Test report :

Performance evaluation in GNSS-denied

Marine & submarine applications

SBG SYSTEMS

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1. Introduction

While GNSS has usually been considered reliable for surface marine vessels, the recent regular jamming detected in various sea and coastal areas around the world, has proven this assumption to be false. Furthermore, reliable submarine navigation cannot depend on GNSS.

In these conditions, where GNSS is unavailable dead reckoning becomes essential, relying on inertial sensors and additional aids like DVL “Doppler Velocity Log” to estimate orientation and position over time.

This test report presents an evaluation of SBG Systems’ INS (Inertial Navigation Systems) across a range of performance levels, focusing on their performance in dead reckoning scenarios with and without DVL aiding.

Three products from our portfolio were selected to represent the spectrum of SBG performance tiers:

- Ellipse: our entry-level INS, equipped with an industrial-grade IMU (Pulse-20) and built-in three axis magnetometers
- Ekinox Micro / Quanta Micro: mid-range solution featuring a tactical-grade IMU (Pulse-40)
- Apogee: our high-end system, based on a high tactical grade IMU (Pulse-80) and a survey-grade GNSS receiver

All evaluations were conducted using Qinertia, our post-processing software. This tool allows for precise control over GNSS availability using its rejection module, which enables simulation of GNSS outages without the need to physically interrupt antenna connections during data acquisition. This approach provided a flexible and repeatable way to assess the performance in GNSS-denied conditions in various configurations (with/without DVL, with/without warm-up,..).

The goals of this report are to:

- Perform a preliminary evaluation of the standalone INS performance (without aiding)
- Evaluate the performance of the products with the DVL aiding
- Analyze the impact of the sensor warm-up before entering a dead reckoning phase

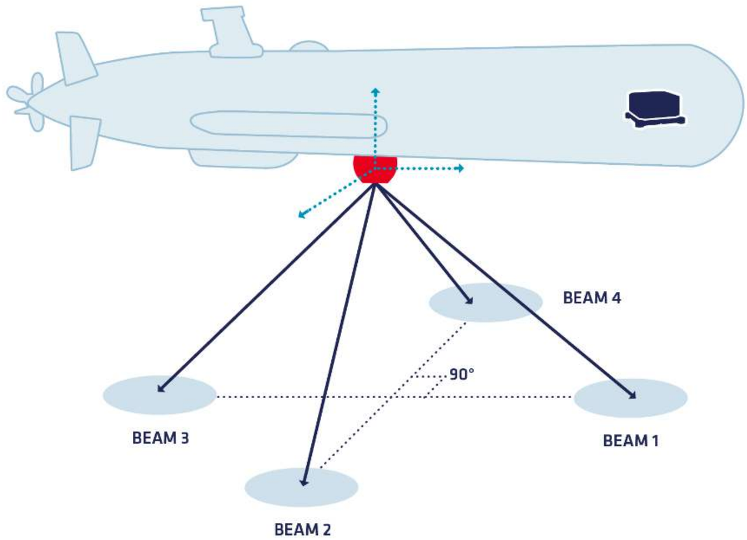
2. What is a Doppler Velocity Log (DVL)

A Doppler Velocity Log (DVL) is an acoustic instrument used in marine and underwater navigation to measure a vehicle's velocity relative to the seafloor or water column. It is widely employed in applications involving autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), submarines, and even surface vessels who are exposed to GNSS challenged environments.

2.1. How does it work?

DVLs operate based on the **Doppler effect**—the change in frequency of a wave relative to an observer moving relative to the wave source. The DVL transmits short bursts of acoustic energy (sound waves) at known frequencies through multiple beams, usually in a 4-beam Janus configuration, angled away from the vertical.

When these beams strike a reflective surface (seafloor or suspended particles in the water), the frequency of the returning echo shifts depending on the relative motion between the DVL and the target. By measuring this **Doppler shift** in each beam, the DVL computes the velocity vector of the vehicle in three dimensions (surge, sway, and heave).



