# QUANTUM WAYFINDER

## NAVISP-EI1-013: Quantum-based sensing for PNT

Final Presentation (Public)

5th November 2020

# Agenda

Project Context

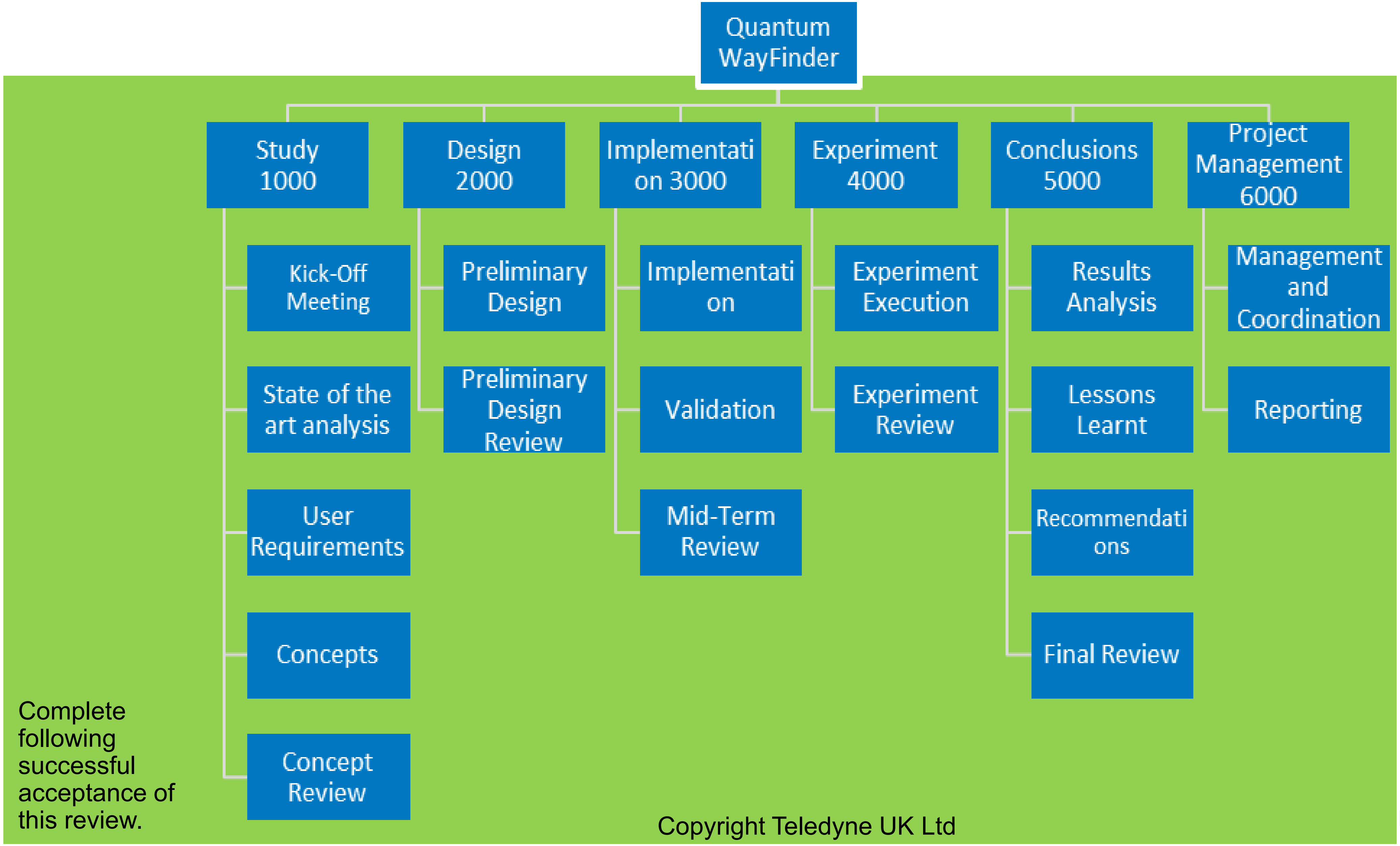
Experimentation Overview and Results

Study Limitations and Next Steps

Conclusions & Lessons Learned

Roadmap

# Project Context - WP Structure



Quantum WayFinder

Study 1000
- Kick-Off Meeting
- State of the art analysis
- User Requirements
- Concepts
- Concept Review

Design 2000
- Preliminary Design
- Preliminary Design Review

Implementation 3000
- Implementation
- Validation
- Mid-Term Review

Experiment 4000
- Experiment Execution
- Experiment Review

Conclusions 5000
- Results Analysis
- Lessons Learnt
- Recommendations
- Final Review

Project Management 6000
- Management and Coordination
- Reporting

Complete following successful acceptance of this review.

