WORKING WEEK 2025
AND Locate25
THE NATIONAL GEOSPATIAL CONFERENCE
FIG Geospatial Council of Australia
Collaboration, Innovation and Resilience: Championing a Digital Generation
Brisbane, Australia 6–10 April

Quantum Sensors for Enhanced Positioning and Navigation

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April 2025, Brisbane

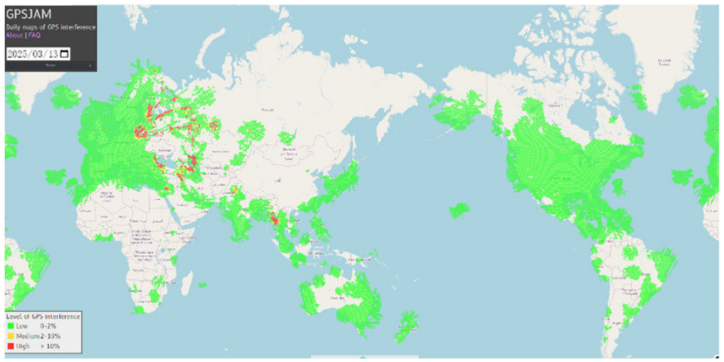
Outline

1. Background and Motivation
2. Quantum Sensors for Navigation
3. Case Studies
4. Other Work
5. Summary and Outlook

GNSS is Vulnerable

Major threats:

- Interference (jamming)
- Spoofing
- Multipath & signal blockage
- Constellation geometry
- System failures (solar emissions …)
- …



Source: https://gpsjam.org/

~$1B/day economic loss in the US only

~£1.4B/day economic loss in the UK only

Urgent need for Augmentation Solutions and Alternative Technologies

Resilient PNT

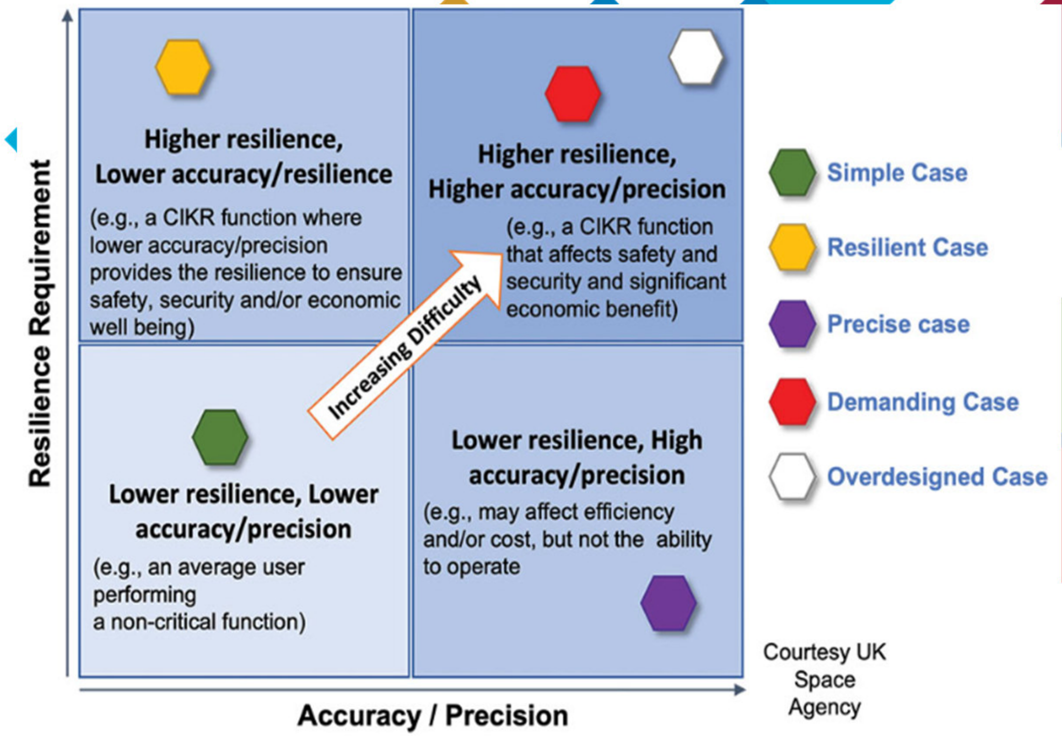
Various conceptual frameworks for PNT

- ✓ **Alternative PNT (AlPNT)** (Narins et al., 2012; FAA)
- ✓ **Assured PNT (AsPNT)** (Parkinson, 2014; DoD)
- ✓ **Resilient PNT (RPNT)** (Yang et al., 2018, 2019)
- ✓…

