Test report
Algorithms improvements of the New Ellipse

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1 About the New Ellipse

The New Ellipse firmware represents a significant advancement for the Ellipse AHRS and INS product family, introducing a range of new capabilities. These include new configuration APIs, real-time advanced rejection mechanisms, support for higher baud rates, and higher frequency IMU and INS data, among other features.

On top of these new features, the most notable improvement lies at the heart of the Ellipse: we have completely redesigned the navigation algorithms. This significantly enhances the accuracy and the reliability of the Ellipse attitude and position measurements. These algorithmic updates are substantial and span several areas: improved performance in single-antenna GNSS operation under low dynamics, increased resilience to magnetic disturbances, better heave accuracy, reliable operation in high-vibration environments, etc.

Given the extensive and impactful nature of these changes, this report has been created to provide a detailed comparison between the Old Ellipse and the New Ellipse. It is intended to help users understand the improvements and set clear expectations on the performance and behavior of the Ellipse under various conditions.

A key advantage of the New Ellipse is that it is available with a firmware upgrade which is fully compatible with the existing hardware architecture (Ellipse hardware v3.x OEM and boxed). This ensures existing Ellipse users can benefit from the enhancements without requiring changing the hardware.

2 Presentation of the test report

This document provides a comprehensive comparison of the performance of the New Ellipse (firmware version ≥ 3.0) against the Old Ellipse (firmware version < 3.0). The evaluation covers all key INS output parameters, such as roll, pitch, heading, heave, and position accuracy. It also examines performance across the various operating modes of the Ellipse series (AHRS and GNSS-aided INS), ensuring relevance for all product models (Ellipse-A, Ellipse-E, Ellipse-N, and Ellipse-D).

This report highlights the enhancements introduced with the New Ellipse, based on tests performed in various conditions, to demonstrate its benefits to current and future users.

In this document:

- The term "Old Ellipse" refers to devices running firmware versions < 3.0.
- The term "New Ellipse" refers to devices running firmware versions ≥ 3.0.

3 Glossary

Inertial Navigation System (INS): A system that uses a triad of gyroscopes and accelerometers to compute a 6 degrees of freedom navigation output, including orientation, velocity, and position. To prevent drift and maintain an accurate navigation solution in all conditions, INS are typically aided by GNSS.

Sensor Fusion Algorithm: Advanced multi-sensor navigation algorithms running in the Ellipse. These algorithms process IMU data and combine it with GNSS, Odometer, DVL, Airdata and Magnetometer data to provide filtered and reliable Position and Attitude outputs.

Vertical Gyro (VG): A mode of operation with the Ellipse’s sensor fusion algorithm that utilizes IMU data only. In this mode, the Ellipse uses a vertical reference (gravity) to stabilize the IMU. The gyroscope data is fused with gravity measurements from the accelerometers in a Kalman filter. The key outputs are Roll, Pitch and Heave.

Attitude and Heading Reference System (AHRS): A mode of operation within the Ellipse's sensor fusion algorithm that extends the Vertical Gyro mode by adding heading determination. In this mode , an aiding sensor, such as a magnetometer or dual-antenna GNSS input, is used to stabilize the heading estimation. The key outputs of this mode are Heading, Roll, Pitch and Heave.

Tight Coupling Post Processing Kinematic (TC-PPK): A post-processing algorithm performed using Qinertia to improve the accuracy of sensor fusion outputs. Techniques include forward/backward processing, reliable PPK corrections, and tight coupling of IMU and GNSS data. In this report, TC-PPK is used to generate ground truth data.

Reprocessing: The act of running the same algorithms as the New Ellipse in post-processing using Qinertia. This process accurately represents real-time outputs as it uses the same data and algorithms but allows parameter adjustments (e.g., rejections, new algorithms). In this report, reprocessing is used to compare the impact of the New Ellipse's sensor fusion algorithms by reusing data logged with the Old Ellipse or to simulate GNSS rejections.

Cumulative Distribution Function (CDF): A function describing the percentage of occurrences where a given error is less than or equal to a specific value. In this report, the CDF is used to analyze the distribution of errors.

1-sigma (1σ): A measure of one standard deviation (σ) from the mean in a statistical distribution. In this report, 1-sigma represents the typical error and is measured at the 68.27% value on the CDF.

Vibration Levels (g RMS): A measure used to quantify vibration levels. It represents the effective value of a vibration signal, taking into account both the magnitude and the duration of vibrations.

MIL-STD-810: A military standard that defines test methods to assess the environmental impact on equipment, including vibration, shock, and more. For the Ellipse product range, the vibration specification is **8g RMS**, in compliance with MIL-STD vibration resistance standards.

