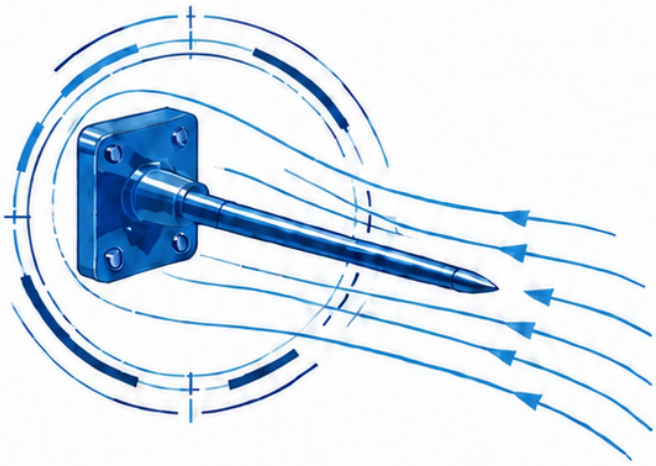
Test Report

Performance evaluation in GNSS-denied airborne applications







Ellipse, Stellar-40 and Apogee

SBG SYSTEMS

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1 Introduction

While GNSS has traditionally been considered the primary source of position and velocity for airborne navigation, the increasing operational relevance of jamming and spoofing makes GNSS continuity and integrity a critical concern. In GNSS-denied environments, navigation must rely on sensors that are not directly disturbed by radio-frequency attacks.

Inertial sensors are the prime solution for these applications, providing a self-measured motion measurement alternative, offering a reliable and independent source of motion information that is not affected by the environment or by GNSS jamming or spoofing.

To assess navigation performance under the conditions of a total GNSS loss, we conducted an extensive flight-test campaign featuring a long-duration trajectory representative of real operational scenarios. The analysis investigates navigation performance during prolonged GNSS outages, covering horizontal and vertical positioning, attitude estimation, and uncertainty consistency. Multiple aiding configurations are evaluated, including pure inertial navigation, air-data-assisted navigation, and magnetometer-assisted navigation where applicable.

Three products were evaluated to cover a broad range of SBG Systems inertial performance classes:

- Ellipse: an entry-level INS equipped with an industrial-grade IMU “Pulse-20”
- Stellar-40: a mid-range INS equipped with a tactical-grade IMU “Pulse-40”
- Apogee: a high-end INS based on a high-tactical-grade IMU “Pulse-80”

All evaluations were performed in Qinertia, SBG Systems post-processing software. Its aiding-rejection capabilities allow repeatable GNSS outages to be introduced without physically disconnecting antennas during acquisition. This approach makes it possible to compare several products over identical flight segments and to assess different aiding configurations.

The objectives of this report are to:

- Quantify the intrinsic drift performance of each system during pure inertial operation
- Evaluate navigation and orientation performance when aided by air-data
- Verify the consistency and reliability of the navigation uncertainty estimates provided by each system

2 Air-data aiding for INS dead reckoning

In this report, air-data refers to measurements derived from the surrounding airflow and atmospheric conditions. Typical outputs include indicated or true airspeed and barometric altitude, calculated from pitot-static, static pressure, and temperature measurements. When fused with an INS, these measurements provide independent constraints that can substantially reduce inertial drift during GNSS outages.

Within the SBG Systems fusion architecture, air-data is used as an external aiding source. During GNSS-available flight, the navigation filter estimates parameters such as the wind vector, pitot tube scale factor, and barometric-altitude correction terms. These calibrated states improve the robustness of the dead-reckoning solution after GNSS measurements are rejected.

Complementary sensors: INS measurements are very smooth and accurate over short durations but naturally drift with time. Aiding sensors such as GNSS, barometric altitude, or airspeed are usually noisier or less complete, but they provide long-term constraints. Sensor fusion combines these complementary behaviors to stabilize the navigation solution during GNSS outages.

Important limitation: Air-data is resilient to GNSS jamming and spoofing, but it is not an absolute horizontal position source. True airspeed can also be sensitive to wind modeling errors, meaning that its benefit depends strongly on the ability of the filter to estimate or constrain wind.

Moreover, these sensors are known to be susceptible to failure due to icing or tube blockage.

3 Test conditions

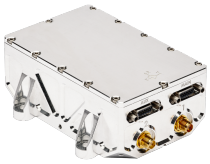
3.1 Environment overview

The flight campaign was conducted in France in June 2026 using an ultralight aircraft. Visibility was clear and atmospheric conditions were sufficiently stable for repeatable data acquisition.

3.2 Products under test

The evaluation includes three products covering a broad range of SBG Systems INS performance classes. All units were operated in a single-antenna configuration.

Table 1: Devices under test

Product	Representative image	Hardware code	IMU class	Configuration
Ellipse		ELLIPSE-D-G4A3-B1	Industrial	Single antenna
Stellar-40		STELLAR-AAB-00	Tactical	Single antenna
Apogee		APOGEE-D-G3A3	High tactical	Single antenna

Single antenna configuration: All the products included in the tests are using single antenna GNSS mode: the heading is determined by the sensor fusion algorithms.

This is the most challenging use-case as single-antenna GNSS must infer heading from vehicle motion, which becomes poorly observable during long straight-line motion. This, however, is often how products are used in aerial dead reckoning applications so the test was designed to remain representative of typical customer use cases.

3.3 Test setup

The products were mounted on a common rigid plate installed at the rear of the aircraft, while the GNSS antennas were installed inside the front canopy. This arrangement allowed all units to experience the same vehicle motion and closely matched environmental conditions.



Figure 1 : Ultralight aircraft and GNSS antenna installation used during the flight campaign

A dedicated pitot-static installation provided the air-data to the sensor fusion algorithm. Dynamic pressure was measured using the external pitot tube, while static pressure was measured inside the cabin.



Figure 2: Dedicated pitot tube installation used for airspeed aiding

3.4 Test route

The selected route was intentionally demanding for inertial navigation. Long, nearly straight and constant-speed segments provide limited dynamic excitation, reducing the observability of heading, wind and some inertial bias states. The resulting performance should therefore be interpreted as a realistic but deliberately conservative assessment of dead-reckoning capability.

Observability: For a navigation algorithm, a state is observable only if the available measurements and vehicle motion contain enough information to estimate it. Straight and constant-speed flight is therefore more difficult than a maneuvering trajectory, especially for heading, wind and some inertial bias states.