Definition of Resilient PNT

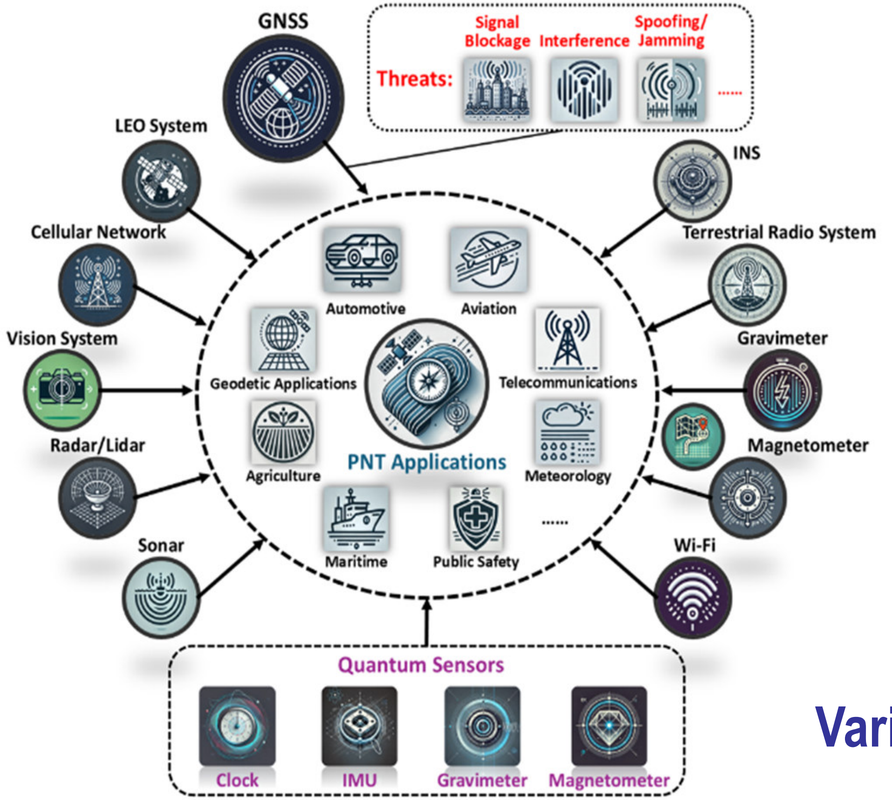
"*Based on the **multi-source PNT sensors and integrated PNT information**, resilient PNT integrates and generates PNT information adaptable to various complex environments by means of resilient adjustment of functional models and stochastic models, to provide PNT services with high **availability, continuity and reliability**.*"

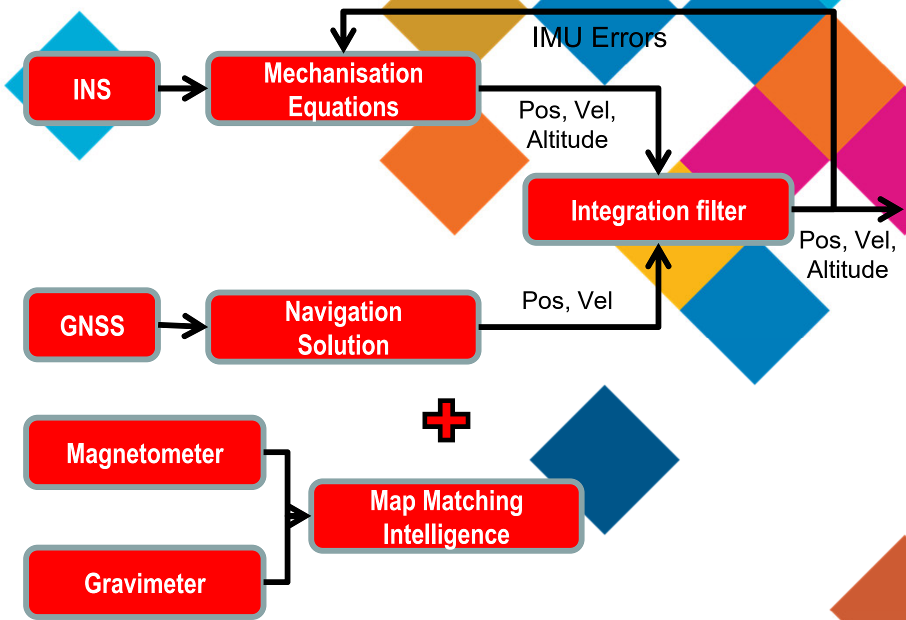
Source: Yang et al., 2019, "Resilient PNT Concept Frame"



Source: https://www.gpsworld.com/delivering-security-through-systems-engineering/

Fusion of Multiple Sensors





Various sources supporting a resilient PNT architecture

2. Quantum Sensors for Navigation

Quantum science (behaviour of particles at scales smaller than an atom)

- **Superposition**: **Multiple states** simultaneously
- **Entanglement**: **Connected** across space/time.

These effects are **fragile** and **collapse** under observation – **ultra-precise sensing**

Basic working principle of quantum sensors: Exploit the extreme sensitivity of atoms to environment