4 AHRS applications

4.1 Roll and Pitch stability in AHRS mode

4.1.1 Overview

The objective of this test is to assess the stability of roll and pitch measurements during rapid maneuvers when the Ellipse operates without GNSS aiding: in Attitude Heading and Reference System (AHRS) or Vertical Gyro mode.

During the test, the Ellipse remains in a fixed position while its heading is sequentially adjusted to align with eight cardinal points (forming a "wind rose" pattern), with each rotation lasting one minute. The aim is to monitor the progression of errors during these heading changes.

This evaluation compares the performance of the Old Ellipse (firmware version < 3.0) against the New Ellipse (firmware version ≥ 3.0). The Qinertia Tight Coupling PPK (TC-PPK) solution generated by the Ellipse serves as the reference for this comparison.

4.1.2 Results

The Figure 1 shows the error roll and pitch error over time. The areas in yellow highlight the phases where the heading was changed.

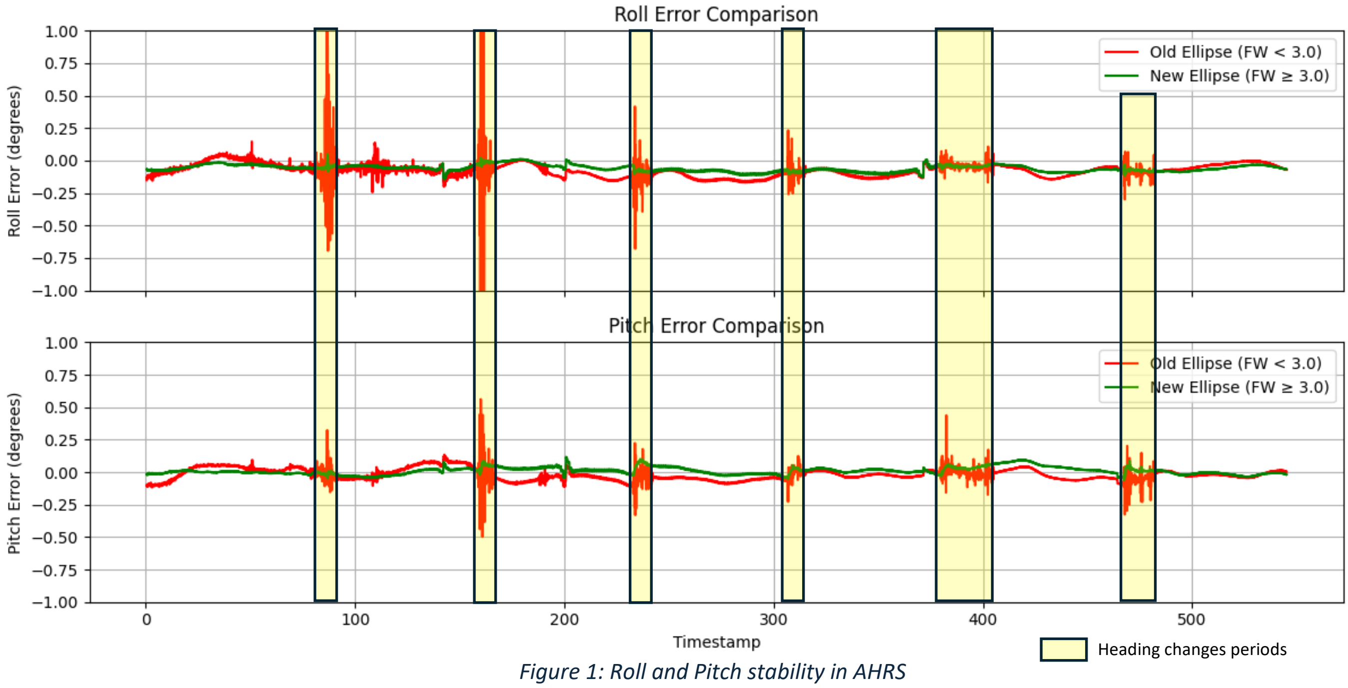

Figure 1: Roll and Pitch stability in AHRS

4.2 Resilience to magnetic disturbances

4.2.1 Overview

This test aims to compare the performance of the Ellipse under magnetic disturbances between the Old Ellipse and the New Ellipse.

The evaluation was performed using real-time data with magnetometers calibrated in 3D. The test involved a setup pedestrian setup, where magnetic disturbances were introduced at various intervals to evaluate the response of the Ellipse with both firmware versions.

For consistency, the Old and New Ellipse units were positioned side by side during the test. The Qinertia Tightly Coupled PPK solution was used as the reference for this comparison.

4.2.2 Results

Figure 2 illustrates the heading error over time for both the Old Ellipse and the New Ellipse, with intentional magnetic disturbances highlighted in yellow.

The results indicate that the New Ellipse exhibits significantly greater resilience to magnetic disturbances compared to the Old Ellipse. During these disturbances, the Old Ellipse exhibits large fluctuations in heading error, characterized by more pronounced spikes and slower recovery times than the New Ellipse.