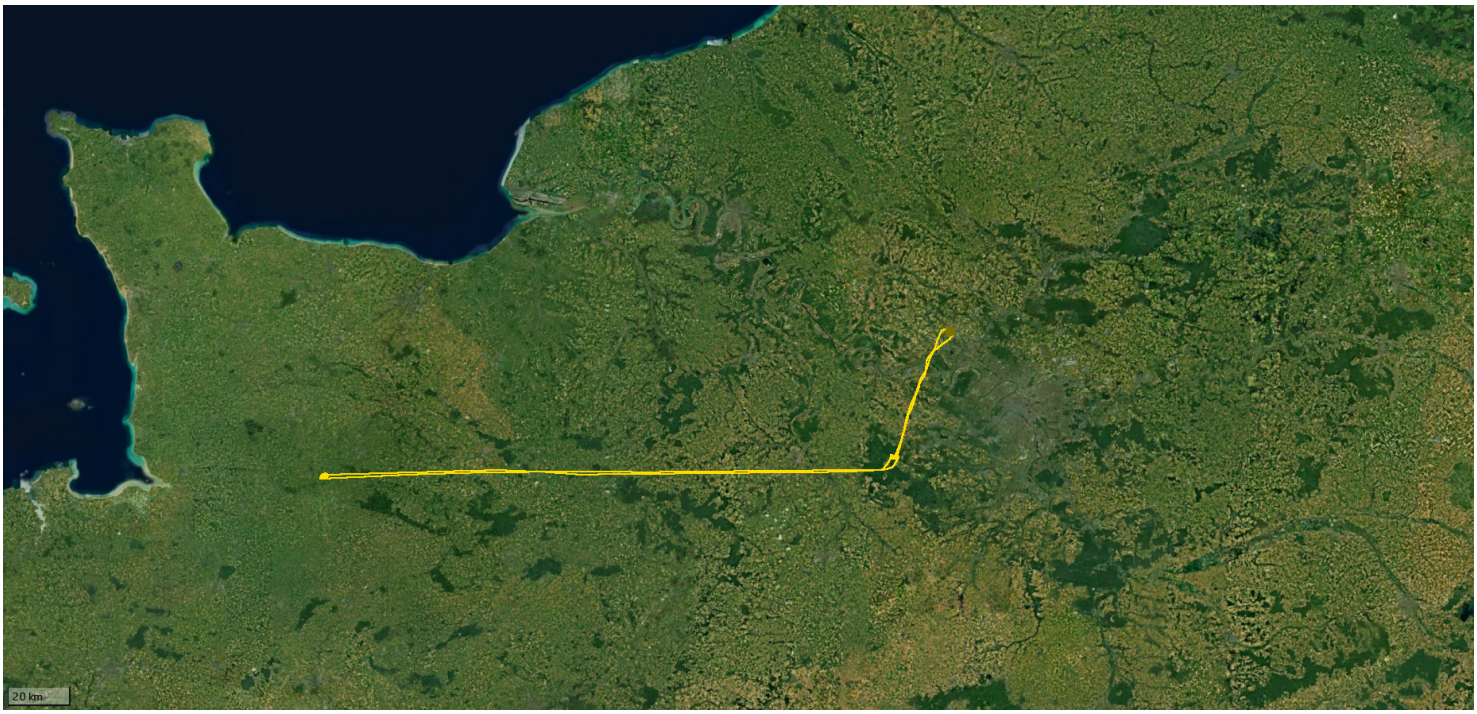


Figure 3: Extended East-West flight route used for the GNSS-denied evaluation

The aircraft flew the extended route at an altitude ranging from approximately 2,300 ft to 4,330 ft. Both the westbound and eastbound legs were flown at an approximately constant speed of 60 m/s (107 kt) for 1 hour.

3.5 Test scenarios

The test campaign was designed to assess navigation performance under representative GNSS-denied operating conditions, ranging from complete reliance on inertial sensors to the use of complementary airborne aiding sources.

- **Scenario 1 - Pure inertial dead reckoning:** GNSS, air-data and magnetometer measurements were rejected. Navigation performance therefore depends exclusively on the IMU and inertial navigation algorithms, representing the most demanding GNSS-denied condition.
- **Scenario 2 - Air-data-aided dead reckoning:** GNSS measurements were rejected while airspeed and barometric-altitude measurements remained available. Magnetometer aiding was enabled where specified. This scenario represents typical fixed-wing aircraft architecture and demonstrates how complementary sensors can significantly reduce navigation drift during prolonged GNSS outages.

To ensure a fair comparison, the exact same GNSS-denied segments were introduced across all tested products and under all scenarios.

4 Ground truth

The reference trajectory used throughout this report was generated using an Apogee INS processed in Qinertia in PPK mode, combining a survey-grade geodetic GNSS solution with a high-tactical-grade IMU. GNSS measurements remained available throughout the entire flight.

This configuration provides a navigation solution **whose expected position and attitude errors are negligible compared with the GNSS-denied errors evaluated in this report**. The resulting trajectory is therefore used as the reference against which all tested GNSS-outage scenarios are compared.

Using the same flight data to generate the reference trajectory and evaluate each product ensures a consistent and highly accurate assessment of position and attitude drift during prolonged GNSS-denied operation.

The accuracy of the reference is:

Table 2: Performance of the Ground truth (Apogee-D with Qinertia Tight Coupling PPK)



Parameter	Accuracy
Horizontal position	1cm
Vertical position	1.5cm
Horizontal velocity	0.01 m/s
Vertical velocity	0.01 m/s
Roll / Pitch	0.005°
Heading	0.01°

5 Pure inertial performance assessment

This section compares the products under pure inertial operation. This aims to characterize the intrinsic drift of each IMU. This is representative of fixed wing motion without any velocity or position aiding and serves as a basis to compare the gain of the air-data aiding.

5.1 Test description

In this test, identical GNSS outages were applied to all devices under test over the same flight intervals, to ensure consistent evaluation under identical motion and environmental conditions.

Besides, GNSS, air-data and magnetometer measurements were rejected so that navigation performance was driven solely by the IMU. This represents the most demanding GNSS-denied scenario, where no external measurements are available to constrain inertial drift. The test configuration used for each product is summarized in Table 3.

Table 3: Summary of the GNSS-denied segments introduced during the pure-inertial test

Product	IMU Grade	Aiding Sources Available	Outage Duration	Number of Tests	Measurement
Ellipse	Industrial	None (pure inertial)	2.5 min	10	Mean error & 1 sigma dispersion
Stellar-40	Tactical	None (pure inertial)	5 min	10	Mean error & 1 sigma dispersion
Apogee	High Tactical	None (pure inertial)	5 min	10	Mean error & 1 sigma dispersion

5.2 Test results

The following plots show the mean error across the ten outage segments. The shaded regions represent plus or minus one standard deviation and therefore illustrate the dispersion between outages. Figure 4 presents the horizontal 2D position error, and Figure 5 presents the corresponding altitude error.

5.2.1 Pure inertial 2D position performance

The horizontal position error grows rapidly during unaided operation and shows a clear dependence on IMU grade. The observed curvature is broadly consistent with the strong time dependency expected when gyroscope errors generate attitude errors and incorrect projection of gravity onto the horizontal plane. The long, nearly straight trajectory further limits the observability of heading and inertial error states, making this configuration intentionally severe.

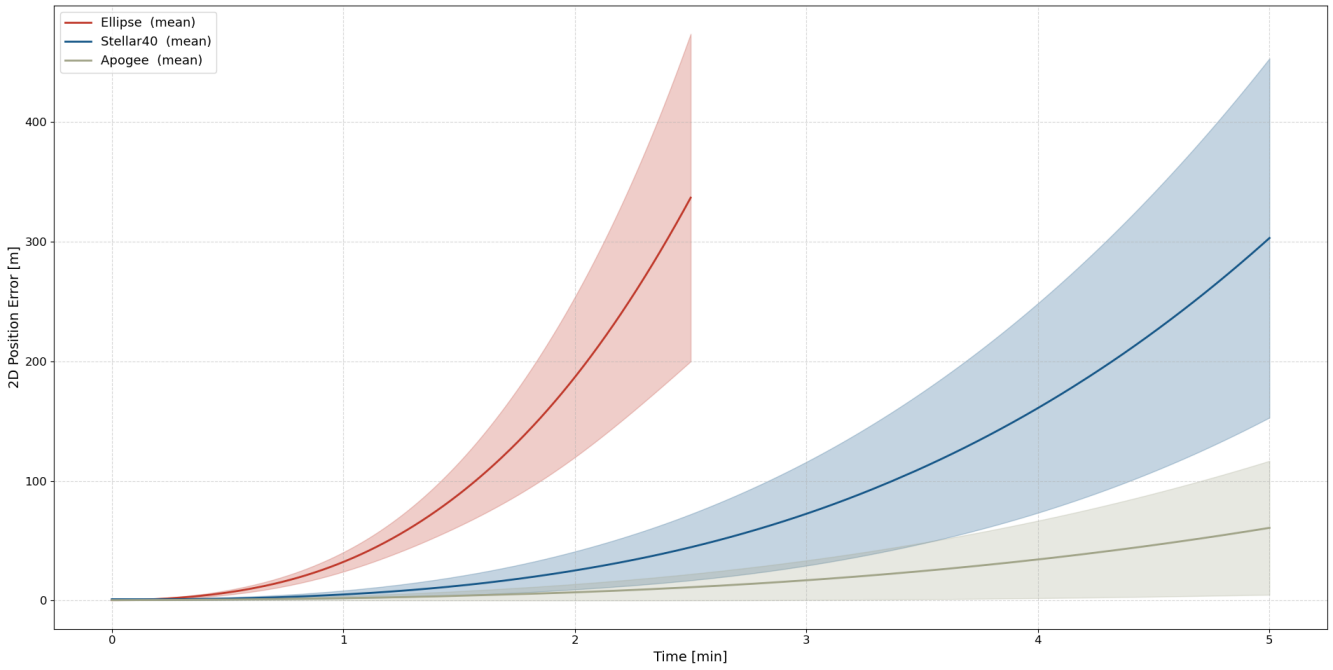


Figure 4: Mean 2D position error in pure inertial operation; shaded regions indicate plus or minus one standard deviation

INS error growth: A constant accelerometer bias is integrated once into velocity and twice into position, leading to a position error that typically grows proportionally to the square of the outage duration. Gyroscope bias can have an even stronger effect: when attitude is badly estimated, part of the gravity vector is incorrectly projected onto the vehicle frame. The resulting apparent acceleration increases with time and, after double integration, may produce position error proportional to the cube of time. These simplified growth laws explain why inertial drift can increase rapidly during unaided operation and why performance strongly depends on the IMU grade.

