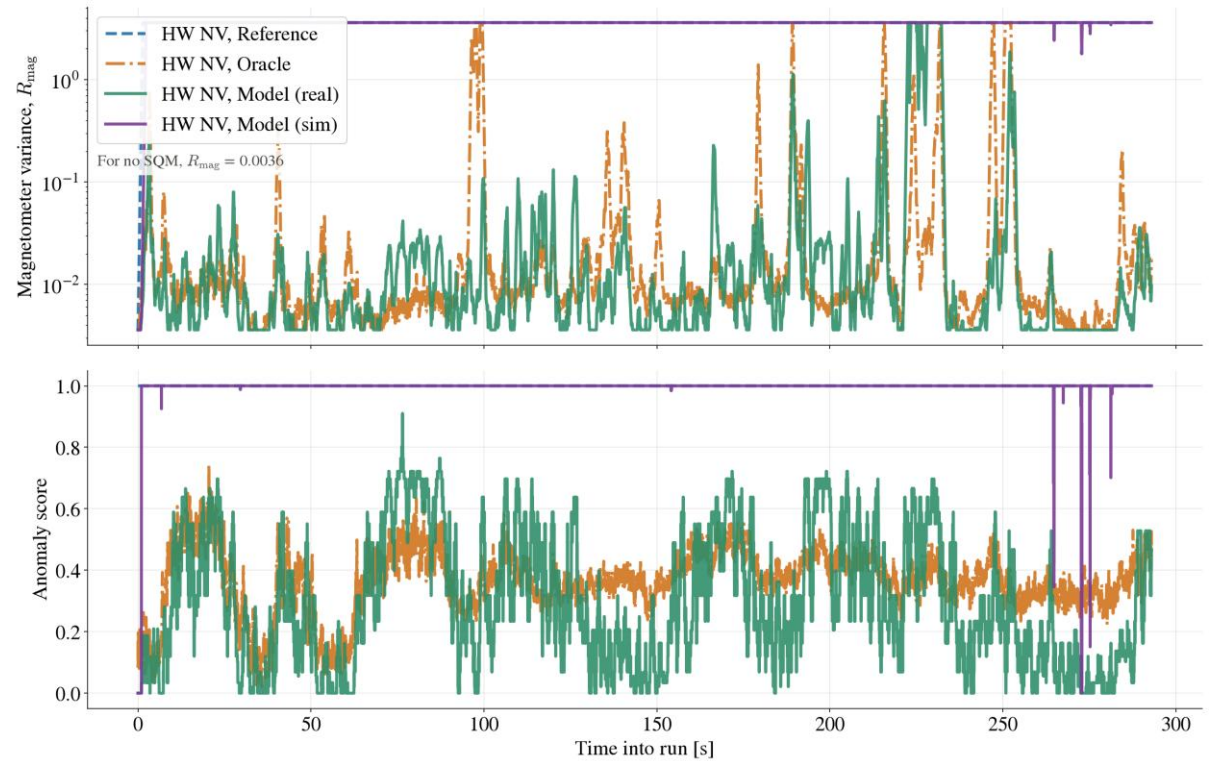
Sensor fusion test campaign, LEO



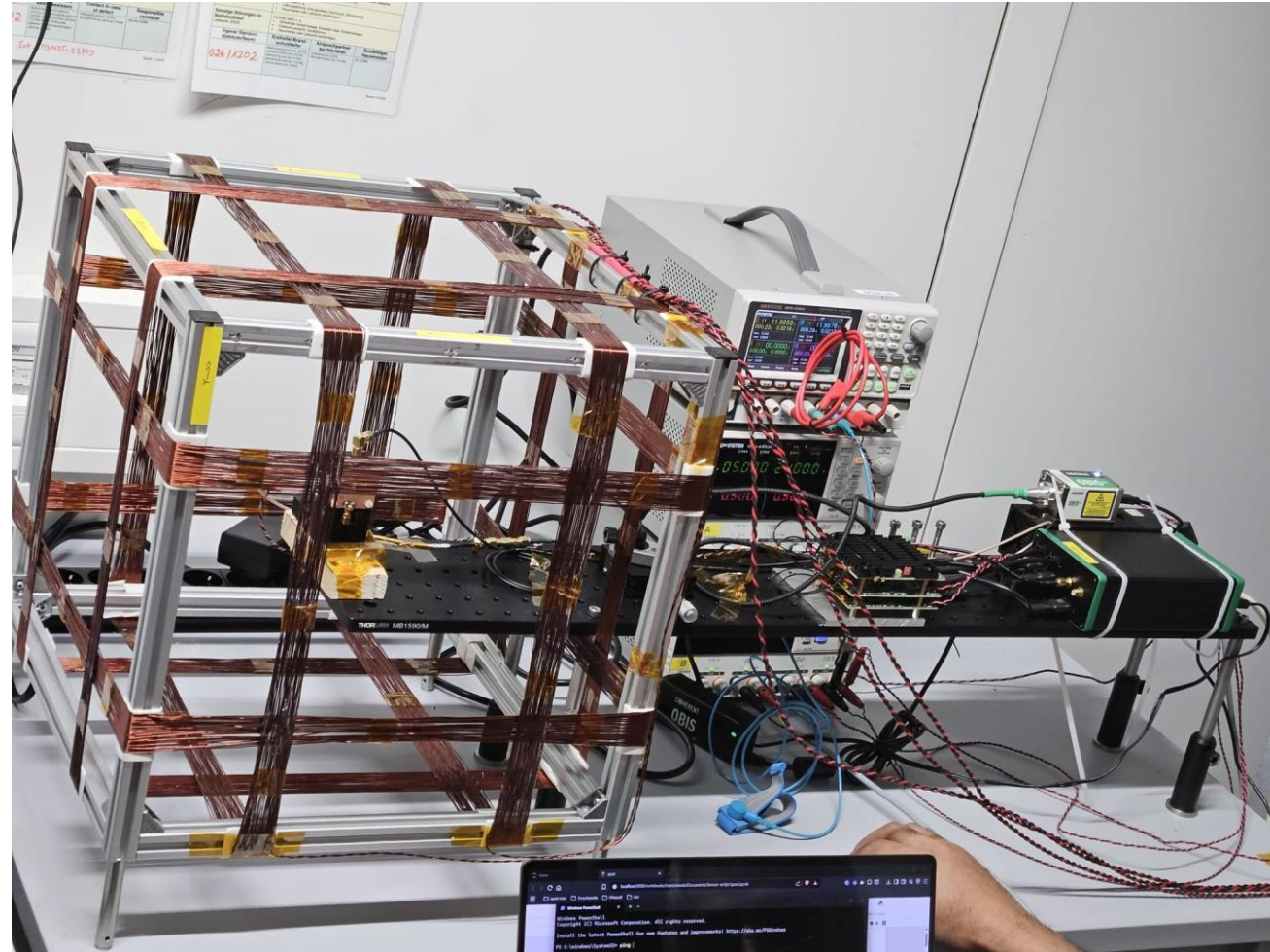
Sensor fusion test campaign, LEO



Sensor fusion test campaign, LEO



Conclusion, Exploitation, Feedback



Conclusion, Exploitation, Feedback

Conclusion:

- Anomaly detection improves navigation performance in the presence of magnetic field disturbances
- Models trained on synthetic data alone do not transfer to the current real instrument
- One of the trained models has performed as well as the reference soft anomaly score
- Sensor maturity is the binding constraint

Improvements:

- Sensitivity enhancement via implementation of advanced coherent control techniques
- Making sensors insensitive to temperature fluctuations via use of double quantum transitions
- Implementation of photoelectrical readout of NV centres for enhanced sensitivity
- Machine learning protocols for data analysis and coherent control
- Realization of magnetometer using space certified electronics for space

Conclusion, Exploitation, Feedback

Four exploitable assets were generated by the activity:

- the **Q-PAD simulation platform**, which has value independently of the sensor as a development and benchmarking environment for anomaly detection techniques used in magnetometers or any other inertial sensor;
- the **trained anomaly detection models** and the associated training and optimisation framework;
- the **RNAC adaptive sensor fusion module**, which is sensor-agnostic and applies to any aiding observation carrying a SQM signal; and