In contrast, the New Ellipse maintains a significantly more stable heading error, minimal deviations and quick recovery after each disturbance, enabled by advanced rejection mechanisms introduced in the new algorithms.

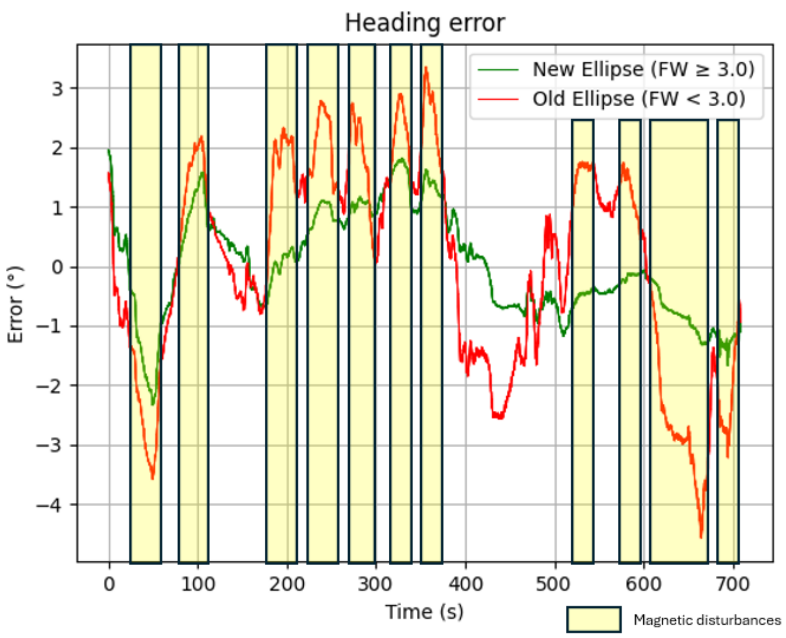

Figure 2: Heading error with and without magnetic disturbances

Overall, the New Ellipse shows a significantly increased **resilience to important magnetic disturbances** which in turns results in a major performance improvement in these conditions

Figure 3: Trajectory followed for the tests, highlighting the dynamics and the harsh magnetic environment of a parking.

5 GNSS-aided INS applications

5.1 Fallback to magnetometer under long GNSS outages

5.1.1 Overview

The objective of this test is to evaluate the impact of a new feature introduced with the New Ellipse: fallback to magnetometers when GNSS is unavailable.

In the Old Ellipse, the combined use of magnetic heading and dual-antenna GNSS was not recommended. However, using magnetometers alongside dual-antenna heading is a very useful solution to maintain precise heading when GNSS is available, while ensuring a reduced drift heading during GNSS outages.

For this test, a marine dataset with dual antenna & DVL input was utilized. Three 5-minute GNSS outages were simulated using Qinertia. During these outages, the Ellipse lost GNSS-based position and true heading. Two scenarios were compared against ground truth data:

- **Scenario 1**: Magnetometers are calibrated and activated, allowing the Ellipse to fallback to magnetic heading during GNSS outages.
- **Scenario 2**: Magnetometers are deactivated, and the Ellipse relies solely on its gyroscopes during GNSS outages.

5.1.2 Results

The results demonstrate that Scenario 1, which leverages magnetometer fallback, significantly reduces heading errors during GNSS outages:

- **Initial Two Minutes**: For the first two minutes of the outage, both scenarios exhibit similar error progression. During this period, the Ellipse's gyroscopes maintain an inertial heading that is more precise than the magnetometer-based heading. As a result, the sensor fusion algorithms prioritize gyroscope data.
- **Beyond Two Minutes**: After the initial two minutes, the gyroscope-based inertial heading error increases significantly. In Scenario 1, the sensor fusion algorithms automatically prioritize the magnetic heading to prevent heading drift and minimize position error.

This test highlights the benefits of the magnetometer fallback, added in the new algorithm of the New Ellipse. It limits heading drift and position errors by **automatically transitioning to magnetometer data when appropriate**.