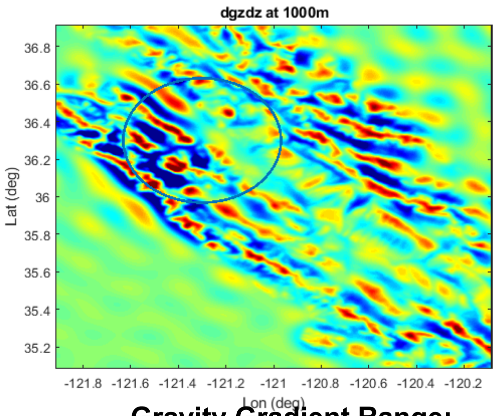
# Experimentation Overview and Results

# Use Cases and Trajectories

- Four use cases were established:
    - Fixed wing commercial aircraft
    - Small van
    - Shipping container ship
    - Submarine
- For all four cases the instrument required was characterized based on the vehicle dynamics environment (expected tilt and rotation, noise etc during operation) as well as available space and power.

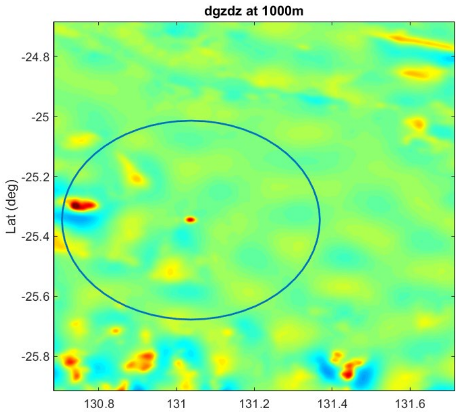
- Initially all 4 use cases were planned to be investigated, however due to constraints with how the gravity gradient map is generated, only the fixed wing air craft use case was explored in further detail during experimentation.

**California - USA**



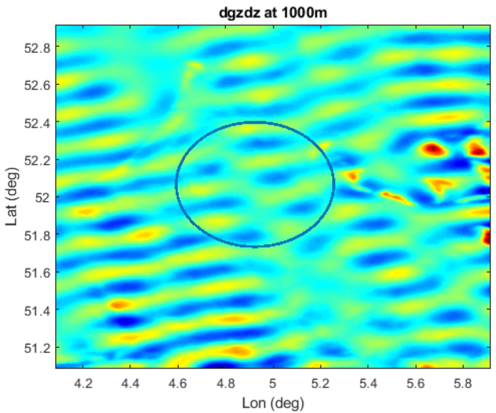
**Gravity Gradient Range:**
**$5e^{-7}$ ($2.9e^{-6} – 3.4e^{-6}$)**

