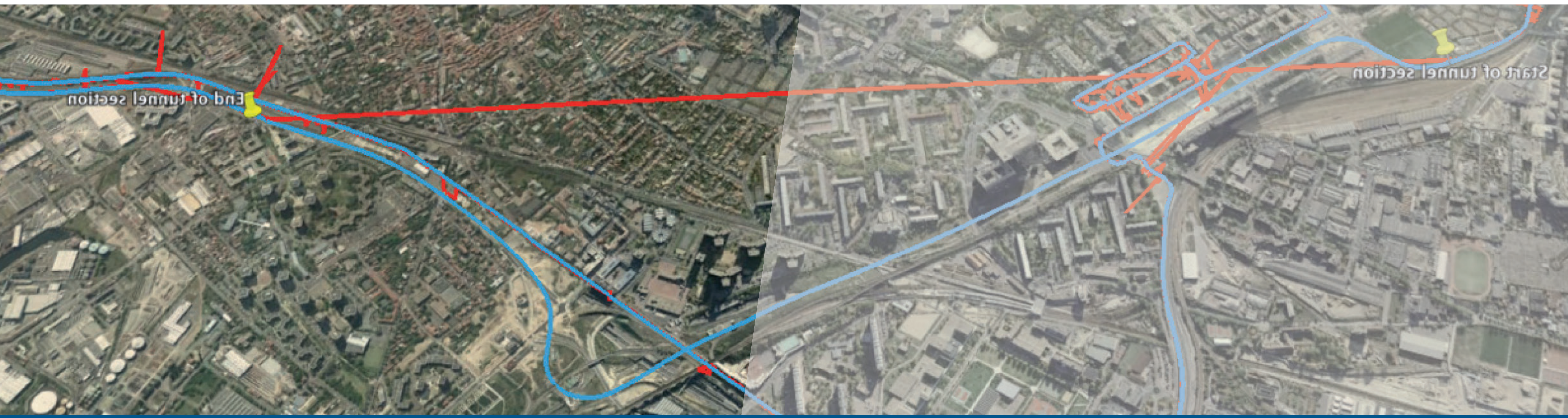
Ellipse 3 | Performance Assessment Report
In automotive application



Test Environment
AUTOMOTIVE

Product on test
ELLIPSE SERIES
Ellipse-D v3

TESTED PRODUCTS
Ellipse-D, miniature inertial navigation system (INS) for low dynamics and robust heading with a full-GNSS dual-antenna RTK receiver.

TESTED PERFORMANCE
Roll, Pitch, Heading, and Position

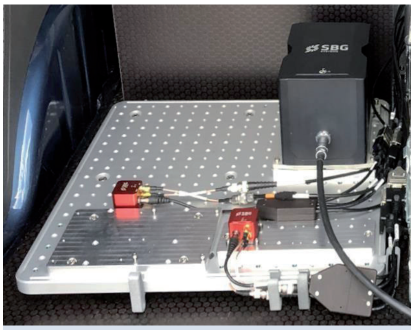
DATE, PLACE
June, 2021 in Carrières-sur-Seine, France

PREAMBLE
For the purpose of this report, SBG Systems conducted a series of road test campaigns to assess the performance of the Ellipse-D under various environmental conditions typical of automotive applications.

The Ellipse-D is a cost-effective entry level INS in the portfolio of SBG Systems well suited for automotive usage.

We assessed the performance of the Ellipse-D in real time receiving RTK corrections and odometer input and in standalone mode (not aided). Measurements were also processed offline using SBG Systems Qinertia PPK software.

The reference system is the SBG Systems Horizon FOG IMU with Navsight-T receiving RTK corrections and odometer input. For this FOG unit, the post-processed accuracy obtained is better than 0.004° on attitude and centimeter-level on position. An RTK base station was installed in optimal conditions with a clear view of sky and logged data during the entire test campaigns.



MOUNTING
Both Ellipse-D (RTK, Standalone) and the Horizon IMU were rigidly mounted on a plate in the car. GNSS lever arms, the vehicle center of rotation as well as pitch/yaw alignments within the vehicle frame were accurately estimated using Qinertia PPK software with a Tightly Coupled computation.

SBG SYSTEMS

TEST CONDITIONS

DEVICES UNDER TEST (DUT)

Ellipse-D production units were used in different operating modes:

- Ellipse-D v3 receiving RTK corrections and odometer input (RTK+Odo)
- Ellipse-D v3 not receiving RTK corrections, nor odometer input (Single Point)
- Ellipse-D v3 tightly coupled post-processing with offline GNSS data (PPK)

Specifications given @1σ.