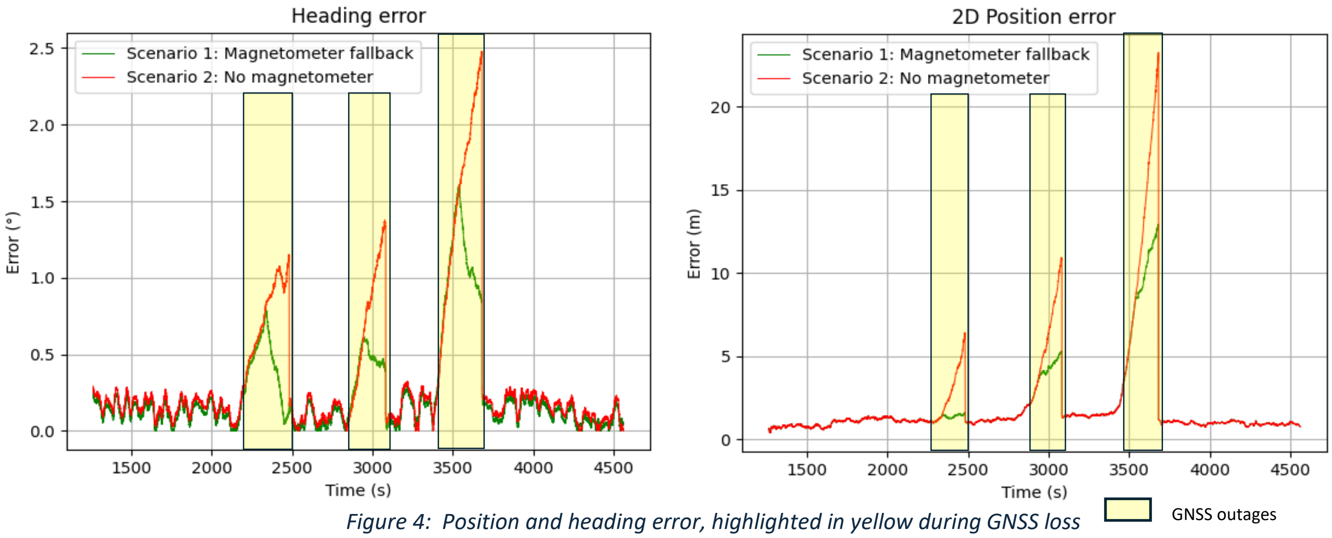

Figure 4: Position and heading error, highlighted in yellow during GNSS loss

5.2 Single antenna applications

5.2.1 Overview

The purpose of this test is to address Ellipse users' for whom a dual antenna setup is too space-constrained and relies on dynamics to initialize the heading with single antenna setup. The test was conducted in real time on an Ellipse-N client logs in a UAV operating at low speeds, with velocities not exceeding 6 m/s. The flight pattern followed a rectangular path with regular heading changes.

Real time data corresponds to the Old Ellipse. The New Ellipse dataset was generated using the same dataset but by reprocessing them with the same algorithm running in the New Ellipse. The Ellipse TC-PPK solution serves as the reference for this comparison.

5.2.2 Results

The graphs provide a comparison of the performance between the Old Ellipse and the New Ellipse:

- Figure 5 displays the trajectory of the UAV with a color-coded heading errors
- Figure 6 displays the CDF of the roll, pitch and heading errors
- Figure 7 shows a timeseries of the 2D position error

Figure 5 illustrates that the Old Ellipse exhibits higher heading error levels compared to the New Ellipse, particularly during turns. This issue has been effectively addressed in the New Ellipse, resulting in a significant improvement.

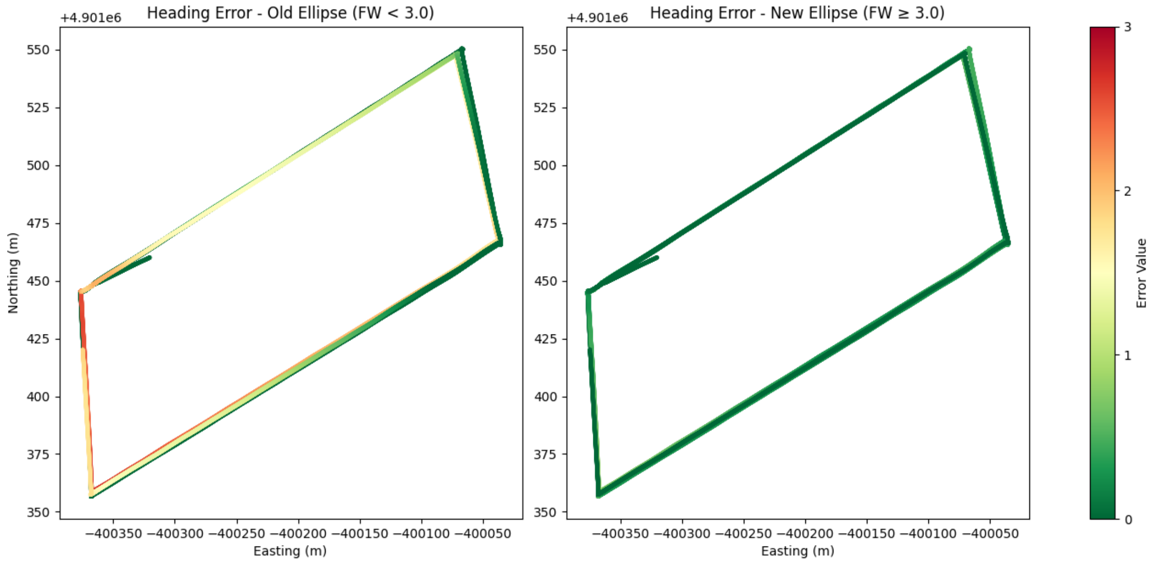

Figure 5: trajectory with color-coded heading errors

As shown in Figure 6, the roll and pitch accuracy saw slight improvements with the New Ellipse. However, the heading accuracy demonstrated a drastic enhancement, with errors reducing by more than five times compared to the Old Ellipse. The 1-sigma heading error **decreased dramatically from 2° to 0.38°.**