**Uluru - Australia**



**Gravity Gradient Range:**
**$6e^{-8}$ ($3.05e^{-6} – 3.11e^{-6}$)**

**Noordwijk - Netherlands**



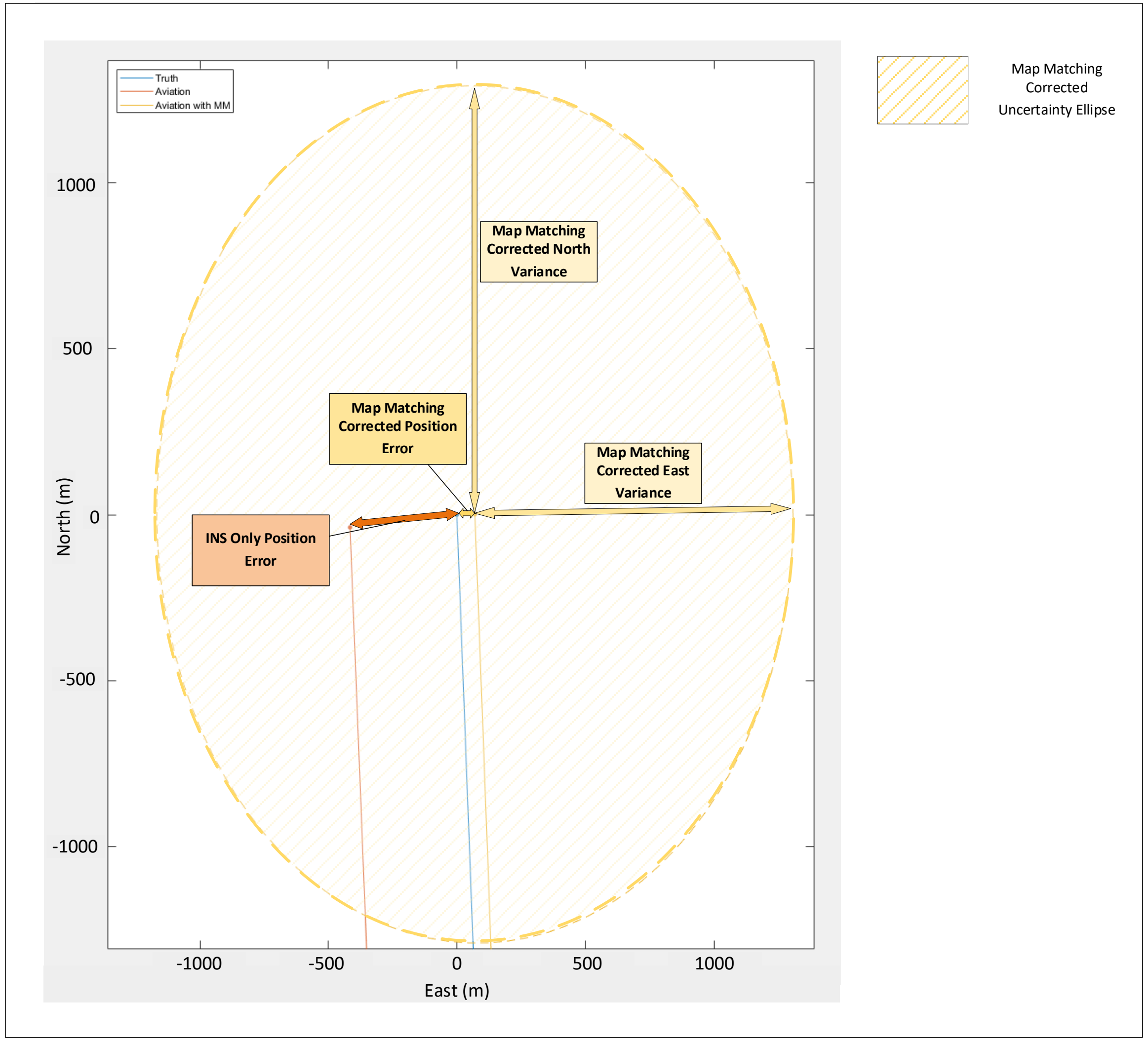
**Gravity Gradient Range:**
**$3e^{-8}$ ($3.07e^{-6} – 3.10e^{-6}$)**