5.2.2 Pure inertial altitude performance

Vertical drift remains substantially better contained than horizontal position drift. Roll and pitch are constrained by gravity more directly than heading, while the vertical channel is predominantly affected by residual accelerometer bias. The product ranking remains consistent with the respective IMU classes, and the altitude-error growth is broadly compatible with the behavior expected from double integration of a slowly varying acceleration bias.

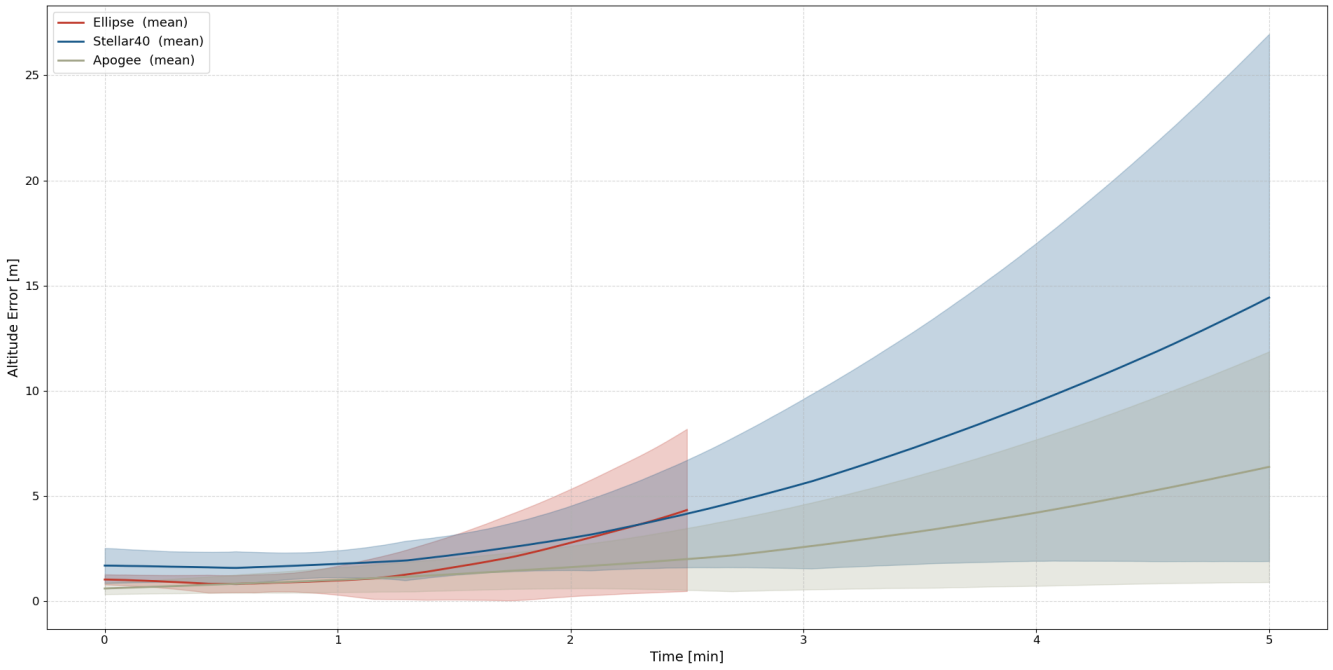


Figure 5: Mean altitude error in pure inertial operation; shaded regions indicate plus or minus one standard deviation

6 GNSS-denied navigation performance with air-data

This section compares the products' performance when aided with air-data. It evaluates the benefit of air-data aiding in reducing navigation drift during extended GNSS outages.

This configuration is representative of the recommended operational setup, as air-data aiding is a low-cost sensor that significantly improves navigation performance during GNSS outages.

6.1 Test description

For this assessment, GNSS measurements were rejected while airspeed and barometric aiding remained enabled. Ellipse was evaluated both with and without its integrated magnetometers, as indicated in the plots.

Table 4: Summary of the GNSS-denied segments introduced during the air-data aided test

Product	IMU Grade	Aiding Sources Available	Outage Duration	Number of Tests	Measurement
Ellipse no magnetometer	Industrial	Air-data	10 min	52	Mean error & 1 sigma dispersion
Ellipse with magnetometer	Industrial	Air-data Magnetometer	15 min	52	Mean error & 1 sigma dispersion
Stellar-40	Tactical	Air-data	15 min	52	Mean error & 1 sigma dispersion
Apogee	High Tactical	Air-data	15 min	52	Mean error & 1 sigma dispersion

For the Ellipse configuration with magnetometer aiding disabled, only the first ten minutes of operation are considered. Beyond this point, accumulated heading drift becomes the dominant error source, resulting in horizontal position errors that can reach several kilometers. Longer outage durations therefore fall outside the meaningful evaluation range for this configuration.

6.2 Test results

As for the previous section, the plot below summarizes horizontal and vertical errors for the tested configurations. Solid lines show the mean over the available outage segments, while shaded regions show plus or minus one standard deviation.

On the following pages, Figure 6 presents the 2D position error, and Figure 7 presents the corresponding altitude error.

6.2.1 2D position error with airspeed aiding

The 2D position results follow the expected overall ranking with IMU performance class. Airspeed and barometric-altitude aiding significantly constrain the fixed-wing navigation solution, but neither measurement provides an absolute horizontal position. Residual heading error and wind-estimation error therefore remain the principal drivers of horizontal drift.

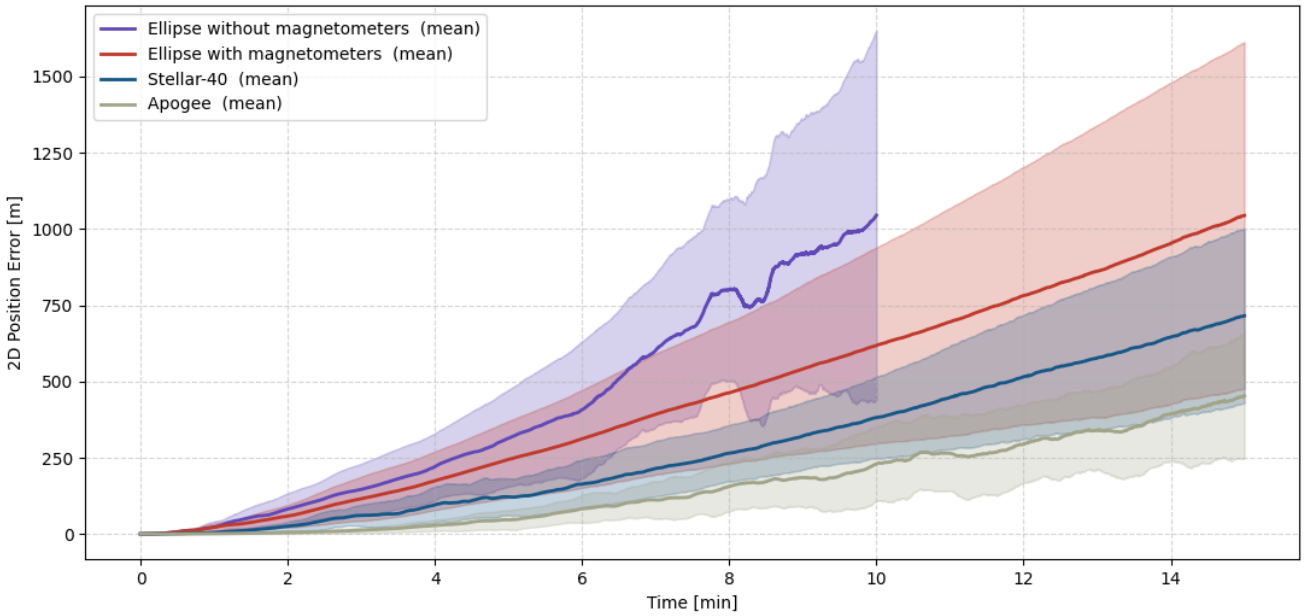


Figure 6: Mean 2D position error with air-data aiding; shaded regions indicate plus or minus one standard deviation

For Ellipse, calibrated magnetometer aiding provides an additional heading constraint and substantially limits yaw and cross-track drift. This benefit depends on the quality and stability of the magnetic environment. Time-varying disturbances generated by the vehicle may not be captured by conventional hard-iron and soft-iron calibration, and the required calibration maneuvers may be impractical for some platforms.

For the higher-grade units, heading drift remains better contained over the evaluated 15-minute outages, even without an external yaw reference, due to improved gyroscope stability. For Stellar-40, embedded magnetometer aiding (that was not used for this test campaign) may still provide value during longer outages, provided that the magnetic environment is sufficiently controlled, and the calibration remains valid.