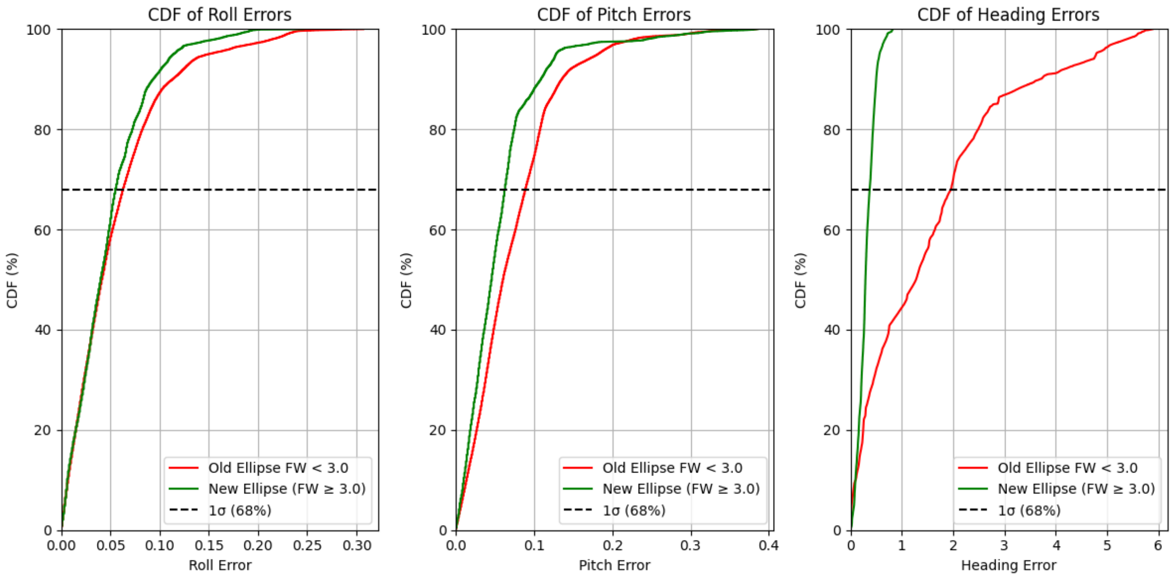

Figure 6: CDF of the roll and pitch errors

Additionally, as is visible on Figure 7, the 2D error is notably more stable during turns with the New Ellipse: Unlike the Old Ellipse firmware, which displayed spikes in position errors following turns, the **New Ellipse maintains consistent performance**, ensuring reliable positioning throughout in low dynamics single antenna.

Please note that the 2D position mean error of ~1 meter is normal, as we are operating in GNSS standalone mode.

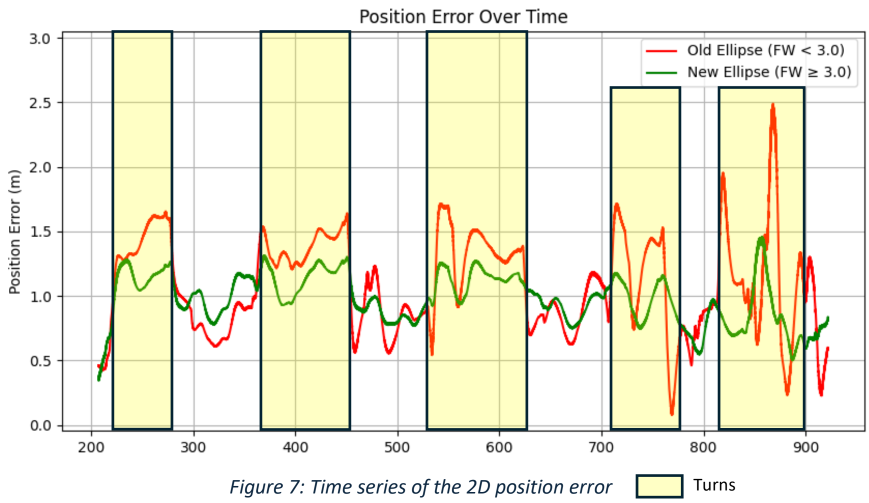

Figure 7: Time series of the 2D position error

5.2.3 And more..

Additionally, the Old Ellipse was unable to initialize the heading at velocity lower than 6m/s in single antenna. However, an additional test performed on the New Ellipse in similar conditions but at lower speed, showed that the New Ellipse overcame this limitation : it operated **flawlessly with a single antenna at just 3 m/s**.