2.2. Modes of Operation

- **Bottom Track Mode:** Measures velocity relative to the seabed. Effective when the vehicle is within a certain altitude range (typically up to 100 to 200 meters depending on model).

- **Water Track Mode:** When bottom tracking is unavailable (e.g., deep water), the DVL uses suspended particulate matter in the water as reference to estimate velocity.

The bottom track mode offers the highest accuracy as it is not impacted by water displacements, sea currents, etc.

3. Test overview

3.1. Environment overview

The test took place in Cagnes-sur-Mer, near Nice, France with data acquisition carried out on a boat. The weather conditions during this period in Cagnes-sur-Mer were favorable, with pleasant temperatures and calm seas, providing an ideal environment for the test.

3.2. Products under test

The performance evaluation will be carried out on the Apogee-D, Ekinox Micro, and Ellipse-D systems. Within the Teledyne product range, we have chosen the Pathfinder DVL for its compact form factor and proven reliability in delivering accurate and consistent measurements.

Product	Hardware code	IMU grade	Performance in marine dead reckoning
	ELLIPSE-D-G4A2-B1	Industrial	1 % DT
	EKINOX-UG-00	Tactical	0.4 % DT
	APOGEE-D-G3A3	High tactical	0.2 % DT
	Pathfinder PATH-SC-OPT004	-	-

3.3. Test setup

All SBG Systems products were securely affixed to a plate. This plate was mounted within a mast using two interface plates. The DVL was affixed at the mast's extremity.

Figure 1: Test setup

3.4. Test route

The graph below shows the trajectory selected for this evaluation: a straight-line path over approximately 45 minutes.

Figure 2: Test trajectory

4. Performance assessment

This section presents a series of tests conducted to evaluate the performance of the three units under different operating conditions. The objective is to assess their behavior in dead reckoning mode, both with and without external aiding, and to analyze the influence of initialization time.

For that, GNSS and other aidings were rejected at various intervals and duration to generate the different Devices Under Test (DUTs). The tightly coupled solution of the high-end tactical-grade Apogee, equipped with a survey-grade GNSS receiver, was used as the reference.

The same outages were applied across all units. However, their durations were adjusted depending on the IMU performance class of each product for a meaningful evaluation.

The section is organized as follows:

- Test scenario 1: performance assessment in dead reckoning in pure inertial without DVL aid
- Test scenario 2: performance assessment in dead reckoning with DVL aid
- Test scenario 3: evaluation of the impact of warm-up phase

4.1. Pure inertial performance

4.1.1. Test description

For this test, both GNSS and DVL signals were rejected from the solution so that the performance will be driven by the IMU only. Note that the Ellipse unit uses its built-in magnetometers reflecting typical usage conditions.

4.1.2. Test results

The graph below illustrates the trajectories of the three solutions alongside the reference in the X-Y plane. The dashed segments highlight the phase during which GNSS signals were intentionally disabled, lasting 5 minutes.