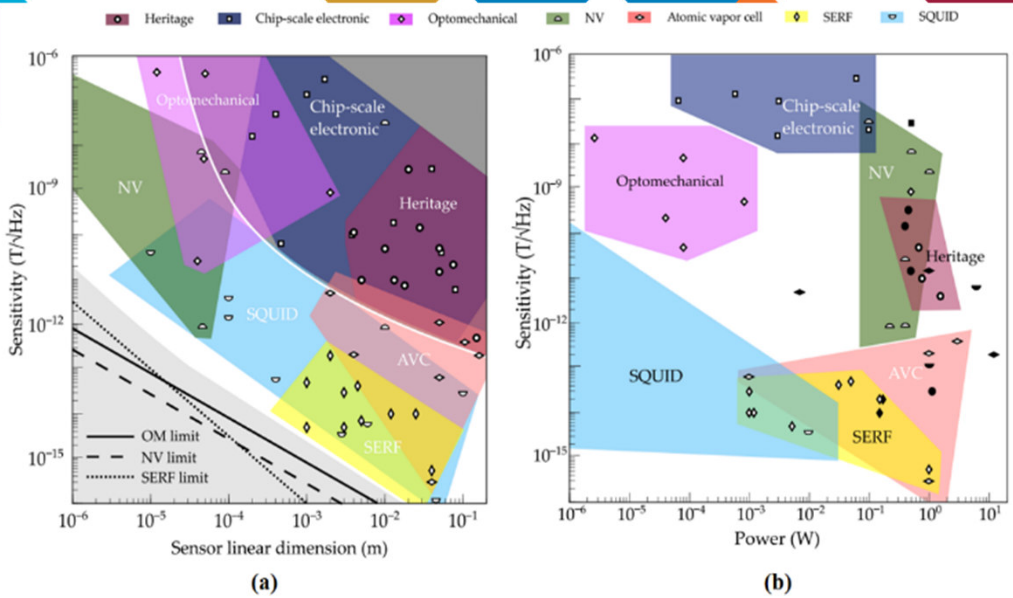
Information → **Atom is prepared** → **Interaction with environment** → **Atom (waveform) is changed** → **Environmental information is extracted**

Acceleration, rotation, gravity/magnetic/electromagnetic fields, etc

2. Quantum Sensors for Navigation

Quantum Technologies:

- **Cold atom technology** (cold atom interferometers)
- **Superconducting quantum interference devices (SQUID)**
- **Atomic vapour cell** (Spin Exchange Relaxation-Free, SERF)
- **Solid-state quantum technology** (NV-centre diamond)
- **Optical quantum technology**
- …



Source: https://www.mdpi.com/1424-8220/21/16/5568

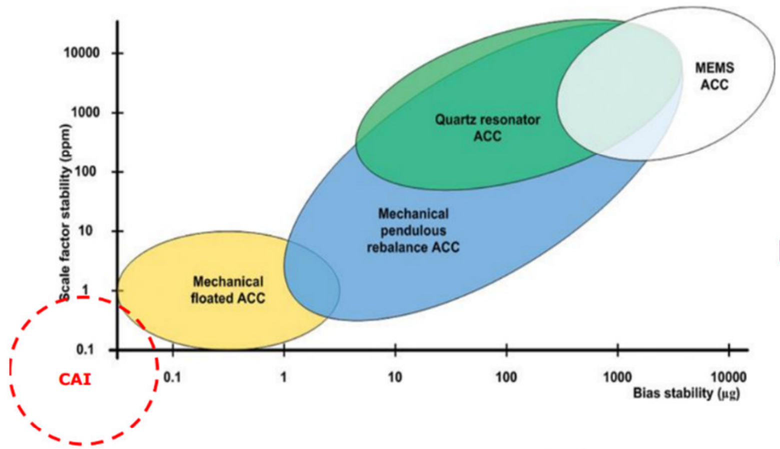
2. Quantum Sensors for Navigation

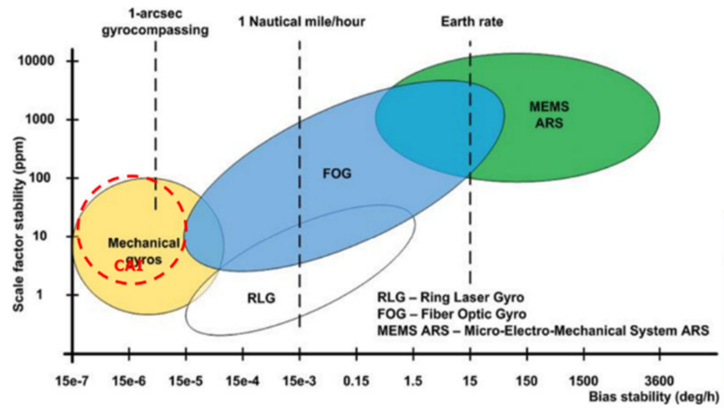
Why cold atom interferometer?

- **Only known tech. providing stable long-duration navigation**
- **Fully autonomous - no external references**

Why NV-centre diamond magnetometer?

- **Solid state design:** robust, stable, compact
- **Room-temperature** quantum performance
- **Low power:** ideal for AUV/portable applications
- **Large measurement range:** sensitive in extreme fields
- **High bandwidth:** fast measurements in dynamic environments
- **Inherent vector capability:** unique to diamond





Source: JRC Technical Reports

2. Quantum Sensors for Navigation

Quantum sensor improves inertial measurement accuracy **by orders of magnitude**.

A key challenge is managing the trade-off between range/bandwidth and accuracy

- **Bandwidth:** Frequency at which the sensor delivers measurements within specifications – *Interrogation time*
- **Range:** Minimum/maximum values it can measure – *Phase-wrapping issues*
- **Accuracy:** Minimum detectable change (in acceleration)

	Classical	Quantum
Bandwidth	300 to 500 Hz	0.5 to 2 Hz
Range	±15 g	±1.2 g
Accuracy	500 µg (micro-g | 10^{-8})	10 pg (pico-g | 10^{-12})