# Performance Metrics

## Metric definitions

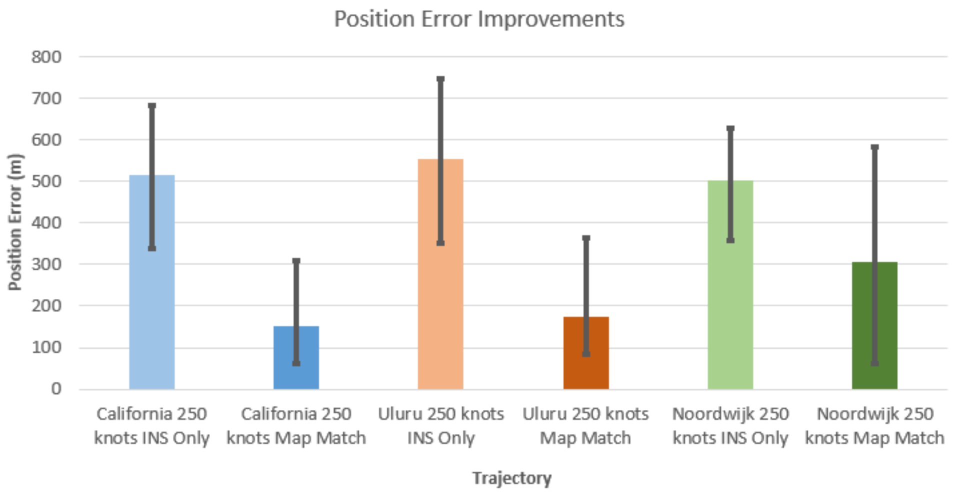
- Two primary performance metrics are used: Final Position Error, and Final Position Uncertainty, for both the INS Only and Map Matching Corrected outputs.
- Final Position Error is given as the distance between the final navigation solution position and the true position, in meters.
- Final Position Uncertainty is expressed in metres, calculated as $\sqrt{(North\ Variance)^2+(East\ Variance)^2}$
- The final position uncertainty in real terms corresponds to an ellipse, inside which the system is confident (to a specified confidence level) that the true position lies. This is indicated by the shaded region on the diagram.

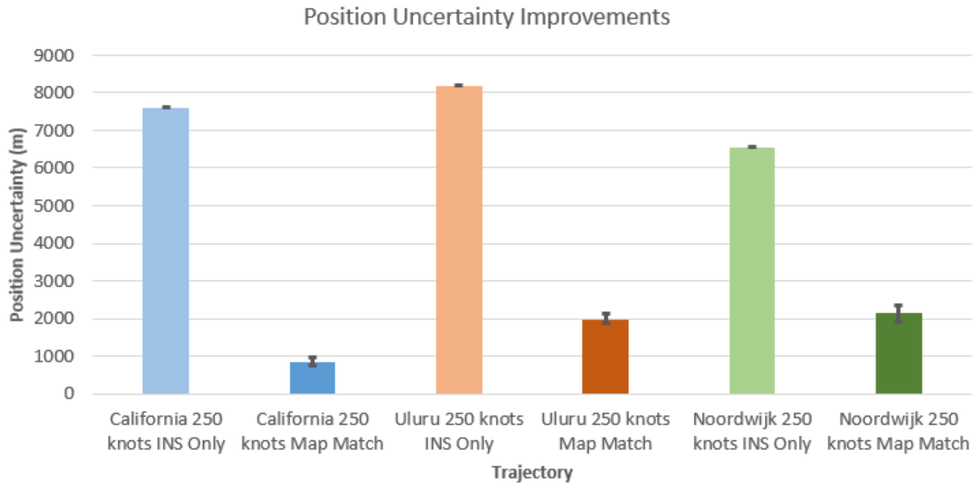
## Final trajectory positions for INS only and Map Matching Corrected navigation solution