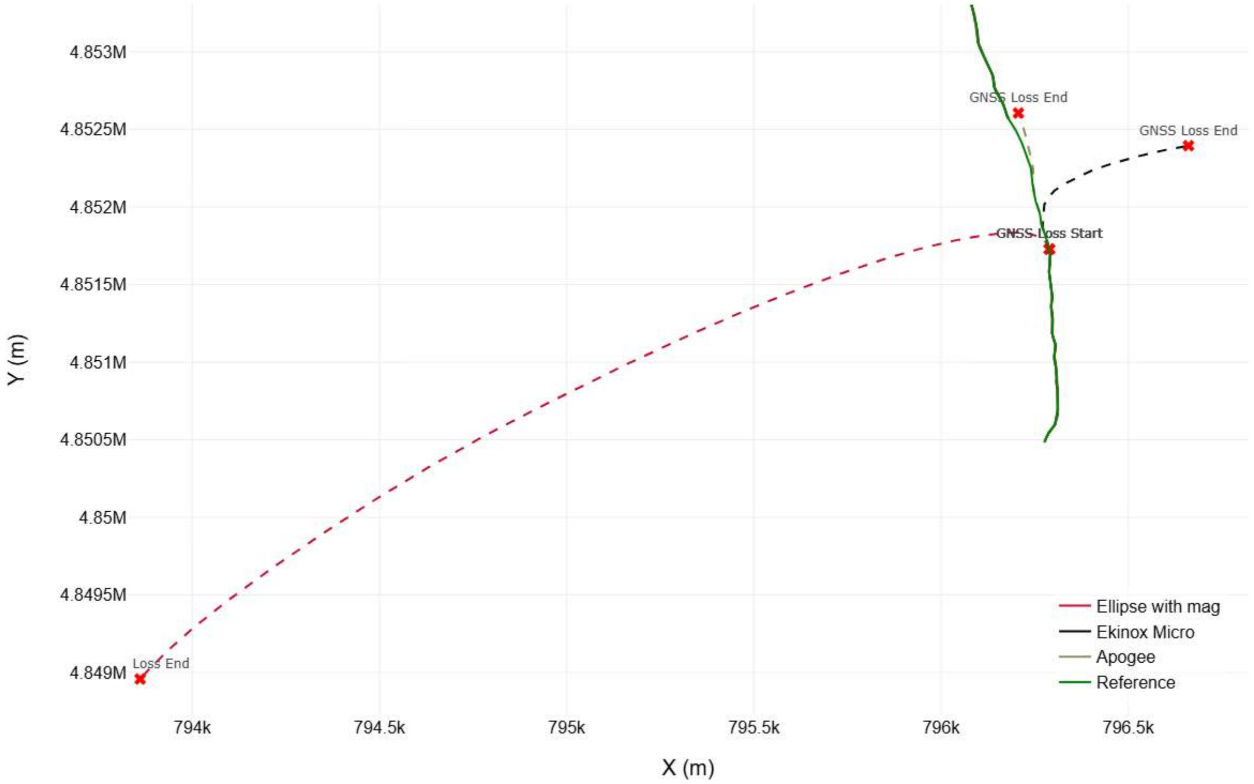


Figure 3: Dead reckoning results over a 5-minute GNSS outage in pure inertial (without external aiding)

The figure 2 shows the 2D position error over time in a pure inertial configuration, where both GNSS and DVL are disabled. It compares the performance of the three products: Apogee, Ekinox Micro, and Ellipse with magnetometer enabled.

We observe that:

- Apogee exhibits the lowest drift, with the 2D error gradually increasing to about 400 meters after 10 minutes. This reflects its tactical-grade IMU, delivering superior long-term stability
- Ekinox Micro, with its tactical-grade IMU, drifts faster and reaches a similar error level as Apogee in roughly half the time (~5 minutes)
- Ellipse, despite using magnetometers to assist heading, shows a very rapid error growth, surpassing 500 meters in just over 2 minutes. This indicates that magnetometers alone are not sufficient to maintain reliable inertial navigation over even short outages

These results clearly illustrate how IMU grade significantly impacts inertial navigation performance, and that magnetometers cannot compensate for the absence of GNSS in terms of position accuracy.