Classical sensors – High update rate and dynamic range

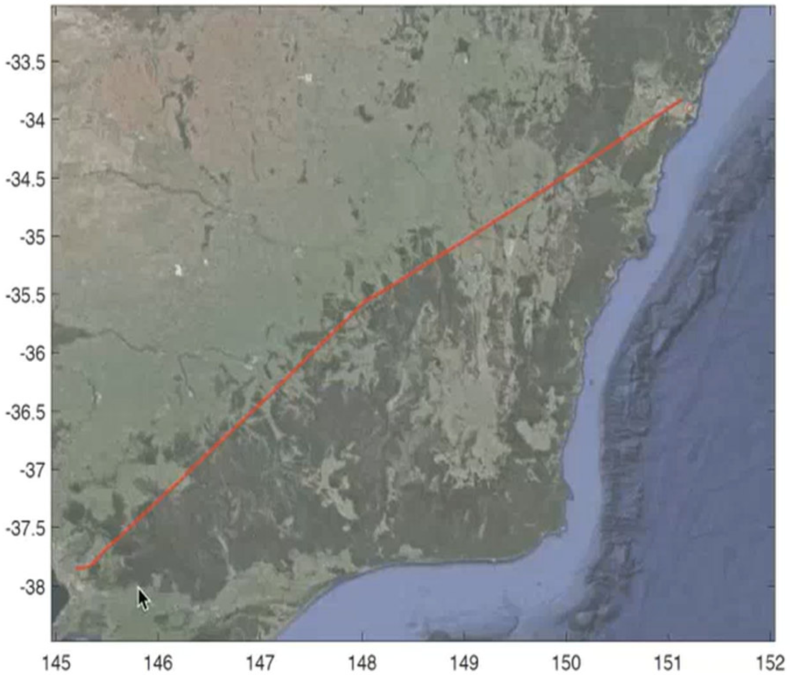
+

Quantum sensors – Extreme accuracy with minimal error/noise

↓

Fusion system – Ultra-precise measurements, with virtually no drift, high dynamic range and high bandwidth.

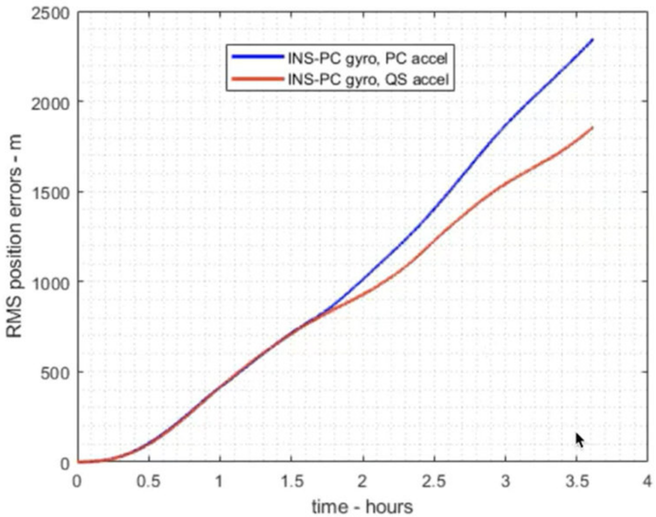
3. Case Studies



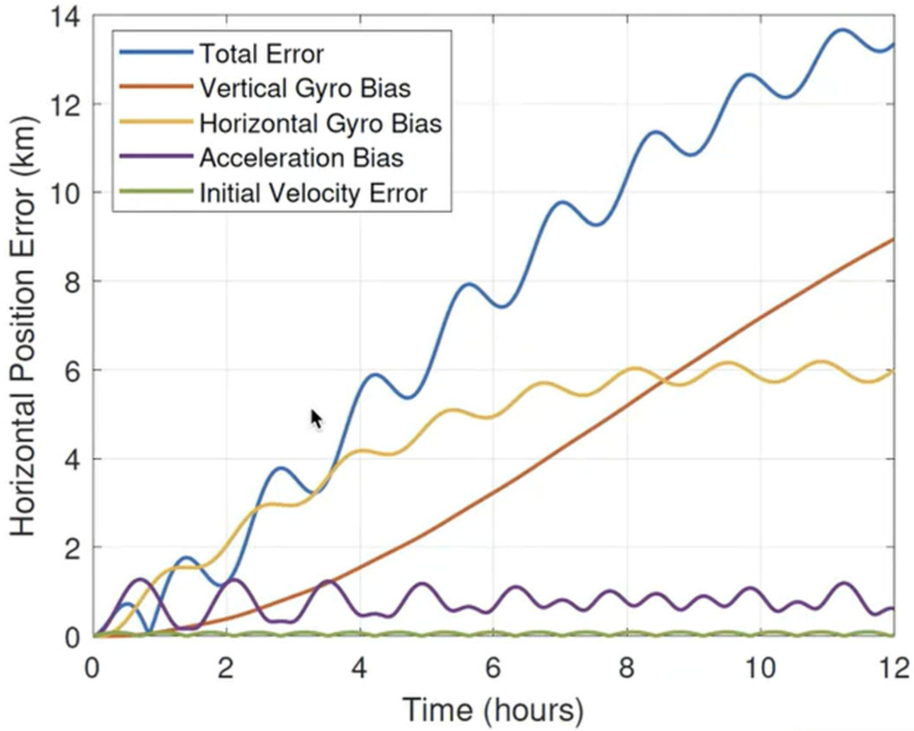
- ✓ Constant velocity (ground speed of 22 m/s)
- ✓ Travel at a fixed height of 100 m
- ✓ From Melbourne to Sydney
- ✓ Takes over 3.6 hours
- ✓ Sampling rate of 1 Hz
- ✓ In GNSS-denied environment