This breakthrough highlights the New Ellipse's capability to deliver reliable performance even in challenging low-dynamics environments.

5.3 Vibration resilience in GNSS-aided INS

5.3.1 Overview

This test evaluates the performance of the New Ellipse compared to the Old Ellipse in a high-vibration environment. While optimal performance is not expected under these challenging conditions, the primary objective is to analyze and compare the behavior of the two versions. The analysis is based on real-world data from a high-dynamics race car application using the Ellipse-N in a single-antenna GNSS configuration, representing the Old Ellipse.

The New Ellipse dataset was generated using reprocessing, employing the same algorithms as the New Ellipse.

The ground truth is created using the same Ellipse data, using Qinertia Tight Coupling PPK (TC-PPK).

5.3.2 Results

For this test, the vibration level in “g RMS” was calculated using real accelerometer data. The scaling was adjusted to cover the full bandwidth of 2000Hz using a white noise assumption to enable comparison with the Ellipse MIL-STD specification of 8g RMS.

At the start of the test, the vibration levels were moderate (<5g RMS) and increased to a maximum of 20g RMS by the end of the dataset, which exceeds our specification.

The figures 8 & 9 below illustrate the roll and pitch errors over time. The right-hand scale indicates the estimated RMS vibration levels as measured by our internal accelerometers.

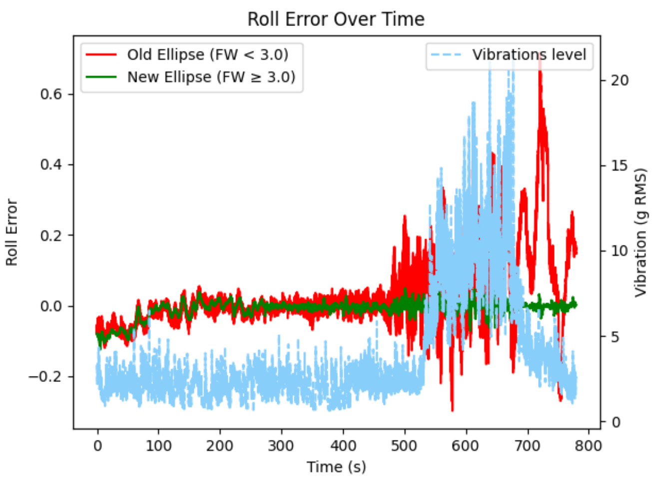

Figure 8: Roll error over time

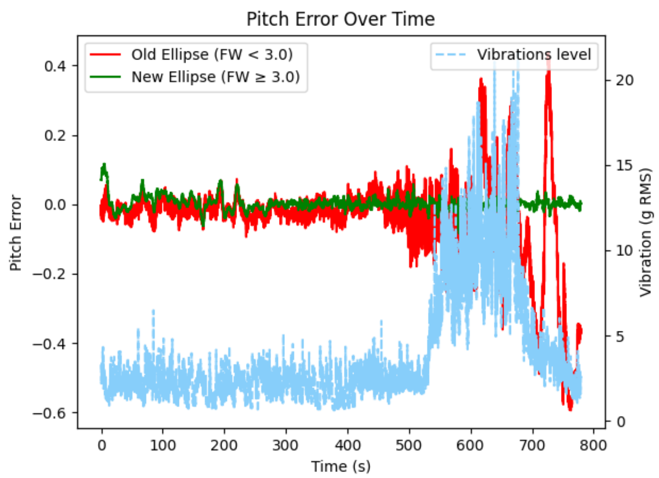

Figure 9: Pitch error over time

The Old Ellipse experienced a significant increase in roll and pitch errors as vibration levels rose, peaking at 0.6°. In contrast, the New Ellipse maintained errors below 0.1°, showing a major improvement.

The figure 10 shows the race car's trajectory is displayed, with the "Old Ellipse" in red and the "New Ellipse" in green. A zoomed view highlights 2D position errors during high-vibration periods.