6.2.2 Altitude error with barometric aiding

Once barometric aiding is enabled, altitude errors are rapidly constrained by the common pressure measurement and become much less dependent on IMU grade.

The approximately one-meter offsets visible at the beginning of some outages are mainly associated with differences between the GNSS-based altitude solutions used before rejection and with the use of absolute error in the plot.

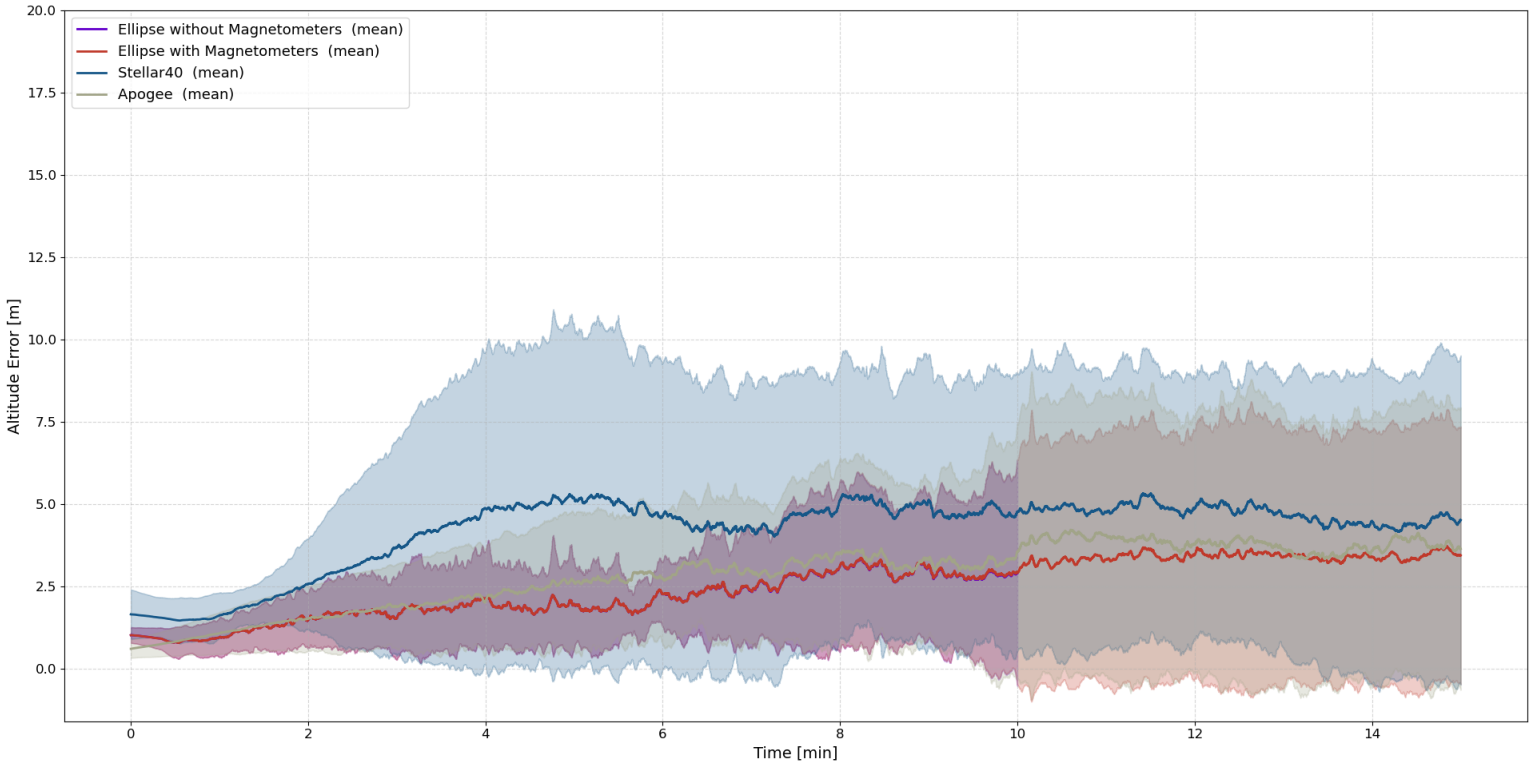


Figure 7: Mean altitude error with barometric aiding; shaded regions indicate plus or minus one standard deviation

Overall, the results confirm that air-data substantially improves GNSS-denied navigation. Horizontal performance remains dependent on IMU grade, heading stability and wind estimation, whereas vertical performance becomes predominantly limited by barometric measurement.

6.2.3 Position Error summary after 10 minutes

To provide a directly comparable assessment across all tested systems, the navigation error is evaluated after 10 minutes of continuous GNSS-denied operation with air-data aiding enabled.

This duration is representative of a realistic operational scenario for fixed-wing aircraft. At the test aircraft's nominal cruise speed of approximately 60 m/s, a 10-minute outage corresponds to a traveled distance of roughly 36 km. Such a distance is comparable to the area of influence that may be encountered when crossing a region affected by a high-power GNSS jammer, making this scenario particularly relevant for evaluating navigation resilience in contested environments.

Table 5: Navigation performance after 10 minutes with air-data aiding

Product	2D position error (m)	Altitude (m)	2D position error (%DT)	Status
	< 650 m	< 5 m	1.72 %DT	OK
	< 400 m	< 5 m	1 %DT	OK
	< 250 m	< 5 m	0.6 %DT	OK

The results show that air-data aiding effectively constrains vertical error, with all tested systems maintaining altitude errors below 5 m after 10 minutes of GNSS denial. Horizontal performance is primarily driven by heading stability and IMU quality.

These results illustrate the benefit of combining airspeed and barometric measurements with higher-grade inertial sensors for prolonged GNSS-denied navigation.

6.3 Angular error analysis

In addition to position and altitude, the analysis includes roll, pitch and yaw errors. Attitude performance is directly relevant to inertial navigation because roll and pitch errors affect gravity projection, while heading error generates cross-track position drift that grows with distance travelled.

Angular accuracy is also important when the INS supports optical payloads or vision-based navigation. In visual odometry, visual-inertial odometry and visual positioning, attitude information supports motion prediction, feature association and estimator robustness. For electro-optical payloads, INS angular errors also propagate directly into line-of-sight and pointing errors.

6.3.1 Roll/pitch performance during low dynamic flight

Roll and pitch errors remain bounded for all evaluated IMU classes during the low-dynamic outages. Gravity provides a strong reference in these nearly straight-flight conditions, and fixed-wing kinematic constraints further support attitude observability. Roll is slightly noisier than pitch, but peak errors remain approximately 0.2° for Ellipse, 0.1° for Stellar-40 and 0.05° for Apogee.