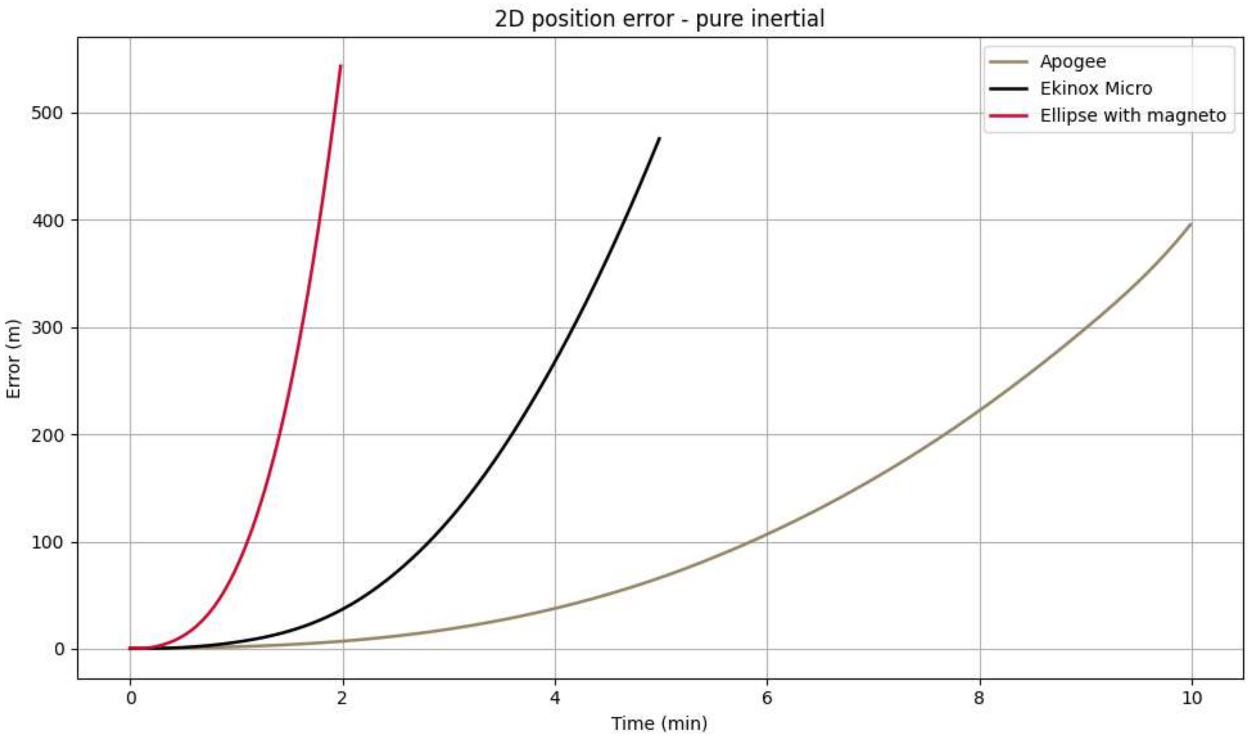


Figure 4: 2D position error - pure inertial – vessel speed of 10km/h

These results clearly illustrate clearly illustrate how the grade of the IMU significantly impacts inertial navigation performance. With a low-end IMU (Ellipse), even the addition of magnetometers cannot compensate for the absence of GNSS in terms of position accuracy.

Moreover, even the highest-grade IMU (as used in the Apogee) shows a steady drift in position over time, with errors reaching several hundred meters.

For longer dead reckoning periods, relying solely on the IMU is not sufficient. Accurate velocity inputs and sensor hybridization — such as integrating DVL measurements — become essential for a reliable and stable navigation. This will be further explored in the next section.

4.2. Dead reckoning performance with DVL input

4.2.1. Test description

For this test, GNSS signals were rejected, while DVL measurements were retained to evaluate the inertial navigation performance with velocity aiding.

The objective is to assess how each system maintains position accuracy in the absence of GNSS, relying solely on DVL and inertial data. For the Ellipse unit, two configurations were tested: one with magnetometers enabled and one without, to evaluate their contribution under velocity-aided conditions.

4.2.2. Test results

The figure below shows the trajectory of the three solutions along with the reference in the X-Y plane. The dashed segments represent the phase during which GNSS signals were disabled.