Sensor		Position (2d) Accuracy	Attitude Accuracy	Heading Accuracy
Ellipse RTK		0.01m (0.8m @ 10s) (5.5m @ 60s)	0.05° (0.05° @ 10s) (0.10° @ 60s)	0.2° (0.2° @ 10s) (0.3° @ 60s)
Ellipse Single Point		1.2m (1.7m @ 10s) (7.0m @ 60s)	0.1° (0.1° @ 10s) (0.15° @ 60s)	0.2° (0.2° @ 10s) (0.3° @ 60s)
Ellipse PPK		0.01m (0.1m @ 10s) (1.0m @ 60s)	0.02° (0.08° @ 10s) (0.1° @ 60s)	0.1° (0.1° @ 10s) (0.2° @ 60s)

REFERENCE

The reference system is the Horizon IMU with Navsight-T receiving RTK corrections and odometer input.

Specifications given for Tight-Coupling PPK with Automotive motion profile @1σ.

Sensor		Position (2d) Accuracy	Attitude Accuracy	Heading Accuracy
Horizon		0.01m (0.01m @ 10s) (0.05m @ 60s)	0.004° (0.004° @ 10s) (0.005° @ 60s)	0.008° (0.008° @ 10s) (0.010° @ 60s)

The specifications of the Horizon FOG (Fiber Optic Gyroscopes) IMU make it a perfect candidate to obtain a tightly coupled PPK solution and to be used as a reference for our tests.

CONFIGURATION & ACQUISITION SETUP

Each sensor is rigidly mounted on a dedicated fixture attached to the test vehicle. The lever arms were first measured and then precisely re-estimated with Qinertia post-processing software (see detailed explanations further in chapter "Lever arms estimation with Qinertia"). The diagram in *Figure 1* depicts the connections to the external aiding inputs, the data logger and the splitters needed to share the dual-antenna system.

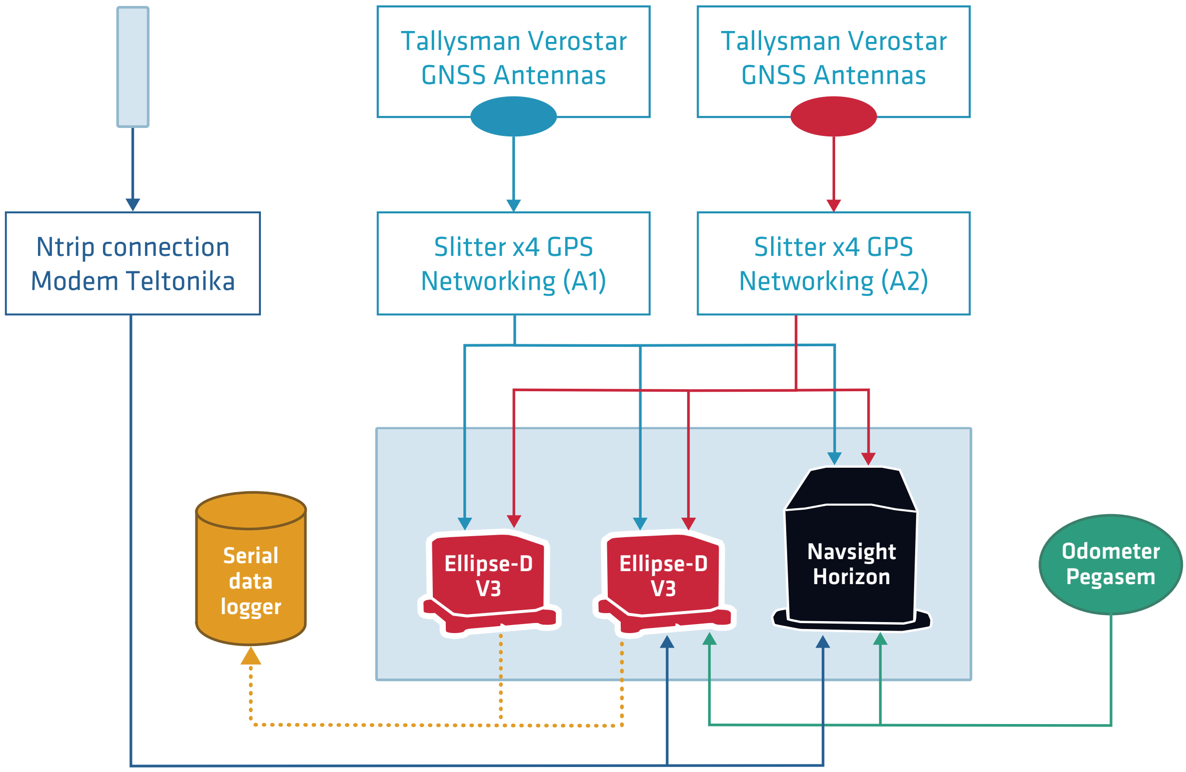


Figure 1 - Systems connection

RECORD DATA WITH SBGDATA-LOGGER

SbgDatalogger is a companion software tool supplied by SBG Systems to record binary data from the two units under test and to feed RTCM corrections from a NTRIP server to the device RTK + Odometer. It allows to use a single serial port to send RTCM corrections while retrieving and logging measurements from an Ellipse.

The *Figure 2* shows the main interface. The left panel controls and monitors the connection to the NTRIP server. The right section displays various statuses information separately for each connected Ellipse.