# Experimentation Results

250 knots (1700 second duration), shot noise only instrument, static sensor

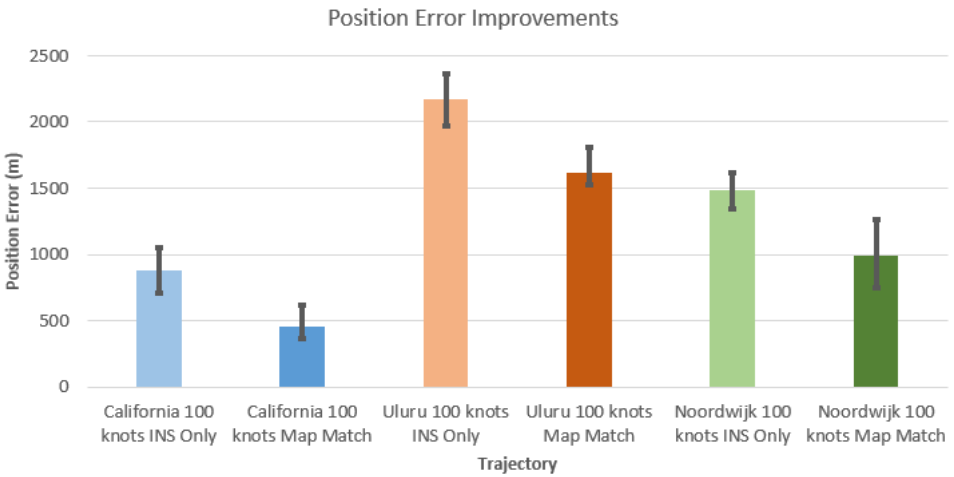


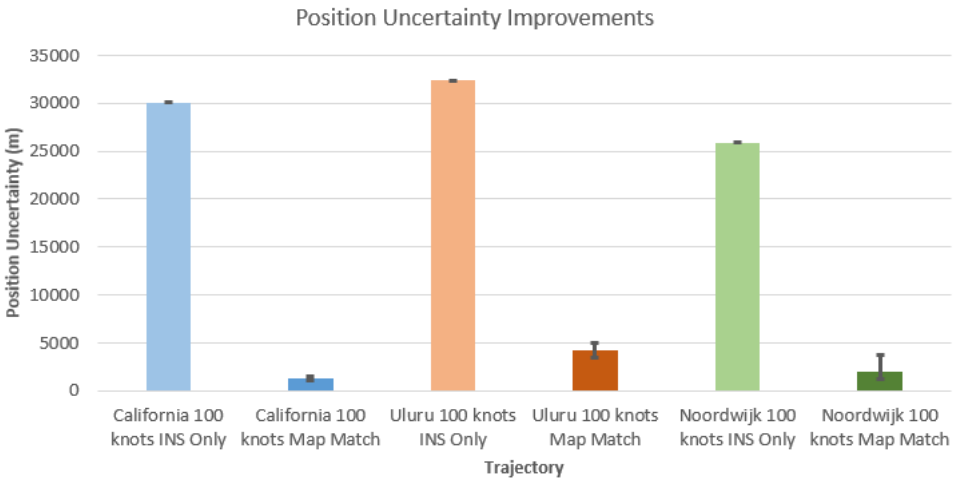


- There is significant variance in the position error improvement depending on the input measurement and IMU seed used.
- This is not unexpected due to the statistical nature of the analysis, and the final position error being highly sensitive to input parameters.
- There are a large number of parameters that can be varied, many of which are likely to have effects on the final navigation solution that depend on other parameters.
- It is possible to tune the instrument and the map matching parameters to produce significant improvements in the navigation solution in all 3 trajectories tested, and this is likely to be the case for any other trajectory that has gravity gradient variations at these levels.
- There is no ‘one solution fits all’ setup and in order to optimize the map matching to provide improvements in the navigation solution a real world instrument would need to be configured to the general area/ trajectory.