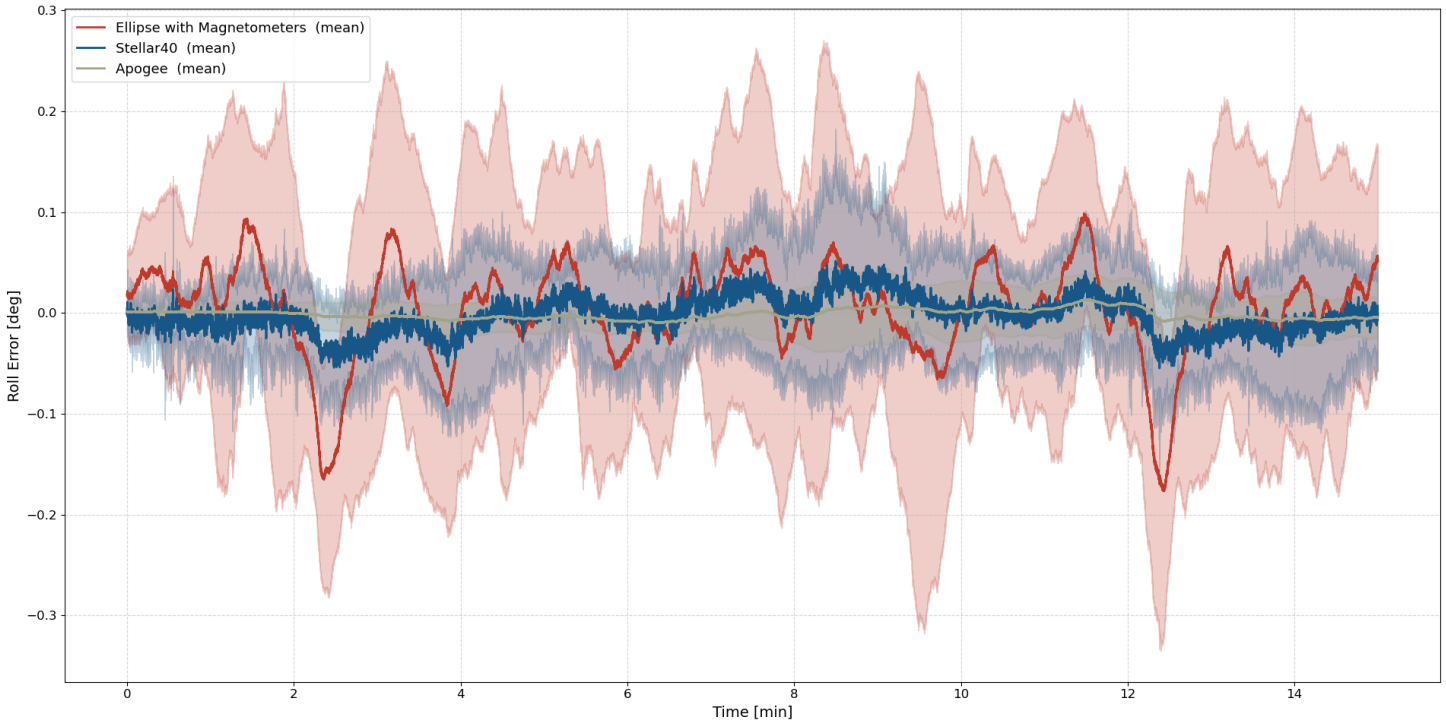


Figure 8: Roll error during repeated low-dynamic GNSS-denied segments

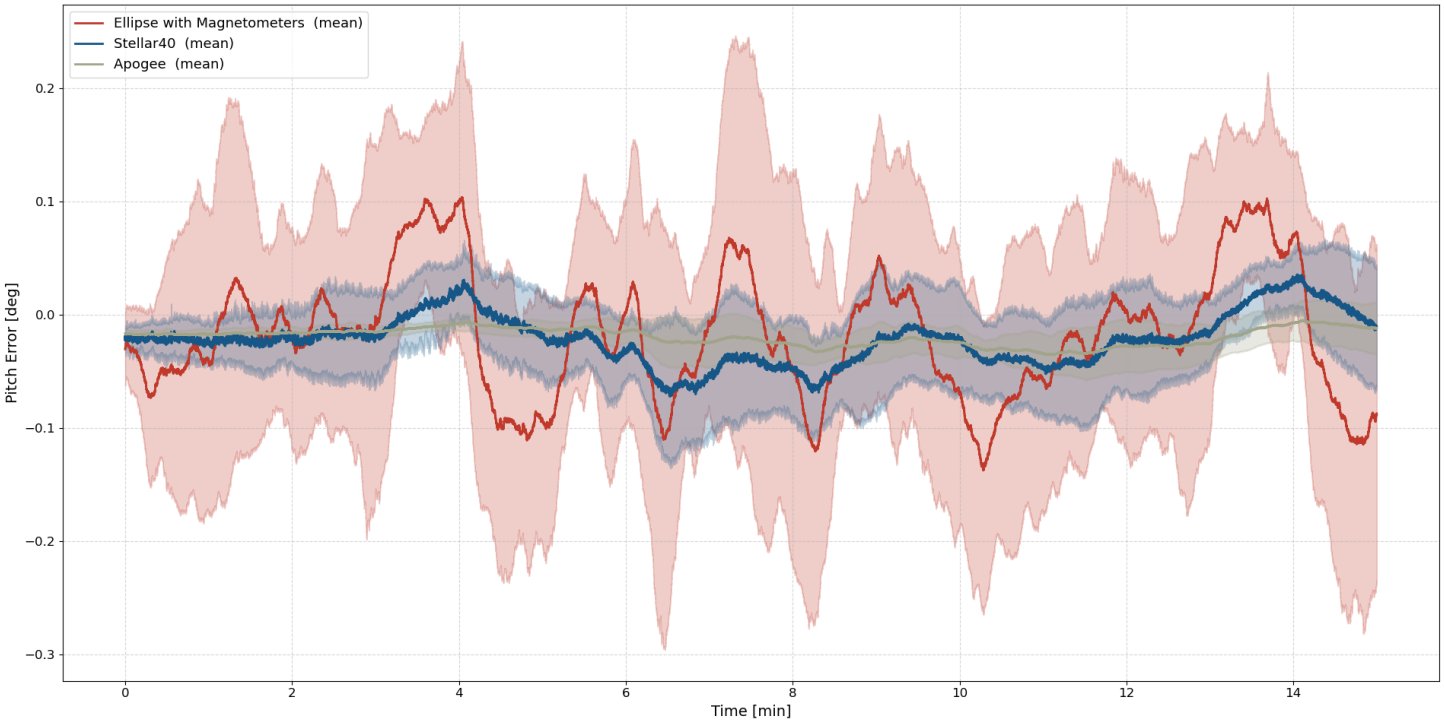


Figure 9: Pitch error during repeated low-dynamic GNSS-denied segments

Since roll and pitch errors remain bounded and show no significant time-dependent drift, a statistical representation is more relevant than evaluating the error at a specific outage duration. The Cumulative Distribution Function (CDF) is therefore used to characterize the distribution of the angular errors over the evaluated intervals. As these errors are approximately Gaussian, particular attention is given to the **68th percentile (P68)**, which corresponds approximately to a **1σ error level** for a zero-centered normal distribution and provides a representative measure of the typical angular accuracy.

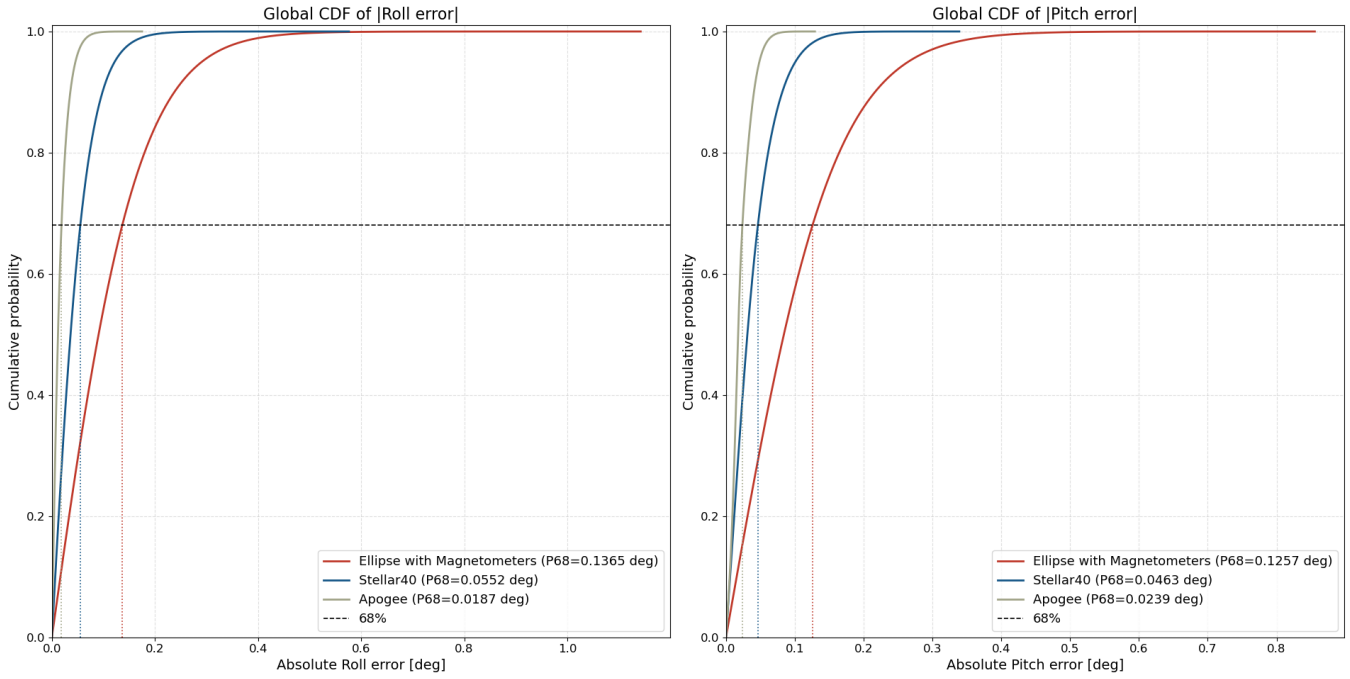


Figure 10: Cumulative Density Function of Roll and Pitch error during repeated low-dynamic GNSS-denied segments

The results follow the expected ranking while confirming stable roll and pitch estimation over the evaluated intervals.