3. Case Studies

Analysis of sensor bias and errors

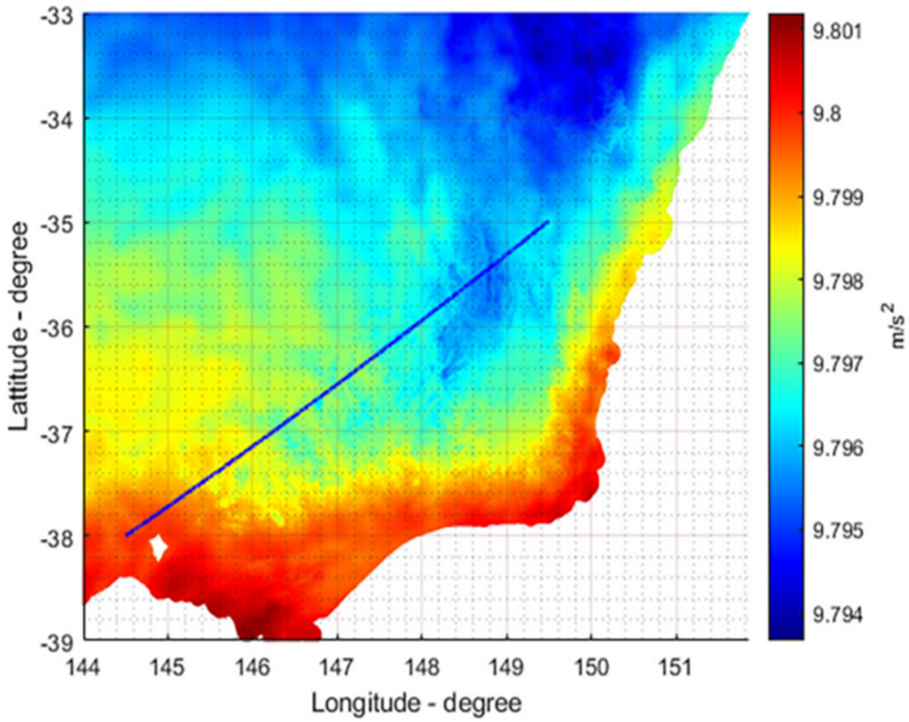


Sensor Grade	Sensor Type	Bias b	White Noise σ
Precision	Accel. horiz.	$2 \times 10^{-6} m/s^2$	$8 \times 10^{-5} m/s^2/\sqrt{Hz}$
	Accel. Vert.	$2.5 \times 10^{-8} m/s^2$	$1.6 \times 10^{-6} m/s^2/\sqrt{Hz}$
	Gyro. horiz.	$2 \times 10^{-5} deg/h$	$1 \times 10^{-3} deg/h/\sqrt{Hz}$
	Gyro. vert.	$1 \times 10^{-3} deg/h$	$3 \times 10^{-2} deg/h/\sqrt{Hz}$
Quantum (QS)	Accel.	$1 \times 10^{-8} m/s^2$	$3 \times 10^{-8} m/s^2/\sqrt{Hz}$
	Gyro.	$1 \times 10^{-5} deg/h$	$1.2 \times 10^{-4} deg/h/\sqrt{Hz}$