# Experimentation Results

100 knots (4000 second duration), shot noise only instrument, static sensor





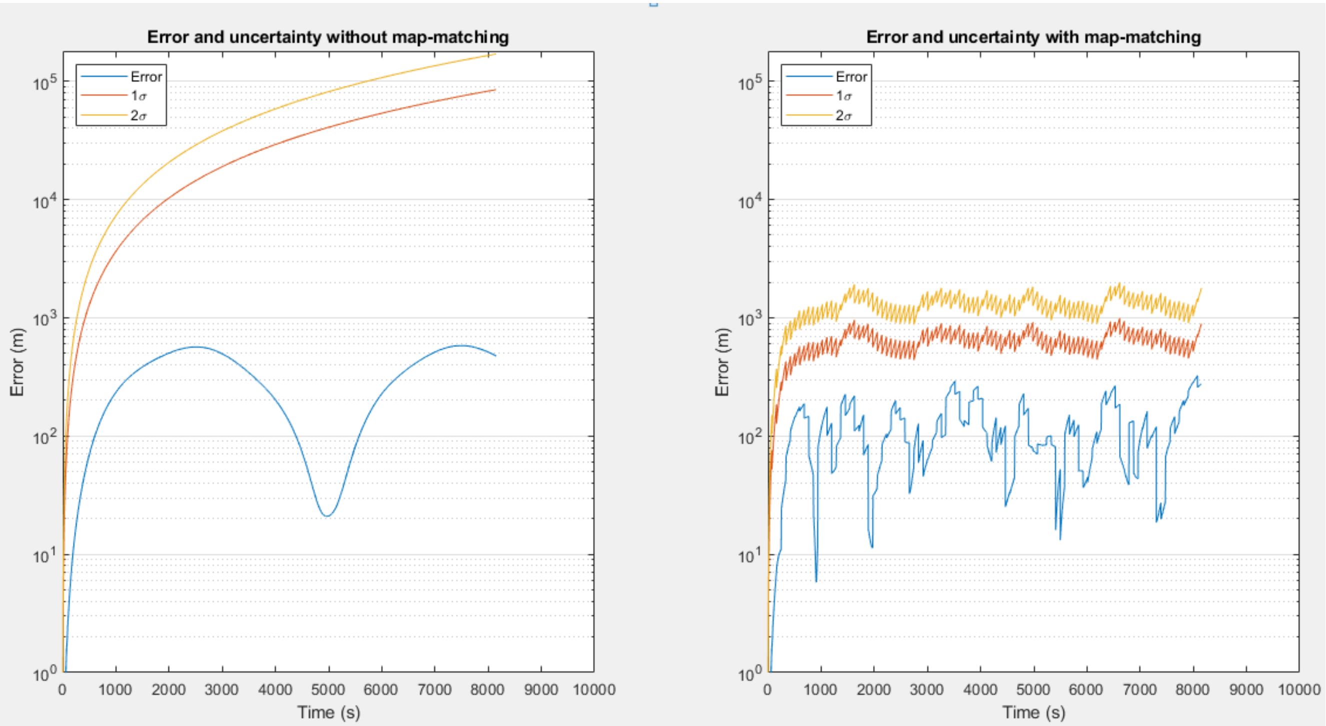
- There is again variance in the position error improvement depending on the input measurement and IMU seed used, however variance is not as large comparatively due to the large errors accumulated along the longer trajectory.
- The position error improvements appear to be less distinct here compared to the 250 knot trajectories. This is likely due to two reasons:
  - The same number of points were used for each map matching update, however at this speed the area covered is 2.5x less. It is likely that utilising more points would result in better matches, reducing the position error of the map matching solution.
  - The Kalman filter is not well tuned for longer trajectories, which results in more INS drift.
- Position Uncertainty is lower than in the 250 knot trajectories, this is due to more gravity gradient measurements being available, and thus more corrections can occur.

# Long Trajectories

A 5 times loop was performed of each of the 3 trajectories at 250 knots using the optimal parameters for the baseline instrument to demonstrate the effect over much longer trajectories

INS Only Navigation Solution

Map Matching Augmented Navigation Solution



INS Only Navigation Solution

Final Position Error: 474.8 metres

Final Position Uncertainty: 84,980.7 metres

Area of 95% uncertainty ellipse: 67,966,392,084.3 $m^2$

Area of 50% uncertainty ellipse: 15,725,942,355.3 $m^2$

Radius of 95% uncertainty ellipse: 147,086.2 $m^2$

Radius of 50% uncertainty ellipse: 70,751.1 $m^2$

Map Matching Augmented Navigation Solution

Final Position Error: 276.8 metres

Final Position Uncertainty: 891.4 metres

Area of 95% uncertainty ellipse: 7,208,056.5 $m^2$

Area of 50% uncertainty ellipse: 1,667,787.2 $m^2$

Radius of 95% uncertainty ellipse: 1,514.7 $m^2$

Radius of 50% uncertainty ellipse: 728.6 $m^2$

This was repeated for both the Uluru and Noordwijk trajectories at 250 knots and similar results are observable, with the position uncertainty being constrained, leading around 98% reduction in the final position uncertainty for both trajectories.

# Further Developments

Moving Sensor

- Next steps in the experimentation were to change the sensor from static mode (stationary during measurements) to moving during the measurement cycle.
- The same parameters were utilised as for the static sensor case, which are likely not optimal, and thus with further work it is likely that results for a moving sensor can be improved beyond what was achieved.
- Utilising the static sensor optimized parameters the final position uncertainty was decreased by 87% for the moving sensor variant of the California 250 knot trajectory, showing that significant improvements are still achievable if the sensor is moving.