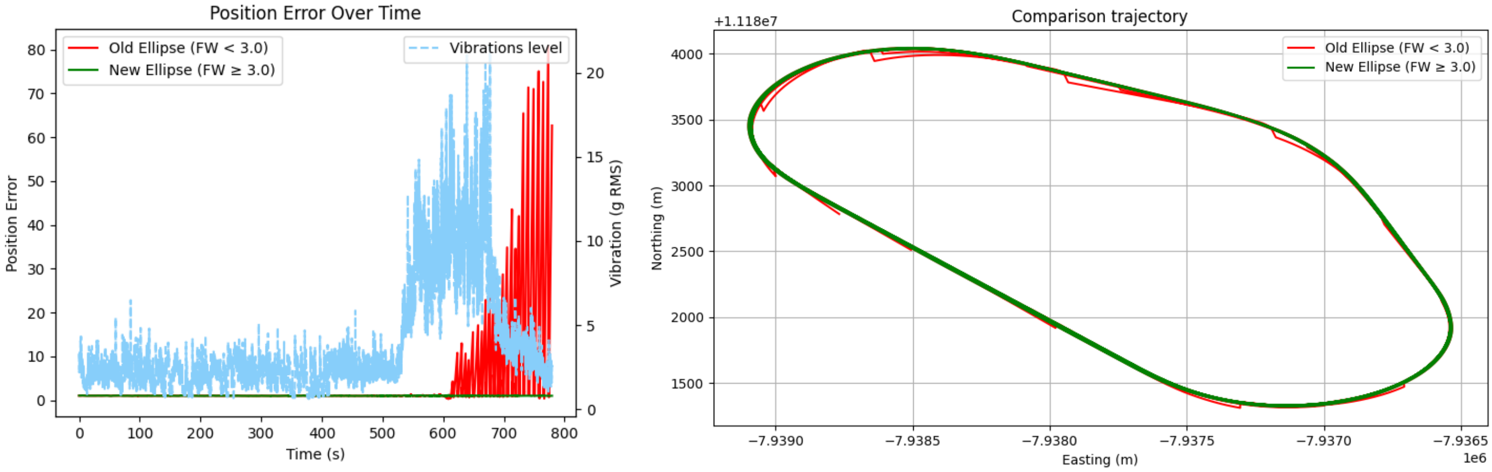

Figure 10: Trajectory with color-coded 2D position error and a zoom on 2D position error over time during vibrations

Similarly, the trajectory of the Old Ellipse exhibited a sawtooth pattern, with high vibrations causing algorithmic drift and resulting in position errors of up to 80 meters.

The **trajectory of the New Ellipse remained smooth and stable**, demonstrating enhanced resilience to extreme vibrations of 8g peak-to-peak.

6 Heave performance

6.1 Overview

This test aims to evaluate and compare the heave performance of the New Ellipse against the Old Ellipse. The TC-PPK solution from the survey grade Apogee has been as a reference unit.

The data for this assessment was collected using both the New and Old Ellipse devices mounted on a small sea vessel, alongside an Apogee unit. The Alignment between the Ellipse and Apogee was verified in CAD and cross-checked for accuracy using Qinertia software.

The sea conditions during data acquisition were classified as smooth, based on the WMO Sea State Code 2, with a swell height of approximately 0.15 m and an average wave period of 2.2 seconds.

6.2 Results

The following results were observed (at a confidence level of 1-sigma):

Device Version	Heave error (m)
Old Ellipse – INS mode	0.041 m
New Ellipse – INS mode	0.017 m
New Ellipse – AHRS mode	0.024 m

The data shows a significant improvement in heave performance with the New Ellipse.

Note that we have also added the data in AHRS mode to show the improvements in use cases without GNSS aiding.

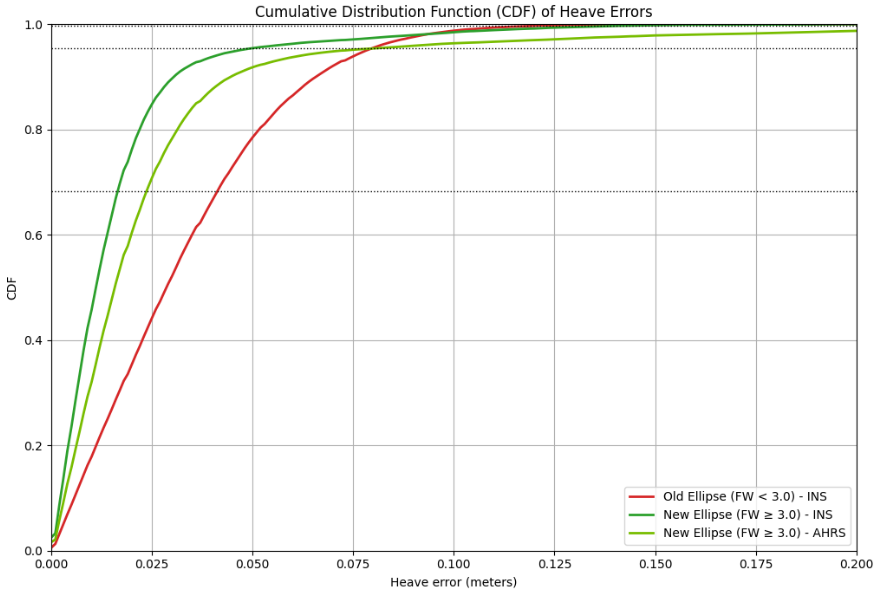

Figure 11: CDF of the heave error for Old Ellipse in INS mode and New Ellipse in INS and AHRS mode

By plotting the heave error over a map (figure 12), we see the improvements are very significant in the parts where Heave is the most meaningful: during the straight lines. These are the sections where Heave is susceptible to be used by surveyors.