6.3.2 Heading performance during low dynamic flight

Heading drift is a predominant contributor to 2D position error. Unlike roll and pitch errors, heading error is more strongly time-dependent and is not similarly bounded during GNSS outages. Heading performance is therefore characterized through its drift over time rather than through a statistical CDF-based metric.

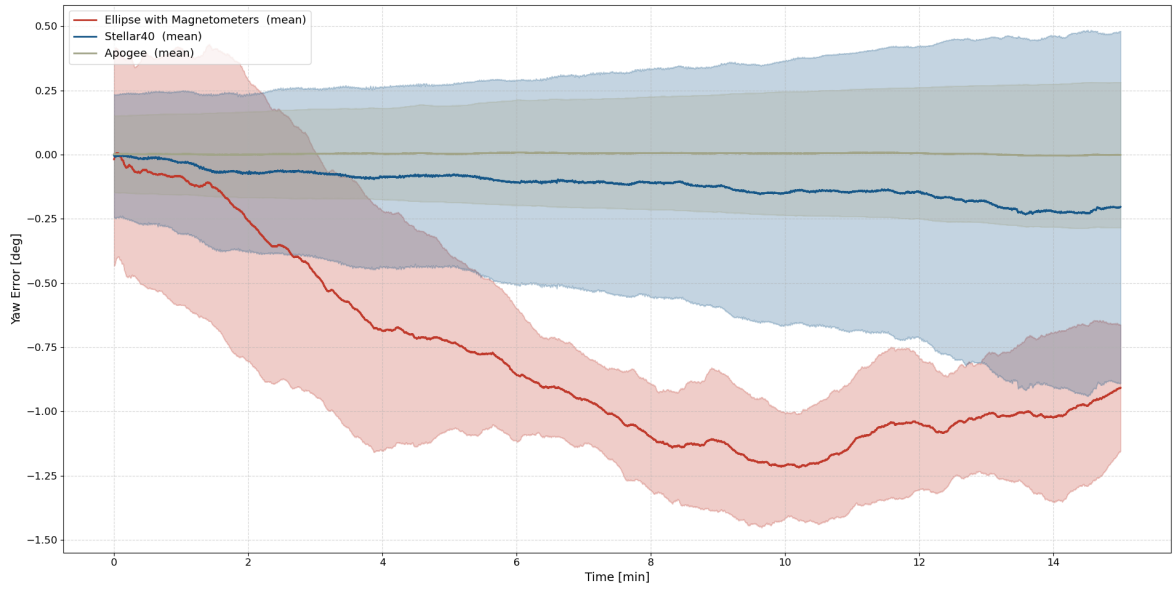


Figure 11: Heading error during repeated low-dynamic GNSS-denied segments

To remain consistent with the position analysis, the **mean heading error after 10 minutes of GNSS outage** is used as the main comparison metric. For Ellipse, calibrated magnetometer aiding constrains heading drift, while Stellar-40 and Apogee rely primarily on their higher-grade gyroscopes and exhibit substantially lower heading-error growth, consistent with their respective IMU classes.

The table below summarizes the attitude accuracy achieved during 10 minutes of low-dynamic flight without GNSS aiding. Roll and pitch errors remain bounded and are largely independent of outage duration and are therefore indicated as a 1 sigma (1σ) error, while heading error accumulates over time and is therefore reported as the mean error of all the outages after 10 minutes of GNSS-denied operation.

Table 6: Attitude-error summary during 10 minutes of low-dynamic flight without GNSS

Metrics	Ellipse	Stellar-40	Apogee
1σ roll error	0.14°	0.06°	0.02°
1σ pitch error	0.13°	0.05°	0.02°
Mean Yaw error after 10mins	1.25°	0.2°	<0.1°

6.4 High dynamic air-data aided performance

To complement the statistical low-dynamic analysis, attitude performance is evaluated during a highly dynamic flight segment featuring several aircraft maneuvers. With air-data aiding available and GNSS unavailable for 300 seconds, this scenario assesses the system's ability to maintain accurate attitude estimation under demanding operating conditions.

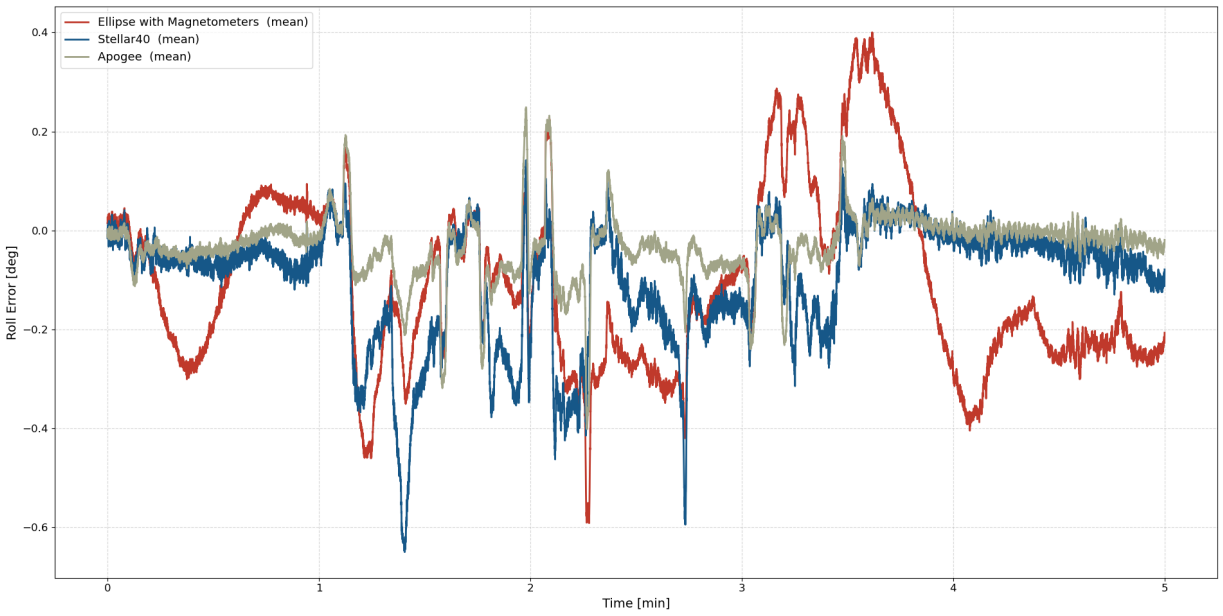
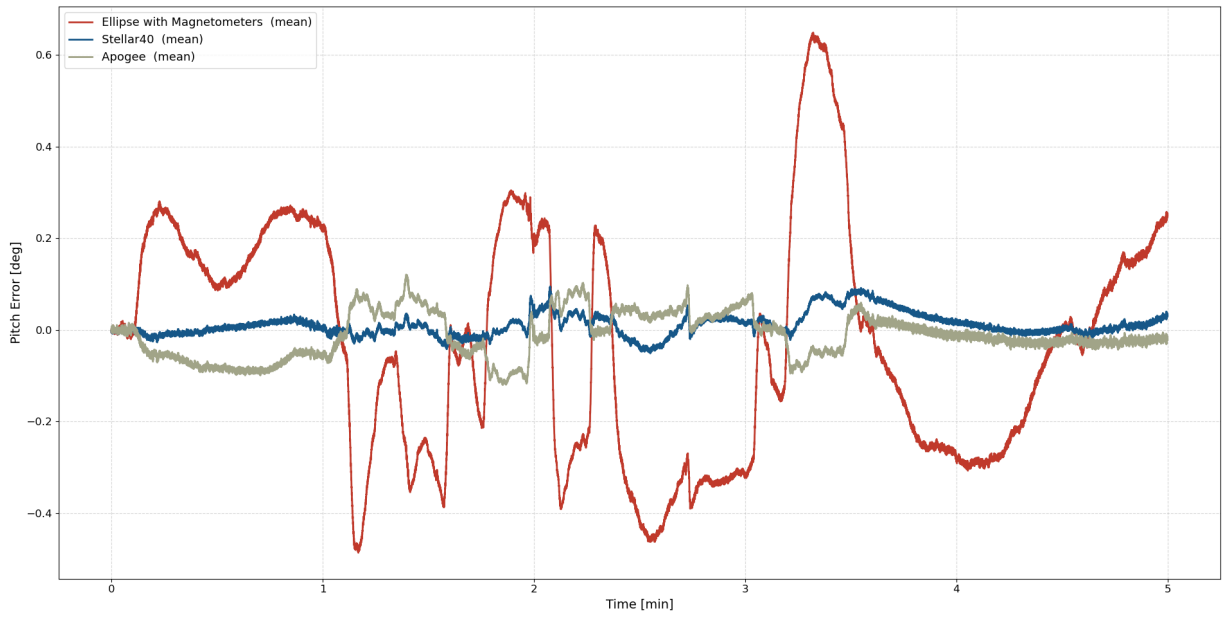
This section evaluates attitude performance during a highly dynamic flight segment containing several aircraft maneuvers. Unlike the low-dynamic results presented previously, which are derived from multiple outages and provide statistical performance metrics, the following results correspond to a single 300-second GNSS outage and should therefore be considered representative of a specific operational scenario rather than a statistical performance bound.