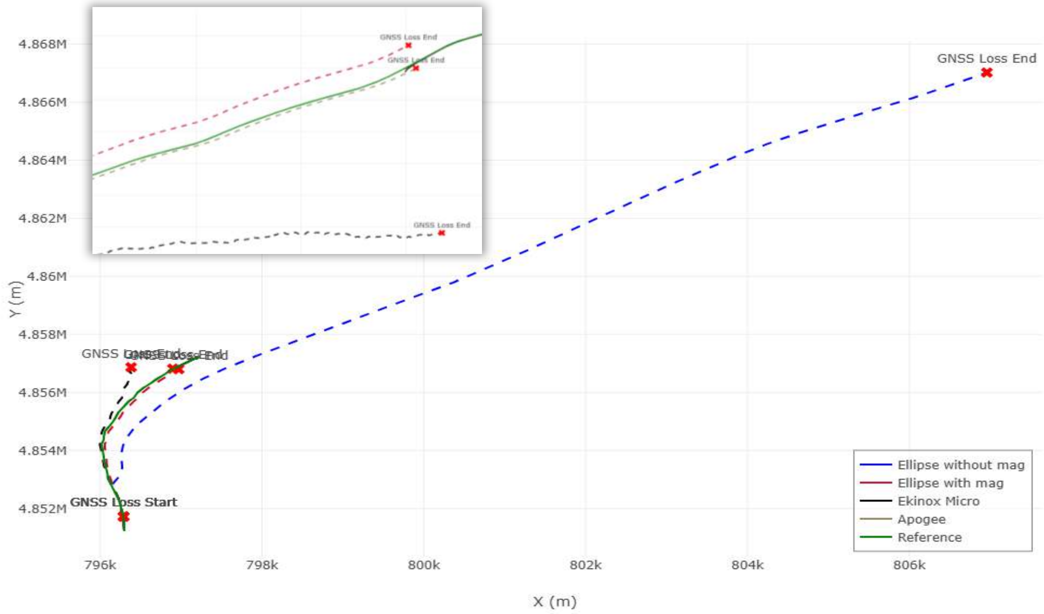


Figure 5: Dead reckoning results over a 20-minute GNSS outage with the DVL aiding
Dashed segments indicate the GNSS-denied portion of the trajectory

The graph below shows the 2D position error over time in DVL-aided INS configuration, where GNSS was disabled and DVL enabled. It compares the performance of the three products: Apogee, Ekinox Micro, and Ellipse with and without magnetometer.