The first Ellipse is receiving RTCM corrections with an RTK fixed GNSS solution whereas the second one is only providing a standalone GNSS position.

BASE STATION SELECTION FOR PPK

The base station used for PPK computations was SBGS, from the provider IGNRGP *(Figure 3)*. The maximum baseline for all the tests was 13 kilometers.

LEVER ARMS ESTIMATION WITH QINERTIA

Qinertia is very practical to estimate GNSS and odometer lever arms. For automotive applications, Qinertia can also estimate the vehicle center of rotation as well as pitch/yaw alignments within the vehicle frame.

We performed an acquisition while driving "8-shape" patterns under an open sky environment *(Figure 4)*. For optimal lever arm estimation, it is always advised to expose the INS to dynamic motions in good GNSS conditions.

The acquired data has been post-processed in Qinertia using a Tightly Coupled PPK computation to estimate accurately the INS installation lever arms and alignment.

Once the computation is completed, Qinertia automatically reports the refined mechanical installation parameters with QC indicators.

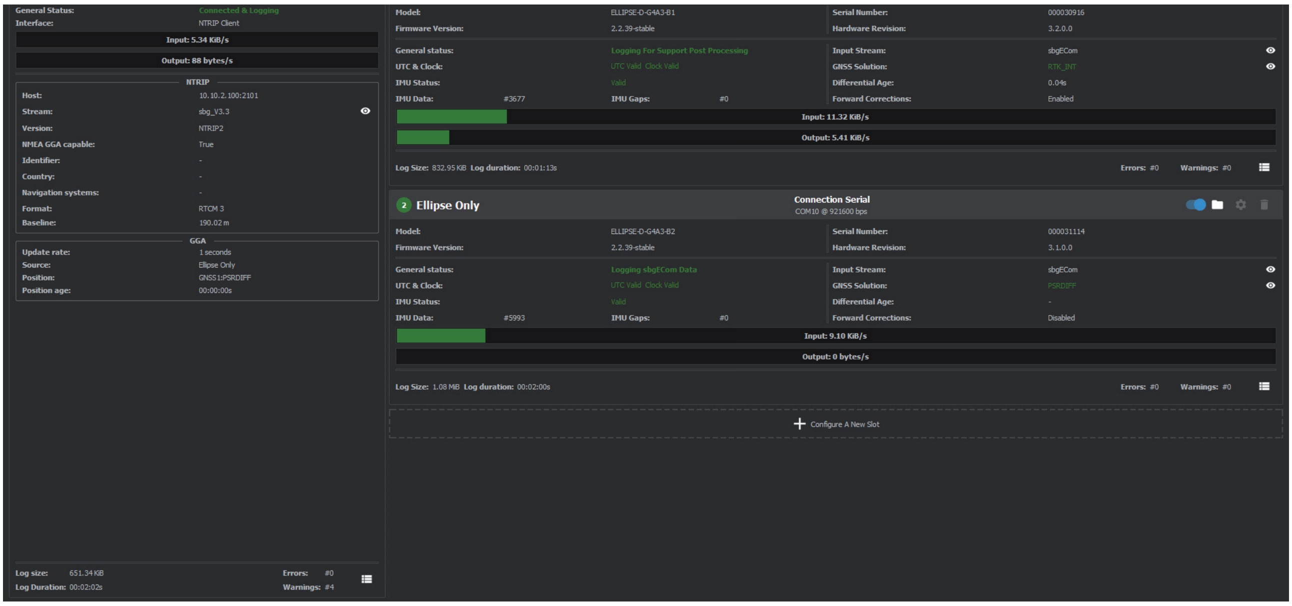


Figure 2 - sbgDataLogger GUI

Figure 3 - Maximum baseline value for all acquisitions

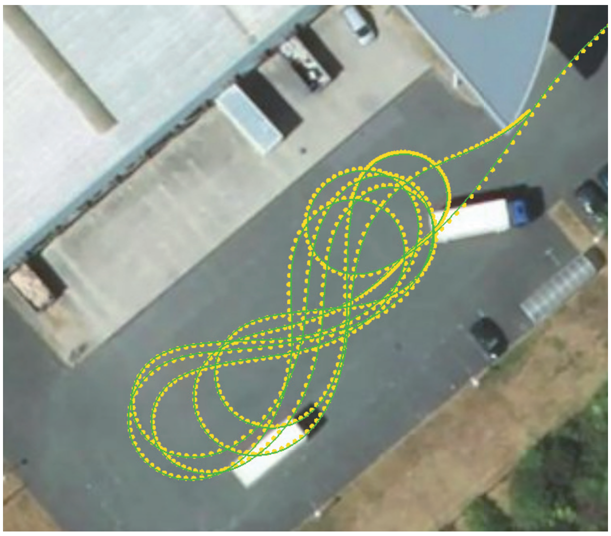
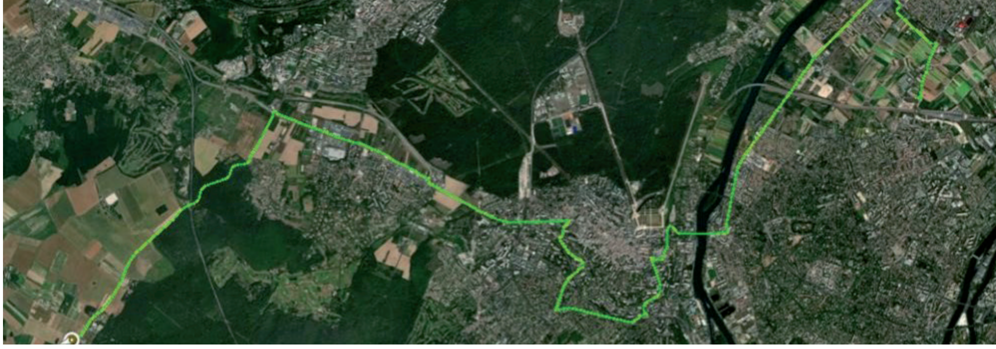