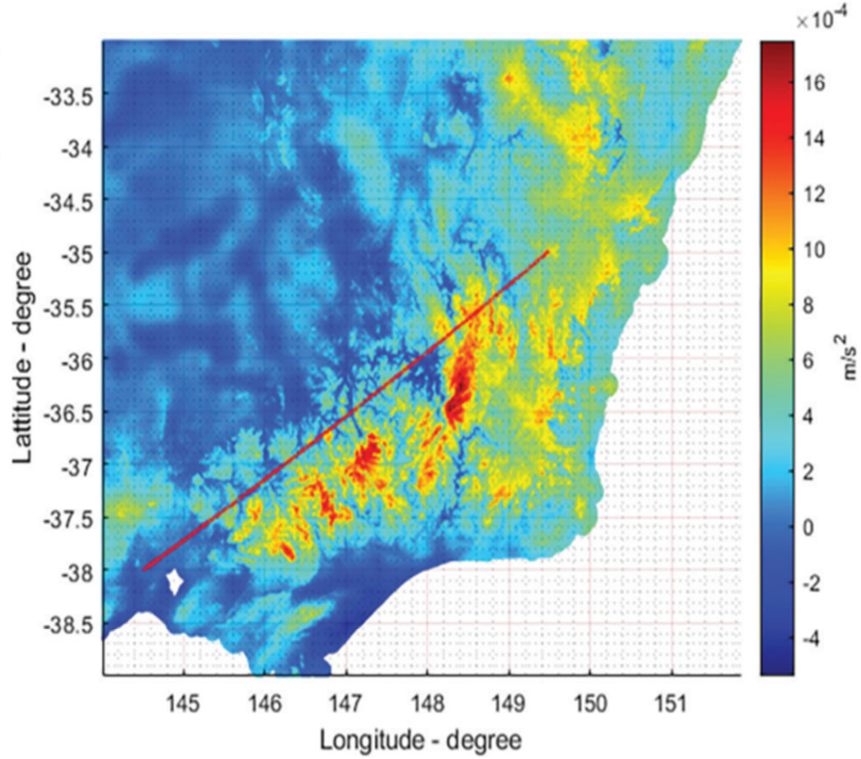


3. Case Studies

Map Aiding – Maps of Gravity Signatures



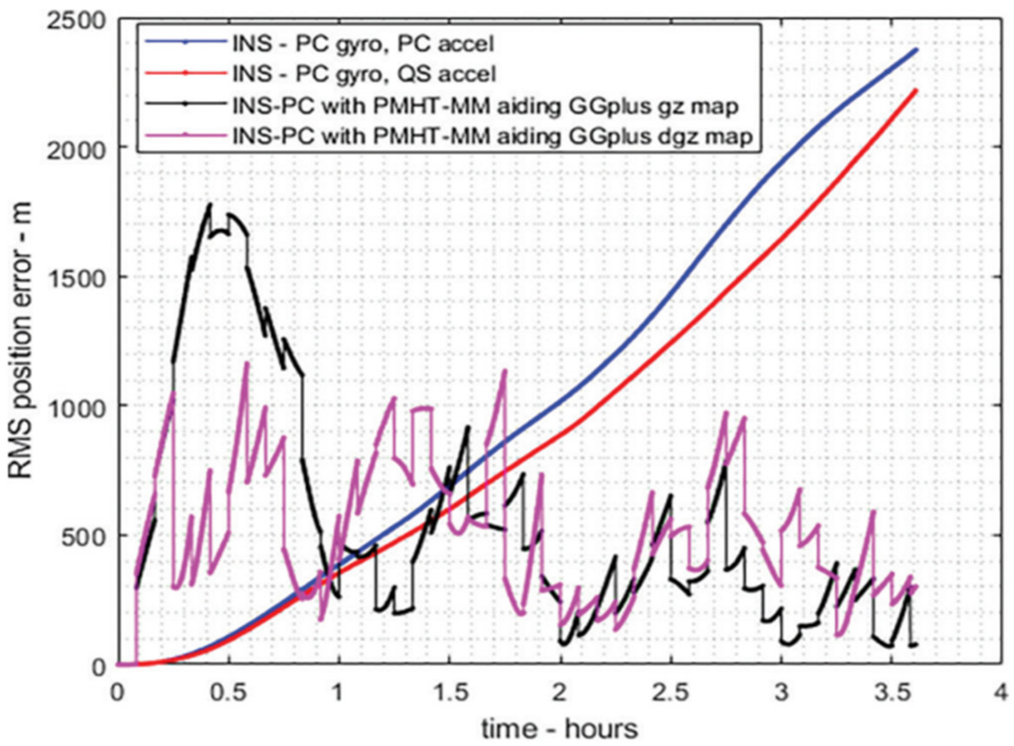
GGMplus: Gravity field



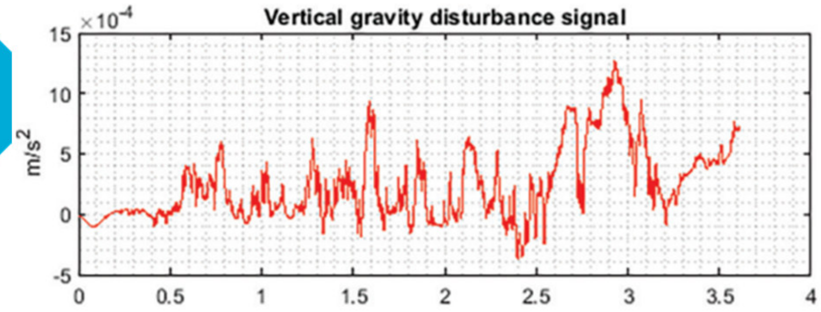
GGMplus: Gravity disturbance

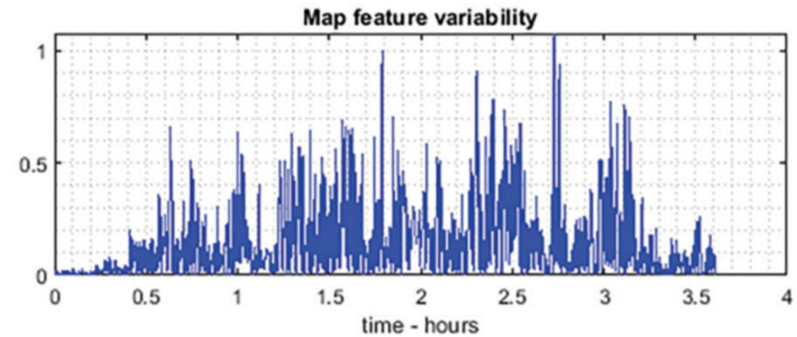
3. Case Studies