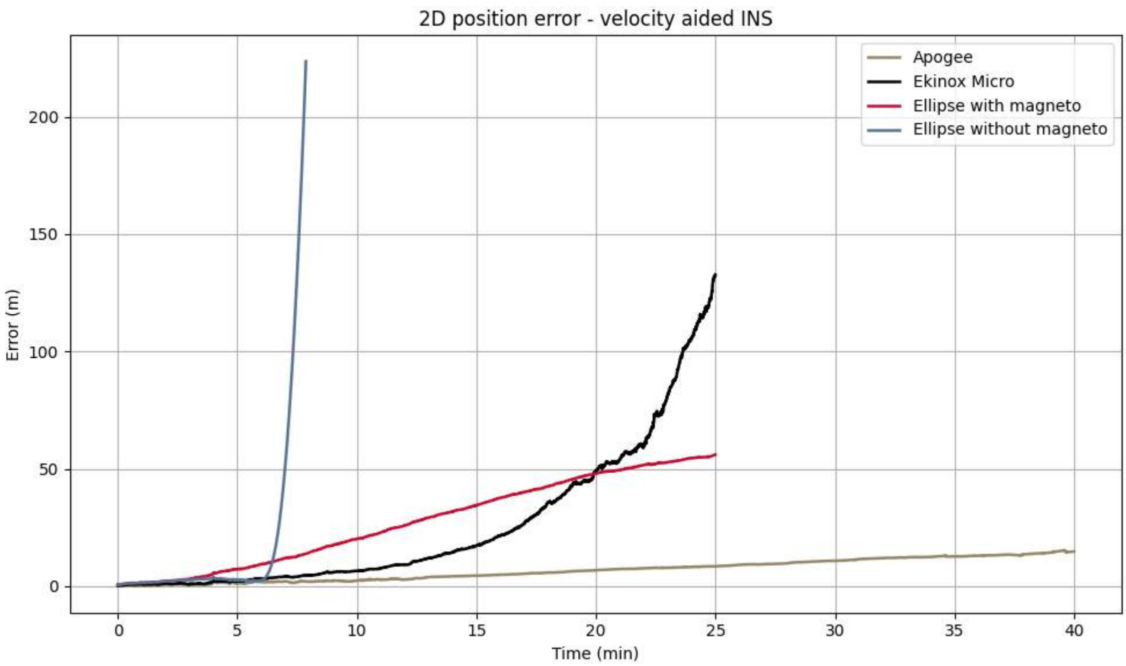


Figure 6: 2D position error - velocity aided INS – vessel speed of 10km/h

The results confirm the value of velocity aiding in improving dead reckoning performance across all IMU classes. We observe that :

- Apogee (high tactical-grade IMU): exhibits excellent performance, with a linear error growth over the entire duration of the outage thanks to its superior IMU performance and efficient fusion with DVL data. Position errors remain under 25 m even after 40 minutes of navigation without GNSS
- Ekinox Micro (tactical-grade IMU):
  - Exhibits a slow linear drift the first 10 minutes (<10 meter errors after 10 minutes)
  - Then shows a moderate accelerating drift, reaching about 130 m of error after 25 minutes
- Ellipse (industrial-grade IMU):
  - **Without magnetometers input**, position accuracy is very limited and degrades quicky with errors exceeding 200 m in less than 10 minutes. This illustrates the difficulty of maintaining stable heading without magnetometers in entry level IMUs, even when DVL is available
  - However, **with magnetometers**, the Ellipse performance improves significantly. The error stays below 60 m of error after 25 minutes. Magnetometers help stabilize heading estimation, which in turn supports better position accuracy when fused with DVL.

These results demonstrate that while DVL significantly improves dead reckoning capabilities, heading estimation remains a limiting factor for lower-grade IMUs. The use of magnetometers clearly improves the performance of the Ellipse, even surpassing that of a tactical-grade IMU after a certain period without GNSS.

This level of performance is achievable only when the products are properly initialized – that is, when they undergo a clean warm-up period with GNSS to correctly estimate IMU biases. The following section explores how different warm-up durations impact overall navigation accuracy when GNSS is compromised.

4.3. Impact of warm-up

To prepare the entry to GNSS-denied environments, inertial systems require a warm-up phase, during which the IMU biases are estimated. This phase typically involves the use of GNSS measurements combined with some maneuvers (e.g., turns, accelerations). The quality and duration of this warm-up have a direct impact on the subsequent dead reckoning performance.

The graph below shows the 2D position error for the Ekinox Micro with different warm-up durations.