Figure 4 - «8» shape pattern acquisition



OPEN SKY ACQUISITION

DESCRIPTION

This acquisition is mostly performed in Open Sky environment between 13:38 to 14:34 UTC.

DUT PERFORMANCE

Error analysis compared to reference

An analysis is carried out on all the data to obtain the quality indicators. The table below shows the percentiles at 68 %, 95 % and 99.7 % on errors between each DUT and the reference measurements.

Percentile Error	2D position 68%	2D position 95%	2D position 99.7%	Altitude 68%	Altitude 95%	Altitude 99.7%
ELLIPSE-D RTK+ODO	0.013	0.033	0.221	0.057	0.072	0.136
ELLIPSE-D Standalone	0.639	1.069	2.212	0.904	1.516	2.111
ELLIPSE-D PPK+ODO	0.006	0.017	0.040	0.007	0.017	0.052
ELLIPSE-D PPK	0.006	0.017	0.038	0.007	0.016	0.047

Percentile Error	Roll / Pitch 68%	Roll / Pitch 95%	Roll / Pitch 99.7%	Yaw 68%	Yaw 95%	Yaw 99.7%
ELLIPSE-D RTK+ODO	0.015°	0.036°	0.077°	0.087°	0.217°	0.481°
ELLIPSE-D Standalone	0.030°	0.089°	0.179°	0.094°	0.208°	0.362°
ELLIPSE-D PPK+ODO	0.006°	0.013°	0.029°	0.072°	0.169°	0.428°
ELLIPSE-D PPK	0.006°	0.014°	0.026°	0.055°	0.139°	0.280°

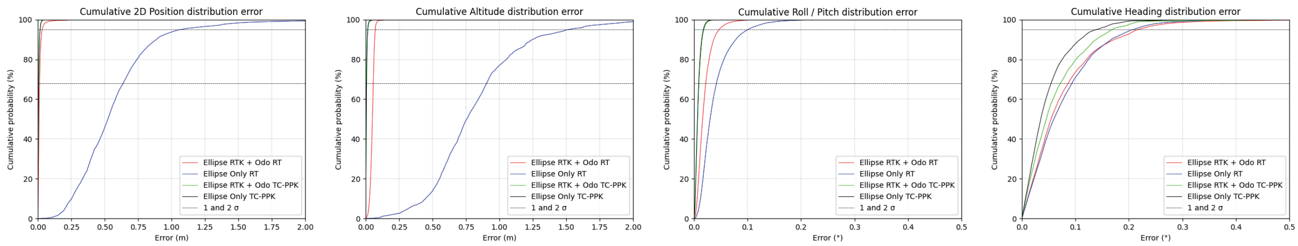


Figure 5 - Cumulative distribution error (Open Sky)

CUMULATIVE ERRORS FIGURES

The graphs above illustrate cumulative distribution errors for 2D Position, Heading, Pitch and Roll i.e. the error percentage below a value. Here for example, the first graph shows that :

- 95 % of Ellipse RTK + Odometer Real Time position errors are below 3.3 cm.
- 95 % of Ellipse Single Point Real Time position errors are below 107 cm.

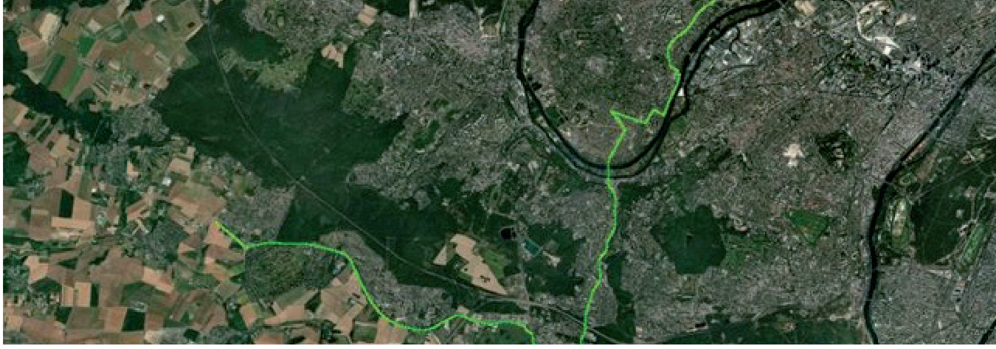
From these results we retain that the accuracy of the solution obtained in the field are totally in line with SBG Systems specifications (see chapter "Devices Under Test"), more precisely:

