

Navigation in GNSS-Denied Environments Using MEMS-Grade Sensors and Geophysical Anomalies

A UKF Approach

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The GNSS Dependency Problem

Modern navigation is critically dependent on GNSS

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Vulnerabilities:

- Urban canyons & multipath
- Indoor/underground environments
- Underwater operations
- Electronic warfare (jamming/spoofing)

*[GNSS Vulnerability
Illustration]*

The Cost-Performance Gap

Historical Geophysical Navigation

High-grade systems only:

- Navigation/Tactical-grade IMUs (\$10K - \$100K+)
- Dedicated gravimeters and magnetometers
- Military & aerospace applications

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The Opportunity

Consumer platforms need GNSS-independent navigation:

- Smartphones, drones, small autonomous vehicles
- MEMS-grade IMUs (\$10 - \$1K)
- Low SWaP constraints

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Can geophysical navigation work with low-cost sensors?

Data Collection:

- Smartphone-grade MEMS sensors
- Sensor Logger application
- Long-duration highway trajectories
- 30 min - several hours each
- Tens to hundreds of kilometers

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Sensors:

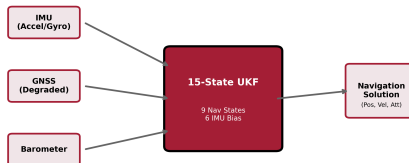
- 3-axis accelerometer
- 3-axis gyroscope
- 3-axis magnetometer
- Barometer
- GNSS receiver

*[Sample Trajectory
Map]*

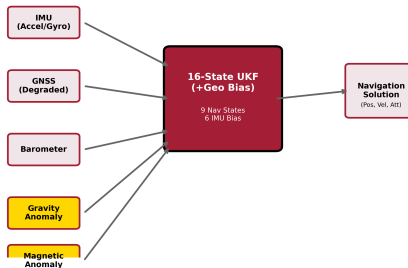
13 trajectories evaluated

System Architecture

Standard GNSS-Aided INS



Geophysically-Aided INS



- **Standard INS:** 15-state UKF (9 navigation + 6 IMU bias states)
- **Geophysical-Aided:** +1 anomaly bias state per measurement

Simulated GNSS Interference

Realistic model of low-quality GNSS (urban canyons, multipath, jamming):

AR(1) Correlated Errors:

- Position: $\rho = 0.99$, $\sigma = 5$ m
- Velocity: $\rho = 0.95$, $\sigma = 5$ m/s
- Slowly drifting biases

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Covariance Inflation:

- 15× advertised accuracy
- Simulates poor DOP reporting

*[AR(1) Error
Visualization]*

Gravity Anomaly Aiding:

- IGPP Earth Free-air Anomaly Map
- 1 arc-minute resolution (~ 1.8 km)
- Mean residual: 5.97 mGal
- Std: 48.93 mGal

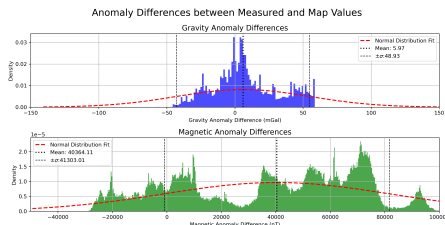
Geophysical Measurement Integration

Gravity Anomaly Aiding:

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Magnetic Anomaly Aiding:

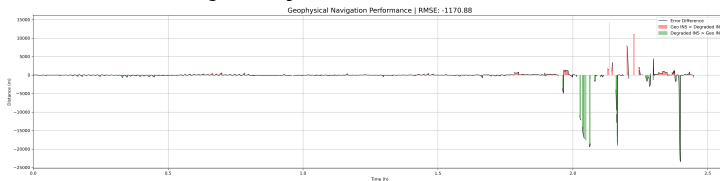
- World Digital Magnetic Anomaly Map (WDMAM)
- 3 arc-minute resolution (~ 5.6 km)
- Mean residual: 40,364 nT
- Std: 41,303 nT