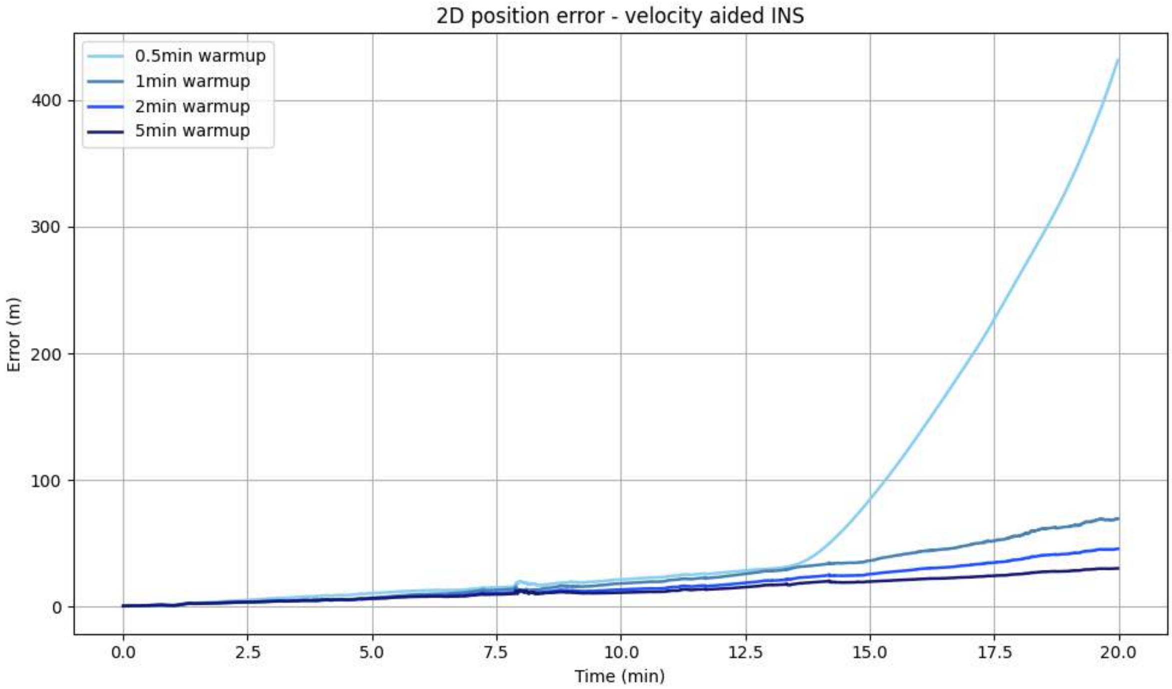


Figure 7: 2D position error - impact of the warm-up – vessel speed of 10 km/h

We observe that during the first 12 minutes, all curves follow a similar trajectory with errors gradually increasing. However, after the 12-minute mark, the differences become pronounced, A 5 min warm-up roughly halves the 20-minute error relative to a 1–2 min warm-up and keeps the system an order of magnitude more accurate than a 30 s warm-up.
Overall, longer warm-up times result in much better long-term stability and lower error.

5. Conclusion

The different tests conducted demonstrate how inertial navigation performance in GNSS-denied environments is heavily dependent on both IMU grade and external velocity sensors.

First, the pure inertial tests clearly showed that IMU grade plays a central role: higher-end systems like the Apogee maintained position accuracy longer, while lower-grade units such as the Ellipse exhibited rapid error growth even when aided by magnetometers.

The velocity-aided INS tests highlighted the significant benefits of DVL integration, which substantially improves dead reckoning performance across all IMU classes. Notably, the Ellipse—when using magnetometers—was able to achieve performance levels after a quick period of time that rivaled or even surpassed tactical-grade systems. However, when magnetometers were disabled, the Ellipse's accuracy quickly degraded, emphasizing that heading estimation remains a limiting factor.

In addition to sensor grade and aiding, the warm-up duration analysis also underscored the critical role of warm-up time on navigation stability. While short warm-up durations (e.g., 30 seconds or 1 minute) may appear acceptable in the first few minutes of operation, they lead to significant long-term drift—especially in position. These results confirm that ensuring sufficient warm-up is essential—especially for applications requiring sustained accuracy in GNSS-denied environments.

Overall, these tests confirm that robust dead reckoning requires a combination of high-quality inertial sensors, reliable heading estimation, aiding inputs such as DVL, and a proper initialization phase.

Finally, the table below summarizes the results and performance for all three units, comparing the achieved performance with each of the product specifications of 10-min dead reckoning.

Product	Target value	Achieved value	Status
	1 % TD	1.1 % TD	OK
	0.4 % TD	0.38 % TD	OK
	0.2 % TD	0.15 % TD	OK

The results confirm that both the Ekinox Micro and the Apogee comfortably meet their target performance levels, with the Apogee even outperforming. The Ellipse, while slightly above its target at 1.1% TD (vs. 1% TD at 1-sigma), remains within acceptable limits. This minor deviation may be attributed to the quality of magnetometers in this segment.

This test highlights that SBG Systems INS are fully capable to operate in Marine environments where GNSS is challenged whether it's the result of jamming or for subsea operations of moderate durations.