- Roll, pitch and heading accuracies are within specifications for Real Time Single point solution, Real Time RTK solution and PPK solution.
- Position accuracy is also perfectly in line with specifications for Real Time Single point solution, for PPK and for Real Time RTK solution.

The Ellipse with Single Point reported 98.49 % of DGPS (SBAS) positioning mode.

The RTK +Odo RT configuration got RTK fixed solutions almost all the time, obtaining the most reliable and accurate positions.

Qinertia is used to post-process both configurations. In open-sky environment, the odometer does not improve the situation.



LIGHT URBAN ACQUISITION

DESCRIPTION

This acquisition is performed in light urban environment between 15:07 and 15:49 UTC, with low elevation buildings, bridges, and avenues lined with trees.

DUT PERFORMANCE

Error analysis compared to reference

An analysis was performed on the entire data to get some quality indicators. The table below shows the percentiles at 68 %, 95 % and 99.7 % on errors between each DUT and the reference measurements. between each DUT and the reference measurements.

Percentile Error	2D position 68%	2D position 95%	2D position 99.7%	Altitude 68%	Altitude 95%	Altitude 99.7%
ELLIPSE-D RTK+ODO	0.020	0.165	0.600	0.057	0.087	0.246
ELLIPSE-D Standalone	0.520	0.890	1.832	0.813	1.325	1.530
ELLIPSE-D PPK+ODO	0.009	0.030	0.129	0.007	0.022	0.152
ELLIPSE-D PPK	0.009	0.027	0.069	0.008	0.022	0.097

Percentile Error	Roll / Pitch 68%	Roll / Pitch 95%	Roll / Pitch 99.7%	Yaw 68%	Yaw 95%	Yaw 99.7%
ELLIPSE-D RTK+ODO	0.017°	0.040°	0.075°	0.089°	0.230°	0.444°
ELLIPSE-D Standalone	0.035°	0.079°	0.165°	0.096°	0.227°	0.474°
ELLIPSE-D PPK+ODO	0.007°	0.014°	0.029°	0.067°	0.147°	0.311°
ELLIPSE-D PPK	0.007°	0.015°	0.028°	0.054°	0.123°	0.424°

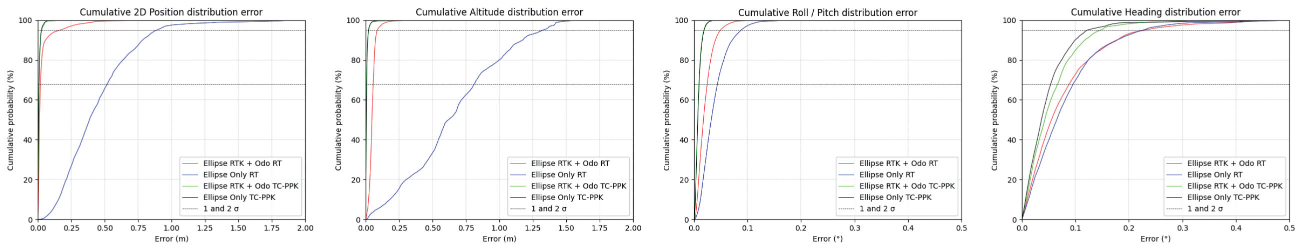


Figure 6 - Cumulative distribution error (Light Urban)

CUMULATIVE ERRORS FIGURES

The graphs above show cumulative distribution errors for 2D Position, Heading, Pitch and Roll.

In the first graph, we can observe that:

» 95 % of Ellipse RTK + Odometer RT position errors are below 16.5 cm.

» 95 % of Ellipse Single Point position errors are below 89 cm.

From these results we retain the same conclusion drawn from the previous test. Indeed, even if the GNSS environment is more challenging, the solution is totally in line with the SBG Systems specifications.

The real time Ellipse Single Point reports:

» 93.15 % of the time the positioning mode was DGPS (SBAS).

» 3.28 % of single point due to limited GNSS reception.

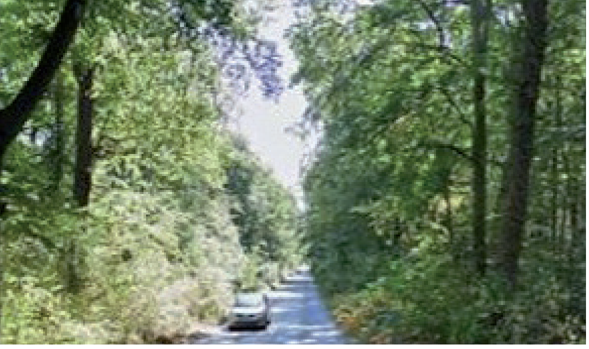
» 2.60 % of ZUPT when the vehicle stalled.