The test shows very notable improvements in heave accuracy with the New Ellipse, with, on this specific test in calm sea, an **error reduced from 4.1cm to 1.7** between the Old Ellipse and the New Ellipse.

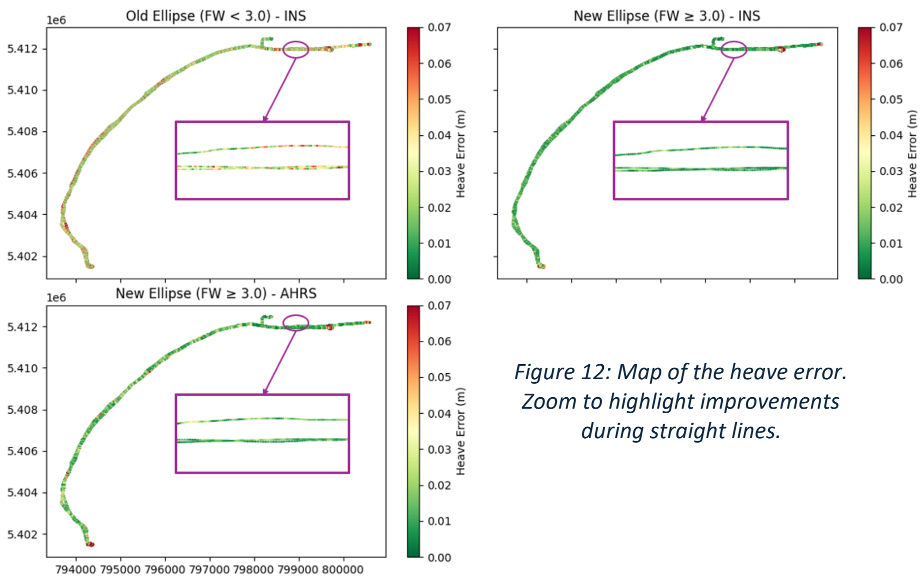

Figure 12: Map of the heave error. Zoom to highlight improvements during straight lines.

7 Conclusions

This report provides an evaluation of some of the advancements brought by the sensor fusions algorithms in the New Ellipse (firmware version ≥ 3.0) compared to its predecessor (firmware version < 3.0).

The series of tests conducted highlights substantial improvements in performance and reliability of the attitude and position information, ensuring the Ellipse is better equipped to handle real-world challenges and diverse operational conditions. The scope of the algorithms improvements is however too large to be covered in a test report, and each user will find different benefits of using the New Ellipse.

The key findings highlighted from the test report:

1. **Roll and Pitch Stability in AHRS Mode:** The New Ellipse demonstrated up to a 75% reduction in roll and pitch errors during rapid maneuvers without GNSS aiding, maintaining errors consistently below 0.2°.
2. **Magnetic Disturbance Resistance:** With advanced rejection mechanisms, the New Ellipse offers improved heading stability and faster recovery during magnetic disturbances.
3. **Fallback to Magnetometer:** The New Ellipse introduces the ability to use magnetometer data during GNSS outages, effectively reducing heading drift and position errors. This capability ensures continued reliable operation in environments prone to long GNSS interruptions.
4. **Single-Antenna Applications:** The New Ellipse enables the usage of the INS in low-dynamics, single antenna applications.
5. **Vibration Resilience:** The New Ellipse demonstrated remarkable resilience when challenged beyond its limits in high-vibration environments (exceeding 20g RMS), with roll and pitch errors reduced by over 80% compared to the Old Ellipse. This improvement ensures reliable positioning, even in extreme conditions such as those encountered in high-dynamics applications.
6. **Heave Performance:** Heave accuracy saw a marked enhancement, with errors reduced by more than 50%, offering significantly improved performance for surveyors and other professionals operating in marine environments.

The New Ellipse firmware represents a major upgrade that extends the capabilities of the existing hardware (Ellipse hardware v3.x OEM and boxed) without requiring any changes to the physical device. This compatibility allows current users to unlock these substantial performance improvements through a straightforward firmware update.

We encourage existing and future users to explore the capabilities of the New Ellipse by testing it in their specific use cases. With enhanced algorithms, increased resilience to environmental challenges, and measurable gains in accuracy across all AHRS and INS outputs, the New Ellipse is designed to meet and exceed user expectations in all scenarios.