- the **HIL emulation testbed** (HW deliverable), which is reusable for the qualification of any magnetometer intended for navigation use.

The consortium is positioned to exploit these along complementary lines:

- **RN** carries the simulation framework, the ML framework for anomaly detection techniques, and the adaptive sensor fusion engine;
- **TOG** provides the route to the GNSS and positioning equipment market; and
- **UULM** and **IMEC** supply the underlying quantum sensing technology.

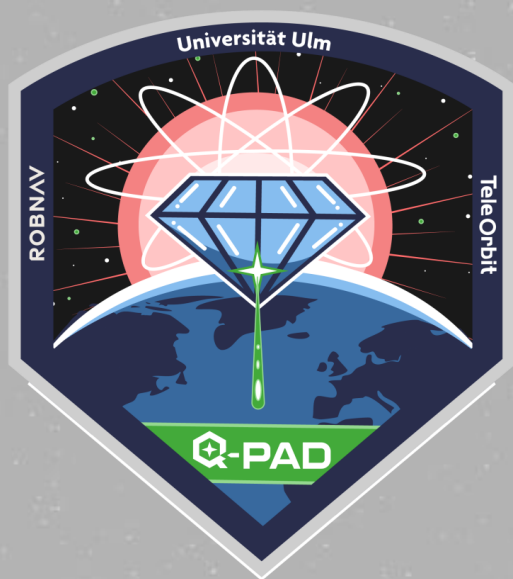
Benefits of working with ESA

The benefit of working with ESA in this project was the **fruitful collaboration with ESA's technical officer Luis Mansilla Garcia** and his colleagues Marnix Meersman, Thomas Klein, Diane Magnin, Jose Pizarro, who were able to give guidance and were very helpful and supportive throughout the project, boosting the results of Q-PAD.

ESA with its many projects in all kind of topics is also always supportive in connecting us with new users, partners and research colleagues.

The project followed a well-structured format, with cumulative reporting of achievements throughout its duration, which helped keep us on track.

Overall, innovative research like in this project wouldn't be possible without the ESA NAVISP funding.



Q-PAD
Final
Presentation

<https://teleorbit.eu>

TeleOrbit
The Locating Company

THANK YOU!
Time for the Q&A

Mail: jseybold@teleorbit.eu
dseybold@teleorbit.eu

Web: <https://teleorbit.eu/>

TeleOrbit GmbH
Postfach 91 02 49 | D-90260 Nuremberg
Sandrartstraße 20 | D-90419 Nuremberg
Tel +49 (0)911 300 339 80
Fax +49 (0)911 300 339 819
E-Mail info@teleorbit.eu
Web <https://teleorbit.eu>