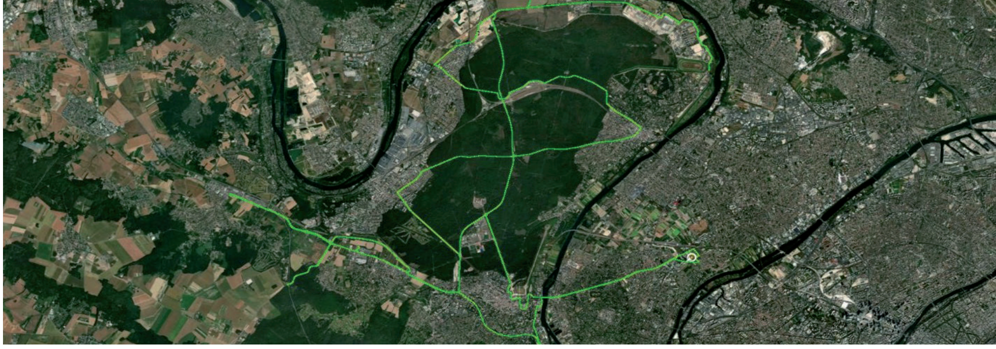
» 0.97 % of velocity constraints when underground or under bridges with no GNSS reception.

The RTK + Odo RT configuration generates RTK fixed solutions 90% of the time. The odometer usage allows the system to maintain a good solution in case of short period of bad GNSS reception.

Using Qinertia, results were improved by post-processing the solution using SBG Systems Tightly Coupled IMU+GNSS algorithms. In this case, the GNSS real time algorithms are completely bypassed and replaced by SBG Systems cutting edge INS positioning engine.

We see that both configurations provide very similar results with much more PPK fixed solutions (89 to 97 % for standalone). RTK + Odo setup reports velocity constraints when the GNSS reception is too disturbed whereas the Single Point configuration uses the odometer velocity information to maintain the solution accuracy.





FOREST CANOPY ACQUISITION

DESCRIPTION

This acquisition is mostly performed in a forest environment for an hour and half, with trees regularly masking most of the sky view. This is a very challenging environment for GNSS receivers prone to output incorrect RTK solutions.

DUT PERFORMANCE

Error analysis compared to reference

For this environment, an analysis was performed on the forest part of the acquisition only to obtain some quality indicators. As before, the table on right shows the percentiles at 68 %, 95 % and 99.7 % on errors for each sensor and the reference measurements.

Percentile Error	2D position 68%	2D position 95%	2D position 99.7%	Altitude 68%	Altitude 95%	Altitude 99.7%
ELLIPSE-D RTK+ODO	0.019	0.130	0.838	0.062	0.107	1.022
ELLIPSE-D Standalone	0.620	0.926	1.232	1.574	3.486	4.463
ELLIPSE-D PPK+ODO	0.011	0.063	0.162	0.011	0.055	0.134
ELLIPSE-D PPK	0.012	0.062	0.493	0.012	0.086	0.470

Percentile Error	Roll / Pitch 68%	Roll / Pitch 95%	Roll / Pitch 99.7%	Yaw 68%	Yaw 95%	Yaw 99.7%
ELLIPSE-D RTK+ODO	0.016°	0.036°	0.061°	0.073°	0.216°	0.477°
ELLIPSE-D Standalone	0.030°	0.067°	0.140°	0.093°	0.196°	0.428°
ELLIPSE-D PPK+ODO	0.007°	0.015°	0.034°	0.053°	0.138°	0.250°
ELLIPSE-D PPK	0.007°	0.016°	0.037°	0.049°	0.102°	0.334°

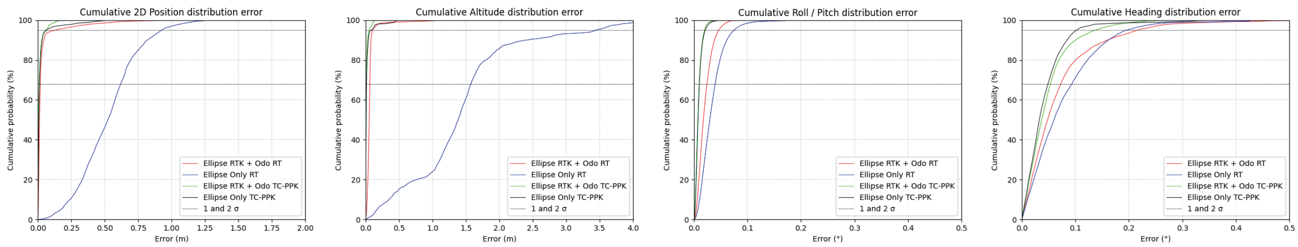


Figure 7 - Cumulative distribution error (Forest)

CUMULATIVE ERRORS FIGURES

The graphs above show cumulative distribution errors for 2D Position, Altitude, Heading, Roll. Here for example for the Ellipse Only (Single Point) in real time, there are about 95 % of the heading errors below 0.21°.