Map Aiding – Maps of Gravity Signatures



Wang et al., 2023, doi: 10.33012/navi.583



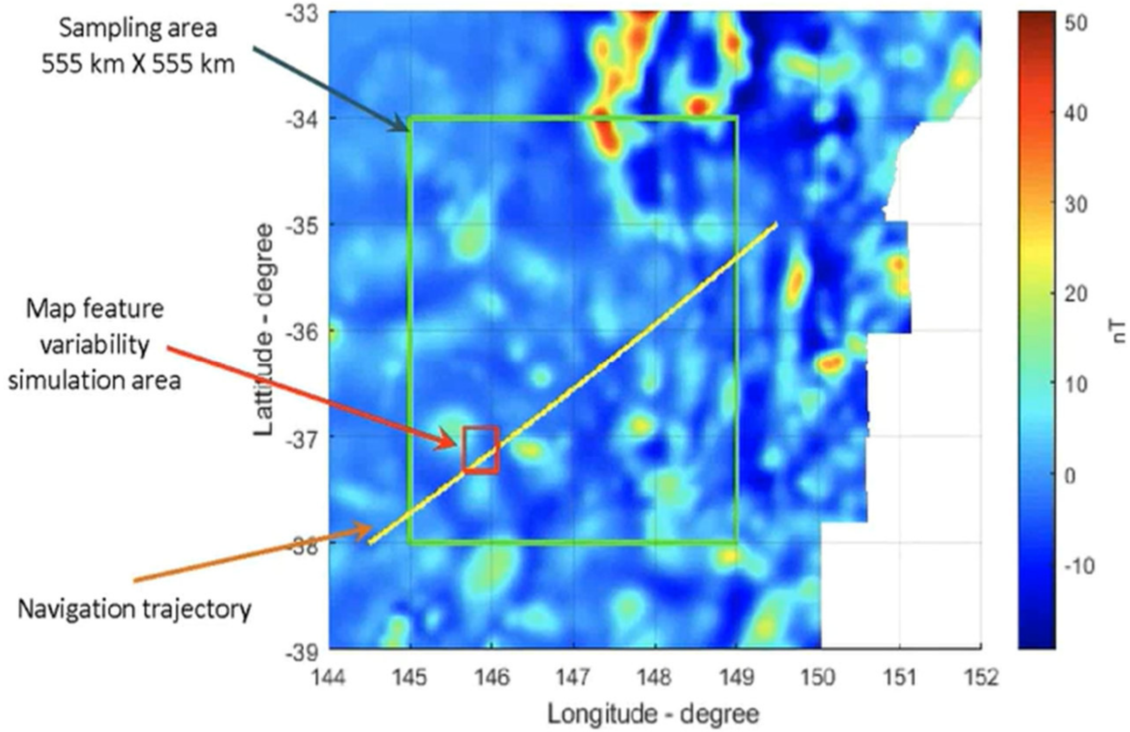


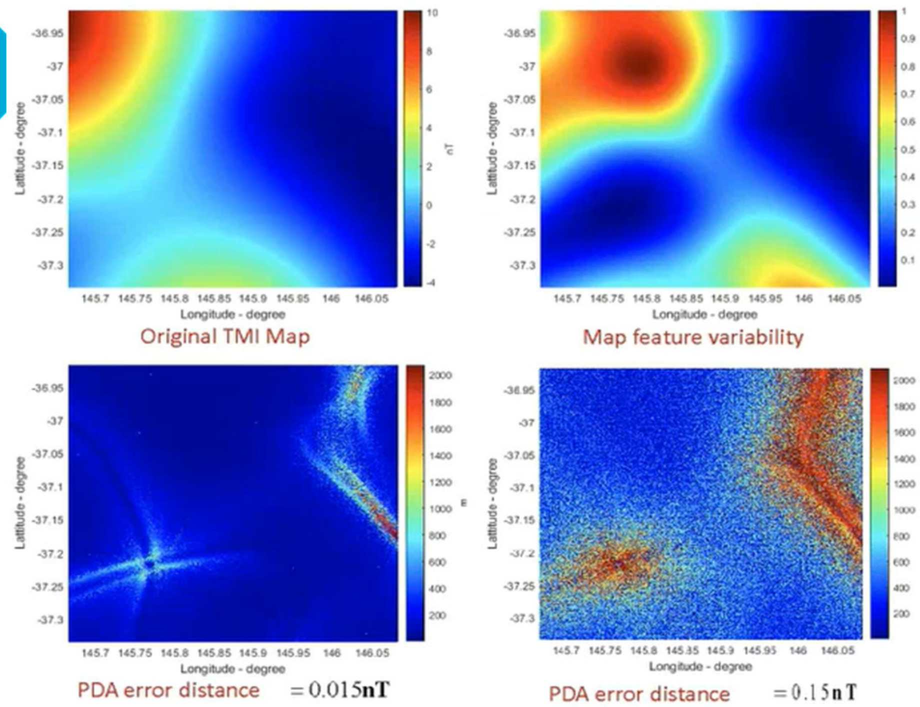
Performance depends on **sensor precision** & **map resolution**

(First 30 min: **low** map variability feature, **flat** sensor signal)