Measurement residual distributions

Results: Gravity Aiding Success

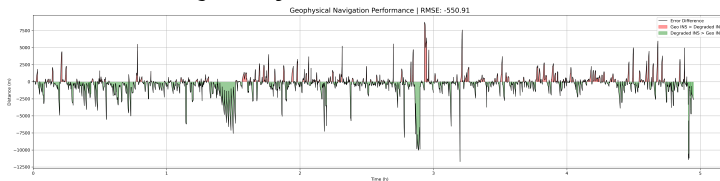
Trajectory 2023-08-04_214758



RMSE Improvement: -1,170 meters

Results: Magnetic Aiding Success

Trajectory 2025-06-27_11-54-35



RMSE Improvement: -550 meters

Results: Dual-Modal Performance

Trajectory 2025-07-31_23-36-03



Gravity: -688m RMSE

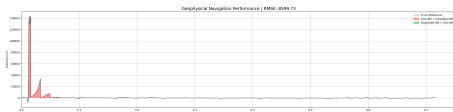


Magnetic: -632m RMSE

Both modalities provide substantial improvements

Results: Failure Mode Analysis

Trajectory 2023-08-09_163741 (Outlier)



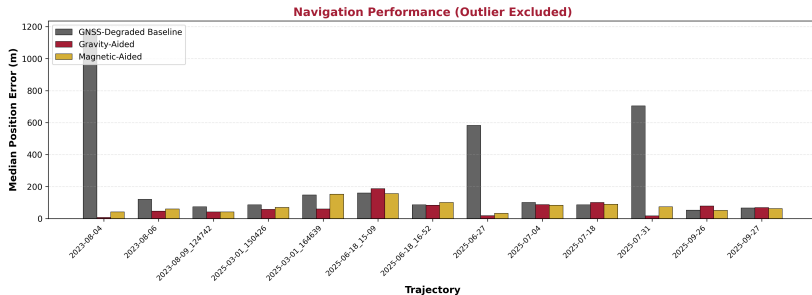
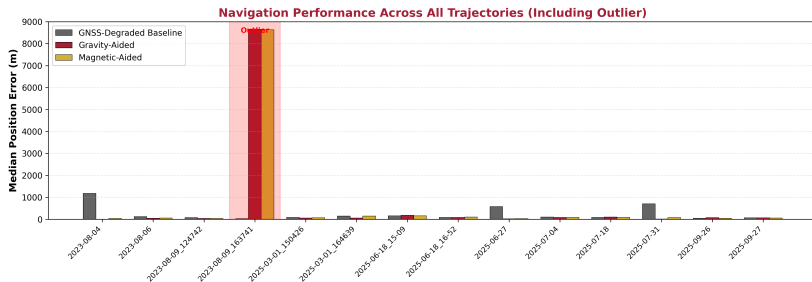
Gravity: +8,659m error



Magnetic: +8,635m error

- Catastrophic initial divergence
- Indicates need for integrity monitoring and robust initialization

Summary Statistics Across All Trajectories



Key Findings

Primary Achievement

First demonstration of geophysical navigation feasibility using only:

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Performance Highlights

- Error reductions: tens to hundreds of meters on favorable trajectories
- Best case: $\sim 1,100\text{m}$ RMSE improvement
- Median improvements: 3-10 meters across all trajectories
- Despite MEMS noise and limited map resolution

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Significance

Opens pathway from niche military/aerospace applications to **mass-market consumer and commercial platforms**

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- Detect and mitigate failure modes
- Adaptive measurement weighting
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- Map-matching performance metrics
- Geophysical gradient requirements

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3 Multi-Modal Fusion

- Combine gravity + magnetic measurements
- Terrain-based aiding
- Enhanced map resolutions

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4 Real-Time Implementation

- On-device processing
- Computational efficiency
- Battery/power constraints

References I

Acknowledgments

- MEMS-Nav Dataset: <https://doi.org/10.5281/zenodo.17582434>
- Strapdown-rs Software: <https://github.com/jbrodovsky/strapdown-rs>
- IGPP Gravity Anomaly Maps (EGM2008)
- World Digital Magnetic Anomaly Map (WDMAM)
- Generic Mapping Tools (GMT)

Questions?

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