From these results we retain that:

- The performance of the DUT matches with specifications.
- The 2D position and altitude errors are higher than obtained during the previous tests, due to poor GNSS reception in this typical environment.

The real time Ellipse Single Point reports:

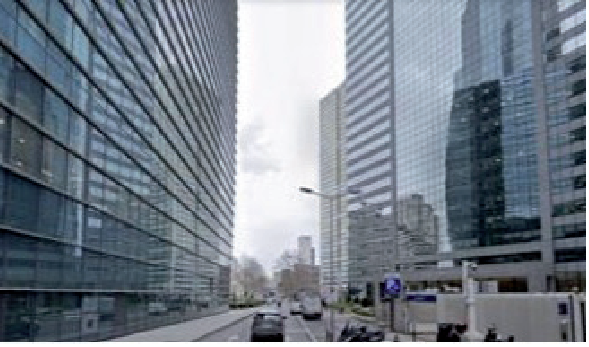
- 83.00 % of the time the reported positioning mode was DGPS (SBAS).
- 1.36 % of ZUPT coincides with stop times.
- 15.07 % of single point mode is due to bad GNSS reception.
- 0.57 % of velocity constraints when the GNSS reception is greatly disturbed.

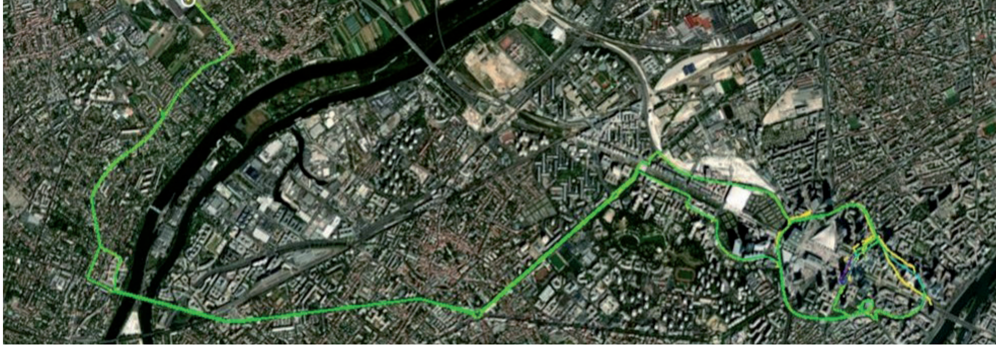
The Ellipse RTK + Odo RT achieves RTK fixed solutions 90% of the time. RTK float solutions are caused by less reliable solution due to blocked reception under trees. Odometer was used when the GNSS signal was too weak or disturbed to deliver a valid position.

Thanks to Qinertia, results can be improved in post-processing the solution using SBG Systems Tightly Coupled IMU+GNSS algorithms.

For Ellipse Single Point configuration, post-processing enables PPK fixed positions for most of the time (92 %) and almost all remaining epochs where able to get PPK float positions that is quite impressive considering the environment.

The Ellipse RTK + Odo RT setup was already delivering very good results in real time with almost 90 % of RTK fixed positions. Qinertia post processing slightly increased fixed solutions but more importantly was able to improve the overall accuracy by recovering PPK float positions instead of Odometer integration.





DEEP URBAN ACQUISITION

DESCRIPTION

This acquisition was mostly performed in harsh urban environment between 11:44 and 13:12 UTC, with high-rise buildings, and tunnels.

DUT PERFORMANCE

Error analysis compared to reference

An analysis was performed on the entire data to retrieve quality indicators. The table below shows the percentiles at 68 %, 95 % and 99.7 % on errors between each DUT and the reference measurements.

Percentile Error	2D position 68%	2D position 95%	2D position 99.7%	Altitude 68%	Altitude 95%	Altitude 99.7%
ELLIPSE-D RTK+ODO	0.096	3.479	10.490	0.075	4.314	11.569
ELLIPSE-D Standalone	1.362	4.337	10.847	4.011	8.011	16.556
ELLIPSE-D PPK+ODO	0.028	0.299	0.789	0.020	0.172	0.814
ELLIPSE-D PPK	0.030	0.471	1.023	0.018	0.171	0.546

Percentile Error	Roll / Pitch 68%	Roll / Pitch 95%	Roll / Pitch 99.7%	Yaw 68%	Yaw 95%	Yaw 99.7%
ELLIPSE-D RTK+ODO	0.021°	0.049°	0.089°	0.161°	0.742°	2.245°
ELLIPSE-D Standalone	0.037°	0.099°	0.164°	0.270°	0.900°	1.749°
ELLIPSE-D PPK+ODO	0.009°	0.019°	0.034°	0.080°	0.233°	0.399°
ELLIPSE-D PPK	0.008°	0.020°	0.047°	0.091°	0.262°	0.701°