3. Case Studies

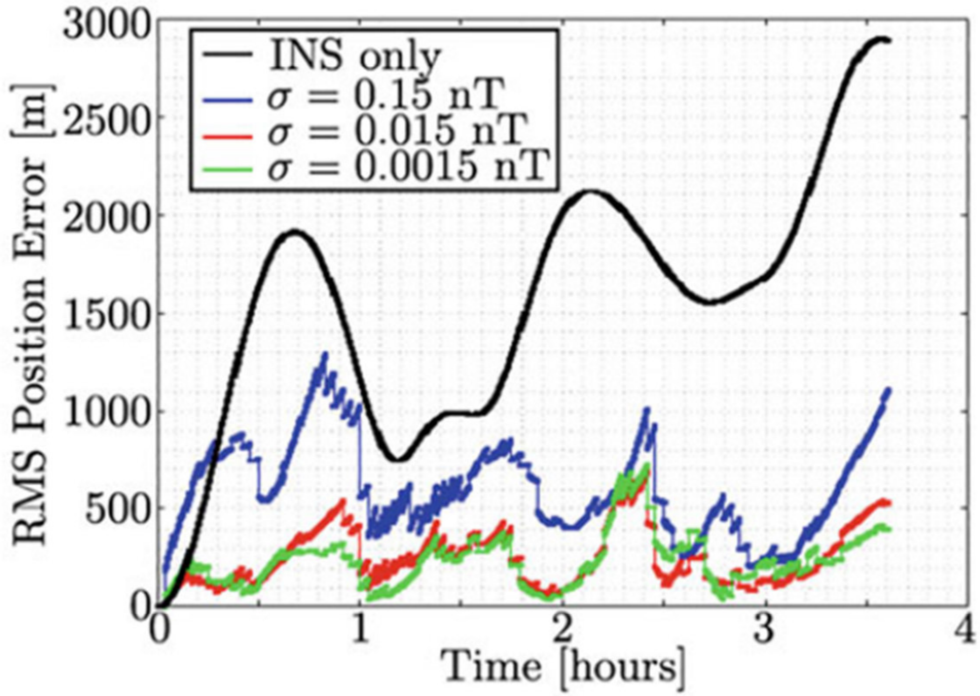
Map Aiding – Magnetic Field (TMI)





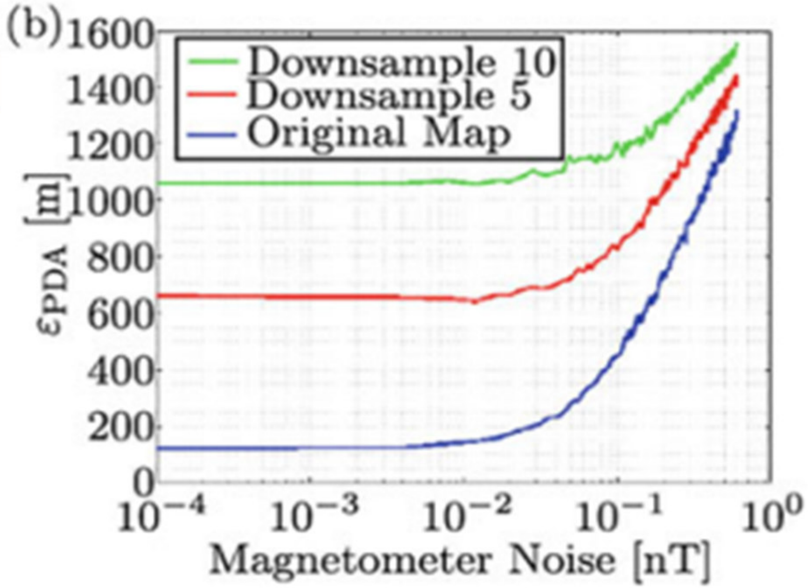
3. Case Studies

Map Aiding – Magnetic Field (TMI)



0.15 nT (COTS); 0.0015 nT (NV diamond)

Wang et al., 2023, doi: 10.1007/1345_2023_218



- ✓ Position error decreases with improving sensitivity
- ✓ For a finite resolution map there is a sensitivity below which no improvement is expected.

4. Other Work

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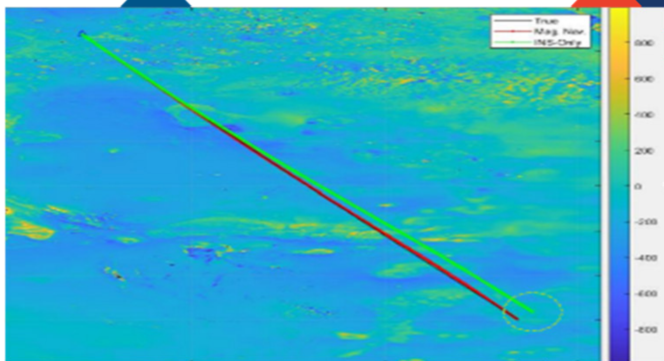
Recent Achievement:

- Translated quantum diamond sensing **from lab to real world applications**
- Built a **field-deployable prototype**: Quantum diamond magnetometer
- Tested in **land** (vehicle-mounted), **deep ocean**, and **airborne** trials
- Deployed on an aircraft in a joint AU/US flight trial – World's first NV-centre diamond magnetometer on an aircraft, collected >8000 km of data
- Achieved GNSS-independent magnetic navigation



5. Summary and Outlook

- **Quantum sensors** are poised to change how we do many PNT tasks (reduce SWaP-C, improve stability, integration, etc.).
- **Bridging the gap** between lab-based experiments and real-world applications.
- **Sensor fusion (Classical/quantum system)** will be essential for achieving resilient PNT.
- **Map aiding** further improves positioning performance (statistical robustness).
- **Sensitivity** depends on sensor and map accuracy (Better sensors also enable better maps).
- Future work will **integrate quantum sensors with classical systems** in various architectures to provide enhanced performance and resilience.

Game-changer for future Resilient PNT

Promise to complement and provide alternatives to traditional satellite-based navigation

Thank you

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The most relevant SDGs related to the presentation and theme of this session

1st relevant SDG: 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

2nd relevant SDG: 11 SUSTAINABLE CITIES AND COMMUNITIES

3rd relevant SDG: 17 PARTNERSHIPS FOR THE GOALS

SUSTAINABLE DEVELOPMENT GOALS | International Federation of Surveyors supports the Sustainable Development Goals