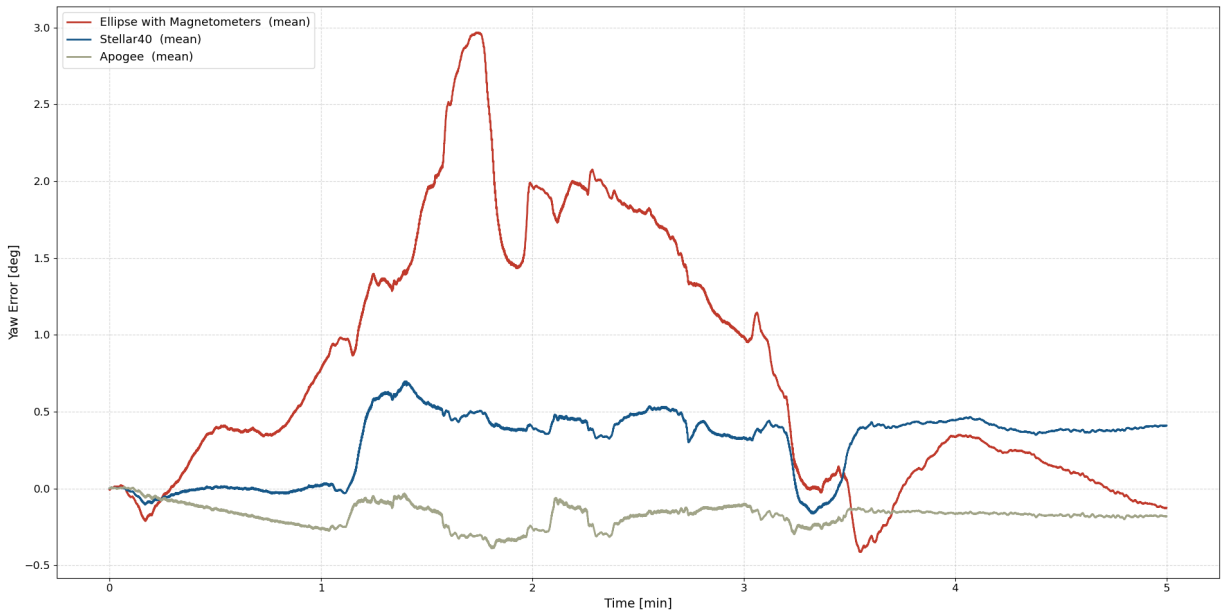
Figure 12: Trajectory during the high-dynamic 300-second GNSS outage

6.4.1 Angular performance during dynamic flight

The graphs below show the time-series evolution of roll, pitch, and yaw errors during high-dynamics flight.

Metric	Attitude error during high dynamic 300-second GNSS outage
Roll error	
Pitch error	

Yaw error



As expected, attitude estimation is more demanding during maneuvering flight without GNSS aiding because the measured specific force contains substantial vehicle acceleration in addition to gravity.

Nevertheless, all angular errors remain bounded and globally centered around zero. There are short-term excursions, which are expected during high dynamics period, but no long-term divergence appears as the error is rapidly corrected after the high-dynamic phase.

Table 7: Attitude performance during a representative high-dynamic GNSS outage

Error	Ellipse	Stellar-40	Apogee
1σ Roll error	0.24°	0.13°	0.05°
1σ Pitch error	0.27°	0.02°	0.05°
1σ Yaw error	1.26°	0.42°	0.18°

These results remain consistent with the expected hierarchy of the IMU classes. Moreover, and as discussed in the next section, these values are consistent with all uncertainty values provided by the INS filter.

7 Uncertainty output from the INS

In addition to position, velocity and attitude, SBG Systems INS provide estimated standard deviations for the main navigation outputs. These values are the real-time estimate of the expected navigation error, based on the available sensors, aiding data, vehicle dynamics and measurement consistency.

During GNSS outages, the INS no longer has direct information about its true position or velocity error. The estimated standard deviations are therefore an important indication of the confidence level that can be placed in the navigation solution. A higher-level system can use them to define limits, switch to a degraded mode or decide whether the navigation solution is still usable.

It is important that these uncertainty estimates are realistic. Over repeated tests, the reported uncertainty should be consistent with the actual navigation error. If the uncertainty is too optimistic, the system may consider a solution reliable when the actual error is much larger. If it is too conservative, the system may reject a solution that is actually good enough.

The figure below shows the 2D position error over 10 GNSS outages, together with the estimated standard deviation reported by the product for one representative outage. As the trajectories are very similar across outages, the reported standard deviations are also highly consistent. The results show that the estimated uncertainty is slightly conservative, as only one error curve temporarily exceeds the reported standard deviation.

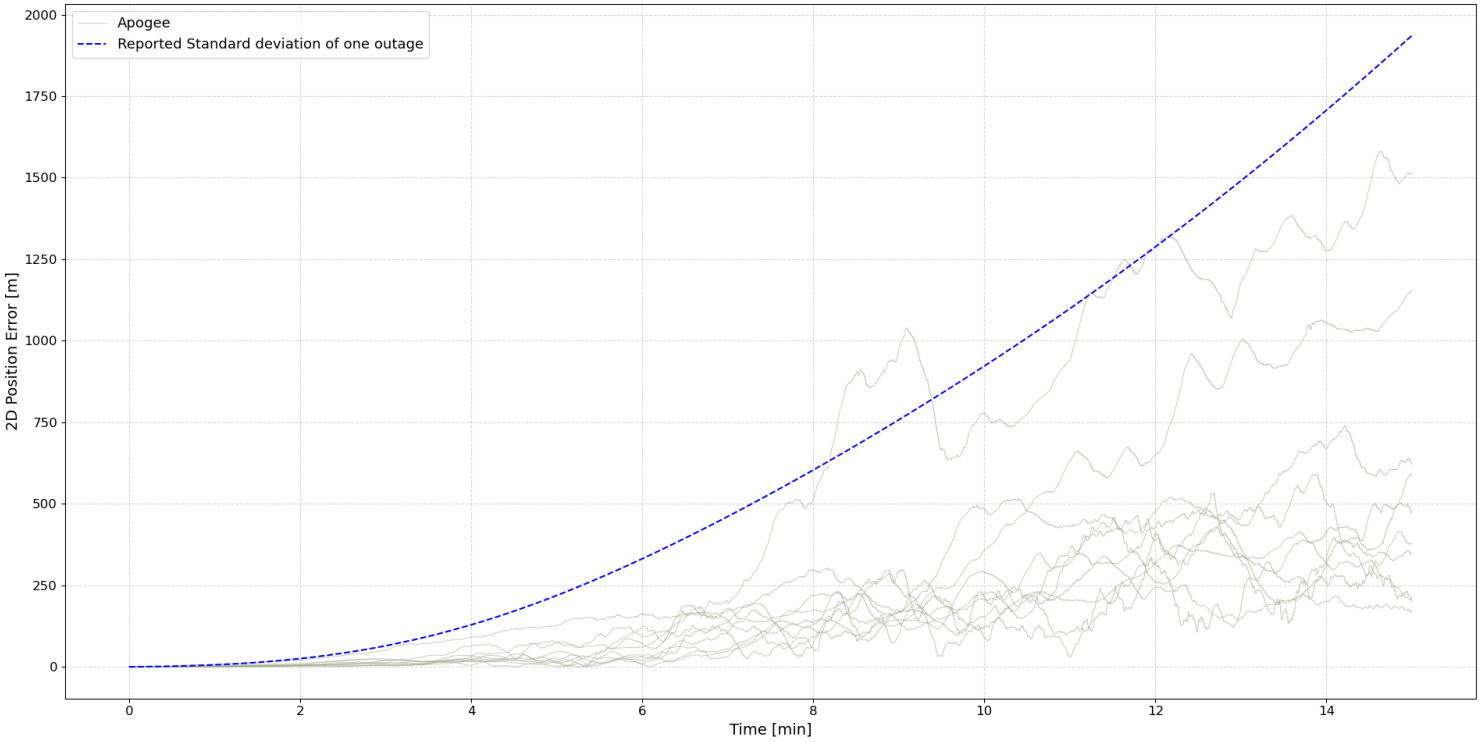


Figure 13: Example illustrating the consistency between observed navigation errors and the uncertainty reported by Apogee during a 15-minute outage.