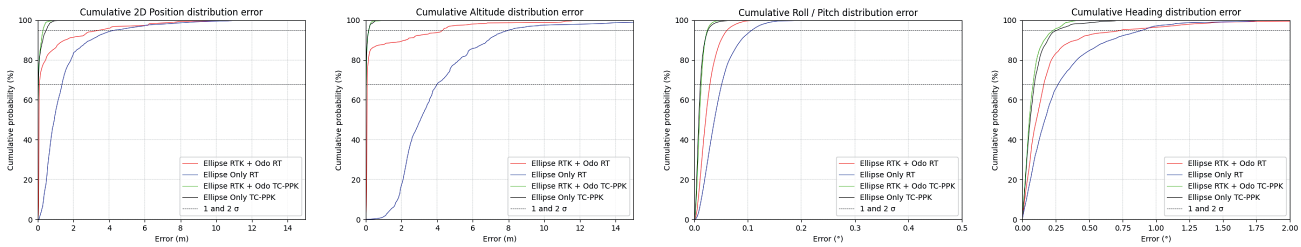


Figure 8 - Cumulative distribution error (Deep Urban)

CUMULATIVE ERRORS FIGURES

The graphs above show cumulative distribution errors for 2D Position, Heading, Pitch and Roll.

As expected, both DUT configurations performance are affected by major GNSS outages. As for the reference, the RTK + Odo setup reports RTK Integer status for only 68.11 % of the acquisition, the single point generates a DGPS status for 70.54 % of the acquisition and a single point status for 14.17 % of the acquisition.

The post processing improves a lot the ratio of PPK fixed vs. float solutions compared to the real time solution. More importantly, the post processing better rejects invalid GNSS signals and as a result the accuracy is greatly improved (10 meters to less than 80 cm for 99.7 % percentile).

In *Figure 9* representing a harsh urban area, the RTK + Odo RT trace (continuous colored line) shows a huge improvement compared to the pure GNSS solution (yellow dots).

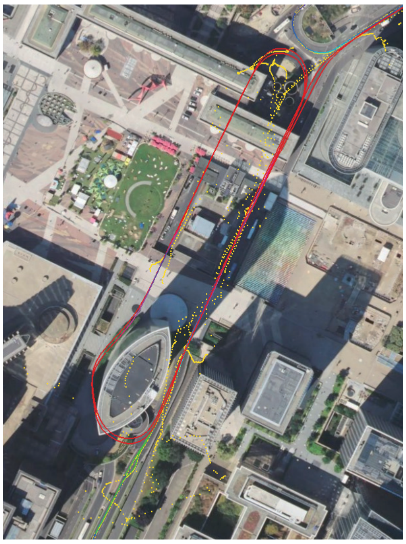


Figure 9 – Comparison between GNSS and INS trajectory in Deep Urban environment

CONCLUSION

The objective of this test report was to assess the performance of the Ellipse-D in real life and various environments representative of automotive use cases for a commercially available INS embedding an industrial grade calibrated IMU. Tests were performed under open-sky conditions, under tree canopy, and inside very challenging dense urban environments.

The real time Ellipse standalone and RTK + Odometer accuracies as well as the Qinertia post processed solutions were compared to a post processed FOG based ground truth (SBG Systems' Horizon).

The analysis was conducted using cumulative distribution function (CDF) and percentile distributions to provide better metrics than "industry standard" RMS (Root Mean Square) or normal distributions methods.

INS manufacturers often report accuracies in good GNSS conditions or in case of a complete GNSS outage. However, in real life, even the best GNSS receiver will report wrong positions with inconsistent accuracies. This could mislead the INS algorithms and results to unnecessary GNSS rejections or even solutions instabilities with bad accuracies.

A trusted INS should cope with these situations and deliver the most reliable and repeatable solution. This test report demonstrates how correctly and consistently the Ellipse-D v3 behaves in all observed situations and more importantly why a calibrated INS is a must have for automotive applications.

Based on the "Ellipse 3, Performance Assessment Report In Automotive Application", we can conclude with the following statements:

- The Ellipse-D v3 demonstrates adequate capabilities and sufficent accuracies for automotive applications,
- Its unique filtering algorithms and its dedicated automotive motion profile lead to obtaining robust and accurate positioning and heading results in all driving conditions,
- Its specifications are met with a comfortable margin in all the evaluated conditions,
- Odometry improves the solution accuracy and robustness especially during long GNSS outages,
- Qinertia Post-Processing extends coverage for centimeter-level positioning even in most challenging GNSS environments,
- Achieved consistent accuracies makes this small and cost effective Inertial Navigation System a suitable all-in-one unit for autonomous vehicles localization.

We hope that you enjoyed the reading of this assessment report. Please send all your comments and questions you may have to **marketing@sbg-systems.com**.

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