Vehicle Dynamics

- Vibrational noise added to the vehicle simulation causes the INS solution to drift more quickly. Additionally, vibrations may cause the atom cloud to leave the beam, leading to sporadic failed measurements.
- The effect of vibrational noise on the ability to perform map-matching was evaluated by performing a statistical analysis on simulated vibrational noise, determining the frequency with which gradient measurements (and subsequently map-matching corrections) would fail.
- The statistical analysis indicated that the typical noise environment of a commercial aircraft would not be severe enough to noticeably hinder the ability to perform map-matching.
- This was confirmed by performing a full simulation on the California 250 knot trajectory with the addition of vibrational noise: the INS-only solution drifts more quickly but map-matching is able to constrain this drift.

# Study Limitations and Next Steps

# Study Limitations

- Navigational modelling is a statistical analysis and only a limited number of runs has been possible due to time constraints - although the system can be shown to work, conclusions drawn regarding optimal parameters would require further validation via additional testing.

- The vehicle dynamics and vibration analysis considered are limited - this is likely to be a large area that affects the performance of a real world sensor and thus would require further study to develop further.

- A particle filter based method was developed for data fusion but was not fully evaluated. It is expected that a particle filter in this setting would provide little benefit over a Kalman filter since all errors are assumed Gaussian.

- Some weak cross-couplings between parameters are not included in the standard Kalman filter but would be present in reality. These errors would need to be accounted for over longer trajectories and as such a practical system would require a more advanced filter.

- The gravity gradient maps are simulated and may contain artefacts. They are representative but may not correspond exactly to the real gravity gradient over a given area. However, these artefacts are small/very small in magnitude relative to the real features in the maps.

# Study Next Steps

Experimentation next steps

- In order to attain a higher confidence level of the results the following next steps should be taken
    1. Repeat the simulation with a higher number of measurement and IMU seeds for each iteration in order to sample a larger number of possible solution
    2. Repeats of the simulation using the varied IMU and measurement seeds for all variants investigated for the optimal number for the rolling average. This will give a clearer indication of where the actual optimum may lie with a higher degree of confidence.

- A similar testing setup should also be completed to establish the effect of a moving sensor on the optimum number of points to average across.

- Limits of the current post processing should be established by adding additional instrument noise more representative of a real world instrument.

- Further vehicle dynamics added and their effects on the navigation solution evaluated.

- To explore the parameter space fully, further investigation would need to be conducted varying the vehicle models and grades of IMU used.

# Study Next Steps

Model development next steps

- The Kalman filter is limited to linear measurements and Gaussian errors. A particle filter based map-matching algorithm allows for better characterization of the (possibly non-Gaussian) uncertainty of the map-matching solution. Alternatively, map-matching could be treated as a tracking problem, using a particle filter to make position corrections with each gradient measurement.

- Over longer trajectories the effect of weak non-linear errors cannot be neglected. Use of an Extended Kalman Filter (EKF) would lead to significant improvements of the error estimation as the duration of the trajectory is increased.

- Use of modelled gravity gradients will be essential to real-world application. Accuracy of gradient modelling from terrain data should be evaluated against surveyed gravity data to determine real-world effectiveness.

# Conclusions and Lessons Learned

# Conclusions

- Gravity Gradient Map Matching is feasible and offers significant improvements in passive navigation.

- The level of improvement offered depends heavily on the use case, vehicle dynamics, trajectory and CAI parameters.
  - For long trajectories (2.5 hours) over terrain with high gravity gradient variations a combined INS and map matching system can reduce the position uncertainty to just 1% of a pure INS solution utilising a shot noise limited, current state of the art CAI.
  - Short trajectories (30 minutes) over areas with relatively low gravity gradient variations reduction in the final position uncertainty by a factor of 3 is possible.
  - As the length of the trajectory increases so does the benefit of utilising map matching, the combined system allows the position uncertainty to be constrained, where as a pure INS solution would continue to drift.

- Current state of the art for the cold atom interferometer is sufficient to achieve significant improvements, however SWAP-C of the system requires further developments to make commercially viable for navigation.

- Based on the results obtained there is confidence that similar improvements could be achieved for the other use cases, in particular for maritime cases, if sufficiently high resolution gravity gradient maps are utilised.