Uncertainty consistency interpretation : For a consistent INS, the real error should remain statistically compatible with the reported standard deviation. In practice, the error should not always remain below 1-sigma (case around 100sec on the example above), but its distribution over repeated tests should match the expected confidence level. This is the basis for using INS standard deviations as operational decision metrics.

Comparisons between observed errors and reported standard deviations are used by SBG Systems to assess and refine the stochastic models implemented in the navigation filter. The objective is to maintain uncertainty estimates that are conservative enough for integrity monitoring while remaining realistic enough to support operational decision-making.

8 Conclusion

This flight campaign confirms that GNSS-denied performance depends on both the intrinsic IMU grade and the availability of complementary aiding. In pure inertial operation, horizontal error grows rapidly, particularly along a long and nearly straight trajectory with limited observability. Higher-grade inertial sensors substantially reduce this drift, but pure inertial navigation remains unsuitable for sustained accurate positioning.

Airspeed and barometric-altitude aiding provide a major operational benefit. Barometric aiding keeps the vertical error within a few meters for all evaluated products, while air speed constrains the horizontal solution. Horizontal drift nevertheless remains sensitive to heading and wind-estimation errors. Calibrated magnetometer aiding can significantly improve Ellipse performance when the magnetic environment is stable, whereas Stellar-40 and Apogee rely increasingly on their higher-grade gyroscopes over the evaluated outage durations.

The attitude analysis shows that roll and pitch remain well bounded during both low-dynamic and maneuvering segments. Heading is less observable and remains the dominant angular contributor to 2D position drift. The reported standard deviations provide an essential indication of real-time confidence, and the example integrity comparison shows the importance of validating these estimates against actual errors observed over repeated tests.

The table below summarizes the position errors for each product, after **5 minutes for GNSS-denied**:

Product	2D position error (m)	Altitude (m)	2D position error (%DT)	Expected value (specs)	Status
	< 250 m	< 5 m	1.4 %DT	2 %DT	OK
	< 150 m	< 5 m	0.7 %DT	1 %DT	OK
	< 60 m	< 5 m	0.3 %DT	0.5 %DT	OK

Overall, the results support the use of SBG Systems INS products for fixed-wing GNSS-denied operation when the selected IMU class, aiding configuration and acceptable outage duration are matched to the mission requirements.

Extending GNSS-denied operation beyond the 15-minute outages presented in this report often requires additional independent sources of information to maintain navigation errors within acceptable limits.

This is where multi-sensor fusion becomes particularly valuable: visual positioning, radar, air-data or other external measurements can continuously constrain inertial drift and enable accurate navigation over significantly longer GNSS outages. This potential has already been demonstrated with **Stellar-40 combined with visual position aiding**, achieving a final position error of **approximately 0.3% of the distance travelled**.

Such results illustrate that resilient navigation is not only a matter of IMU performance, but increasingly combining a high-quality inertial core with complementary and independent aiding technologies.



Appendix A - Glossary

1σ error: Error bound corresponding to one standard deviation (1σ). For a Gaussian distribution, ~ 68% of samples are expected to fall within this bound. Also see Standard Deviation.

2D position error: Horizontal position error computed from the north and east position errors and expressed as a single distance metric.

Absolute error: Magnitude of the difference between the estimated value and the ground-truth value, irrespective of sign.

Aiding: External measurements or constraints provided to the navigation filter to limit inertial drift and improve the estimation of position, velocity, attitude, or sensor errors. Examples include GNSS, magnetometer, air-data, odometer, visual positioning, and barometer.

Air-data: Use of airspeed and barometric-altitude measurements as aiding inputs to the navigation filter to constrain velocity and altitude errors during GNSS-denied operation. Typically provided by a pitot tube and an air-data computer on a fixed-wing aircraft.

Attitude: Orientation of a vehicle in three-dimensional space, typically described by its roll, pitch, and yaw angles relative to a reference frame.

Bias: Slowly varying offset affecting accelerometer or gyroscope measurements. Uncompensated biases are one of the primary sources of inertial drift during GNSS outages.

Cross-track error: Position error perpendicular to the intended direction of travel. In GNSS-denied operation, heading errors commonly generate cross-track drift that increases with distance travelled.

Dead reckoning: Navigation mode in which position is estimated from previous position, velocity, and attitude information without external position updates.

Dead-reckoning drift: Accumulation of navigation error during GNSS-denied operation due to inertial sensor errors, temporal variations in aiding measurements (for example changes in wind speed or direction), and imperfect state estimation. Dead-reckoning drift is commonly expressed as position, velocity or attitude error as a function of outage duration.

Dispersion: Variation of performance between different outage segments. In this report, it is represented by ±1 standard deviation around the mean.

Distance Travelled (%DT): Horizontal position error expressed as a percentage of the total distance travelled during the GNSS outage.

Drift: Accumulation of navigation error over time caused by sensor errors and imperfect state estimation in the absence of sufficient external aiding.

GNSS-denied operation: Operating condition where GNSS measurements are unavailable, rejected, jammed, spoofed, or otherwise unusable by the navigation filter.

GNSS outage: Time interval during which GNSS measurements are unavailable, rejected, or otherwise not used by the navigation filter.

Heading: Orientation of the vehicle relative to geographic north, typically expressed as a yaw angle.

IMU (Inertial Measurement Unit): Device containing accelerometers and gyroscopes used to measure linear acceleration and angular rate.

Industrial-grade IMU: Inertial sensor designed for industrial applications, providing navigation performance suitable for short GNSS outages and aided navigation scenarios.

INS (Inertial Navigation System): Navigation system combining IMU measurements with navigation algorithms and optional aiding sensors to estimate position, velocity, and attitude.

Magnetometer aiding: Use of Earth's magnetic field measurements to constrain heading drift.

Mean error: Arithmetic average of the error over all evaluated outage segments.

Observability: Ability of a navigation filter to estimate a state (for example heading, sensor bias, or wind) from the available measurements and vehicle dynamics.

P68: 68th percentile of the error distribution. For a zero-centred Gaussian distribution, P68 is approximately equivalent to a 1σ error level. In this report, both metrics are used interchangeably as they yield similar values for near-Gaussian error distributions.

PPK (Post-Processed Kinematic): GNSS processing technique in which corrections are applied after data collection to achieve centimetre-level positioning accuracy. In the context of

this report, PPK is performed using Qinertia and includes Forward/Backward/Merge processing to further improve trajectory accuracy beyond the application of GNSS corrections.

Pure inertial navigation: Navigation mode where all external aiding sources are removed and the solution relies solely on the IMU.

Reference trajectory (ground truth): High-accuracy reference trajectory used to evaluate navigation errors. In this report, the reference trajectory is generated using an Apogee INS processed in Qinertia using PPK corrections and continuous GNSS availability.

Roll / Pitch / Yaw: Roll is rotation about the longitudinal axis, pitch about the lateral axis, and yaw about the vertical axis. Also see attitude.

Sensor fusion: Process of combining measurements from multiple sensors to produce a navigation solution that is more accurate, robust and stable than any individual sensor alone.

Standard deviation (σ): Statistical indicator describing the dispersion of a population of measurements around their mean value. For a Gaussian distribution, approximately 68% of samples lie within ±1σ of the mean.

Tactical-grade IMU: Class of inertial sensor providing significantly lower bias and drift than industrial-grade sensors, enabling improved navigation performance during prolonged GNSS-denied operation. In this report, the term **high-tactical-grade IMU** is used to describe the Pulse-80 and Apogee IMUs, which provide performance beyond the typical tactical-grade category while remaining below the navigation-grade threshold.

Uncertainty estimate: Uncertainty estimate: Real-time estimate of the expected navigation error provided by the navigation filter, typically expressed as a standard deviation (1σ). These estimates are generally derived from the filter covariance.

Wind estimation: Internal filter estimate of the wind vector used to relate measured airspeed to ground velocity.

Wind vector: Estimated wind speed and direction relative to the Earth frame, used to relate airspeed measurements to ground velocity.

Yaw drift: Progressive heading error accumulation during GNSS-denied operation, typically caused by gyroscope errors and limited heading observability.