▲ **MERCEDES** vision of future mobility, autonomous driving.

On the Road to Driverless

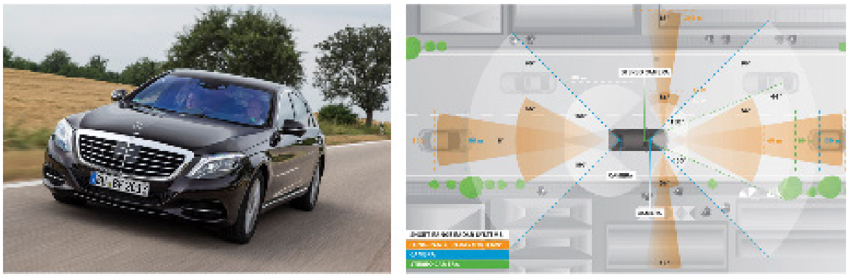
Differential GNSS+INS for Land Vehicle Autonomous Navigation Qualification

Land-vehicle autonomous navigation requires centimeter-level qualification tools to enable confidence build-up for delivery to open-road traffic insertion. External positioning sensors over a dedicated road section can be replaced with an embedded high-accuracy, highly responsive epoch-by-epoch differential GNSS receiver coupled with an inertial navigation system. The demonstated absolute accuracy and mobility extends the potential test area and minimizes cost for multi-environment validation.

Gilles Boime, Emmanuel Sicsik-Paré and John Fischer

Personal cars and commercial trucks are continuously improving the driver experience and safety thanks to integration of more significant and machine-assisted control systems. Advanced driver-assistance systems (ADAS) are now integrated in all luxury cars and moving into mainstream products. Technologies covered by ADAS are specific for each car integrator, but increasingly they include now involving more safety features, such as driver assistance and partial delegation to autonomous control for small maneuvers such as lane control. The generation of ADAS systems introduced in early 2015 on high-end models are engaging more intelligence from the control system such as:

- Lane departure warning system



▲ **FIGURE 1** Bertha Benz test car, left, running fully autonomous 103-kilometer trip in open road including 27 percent narrow urban roads. Right, networked sensor systems of the S 500 Intelligent Drive research vehicle.

- Speed assistance and control
- Driver assistance and control
- Autonomous emergency braking.

It is not only individual drivers who want this technology, but also governments that are getting involved to prevent accidents and minimize the economic impact associated with them. In the European Union, the general safety regulation 2009/661 was the first step to engage member-states to act as a regulator to mandate car safety improvements. The European Transport Safety Council, a non-profit private association, released in March 2015 a position paper titled "Revision of the General Safety Regulation 2009/661." It promotes the introduction of lifesaving technologies like intelligent speed assistance, autonomous emergency technology including all speed and pedestrian detection, and lane-departure warning systems as the next step of regulation.

Car manufacturers are not far behind. They understand their customers' expectation of minimized risk and enhanced driving experience. Telematics is also a path to convert a single vehicle into a fully intelligent, connected and entertainment object with an associated high value. So, every car manufacturer is willing to be seen as a technology master.

Toyota, for example, plans to integrate collision-prevention technology in all its mainstream and luxury cars by 2017. The ADAS new generation focuses on radar-activated cruise control technology for the collision-prevention system. The control system maintains distance from a vehicle ahead and can stop the car if driver doesn't react. The next step is to monitor driver attention with sensors like cameras focusing on the driver's eyes, and the pressure of the hand on the steering wheel.

However, no fully driverless car is expected in the next 10 years. This technology is limited by legal issues and the lack of reliable nationwide mapping data.

Since the technology must be fully proven to prevent any lethal threat on the user and other drivers, most car and truck companies are working actively on qualifying driverless technology today. **Nissan** began

▲ **FIGURE 2** Renault outdoor test center at Aubevoye, France

testing driver-assist technology on open-road traffic in Japan in late 2013. It enables highly advanced systems such as lane-keeping, automatic lane change, automatic exit, automatic overtaking of slower or stopped vehicles, automatic deceleration during congestion on freeways, and automatic stopping at red lights. This is a step towards attaining fully automatic, driving targeted for 2020 by Nissan.

Some European manufacturers such as **Daimler Benz** are also early adopters. Daimler/Mercedes uses the Bertha Benz prototype car to test autonomous driving technologies. It merges multiple vision, radar, and GPS sensor with digital map to monitor an open-road 100-kilometer trip in August 2013 (**FIGURE 1**).

All manufacturers are building driverless capability into their technology demonstration concept cars:

- **Mercedes** with F 015 Luxury presented at the Consumer Electronic Show, early 2015;
- **Audi** with Prologue, an

extrapolation of test car RS7 concept equipped with SuperFast driverless pilot;

- **BMW's** electric i3 car is integrating ActiveAssist technology that enables portions of drive to be without any manual intervention, such as car parking and autonomous rally to a meeting point;
- **Google's** self-driving vehicle that conforms to California license requirements for driverless tests in open traffic
- **Tesla** model SD autonomous test car.

Although most market leaders agree that this is not a technology for mainstream production in the next few years, they all work very efficiently to master the technologies. It is a big challenge to integrate all the sensors and the navigation functions to autonomously and accurately position the vehicle on a map. The whole system must be certified to prevent any liability in case of a crash, a case that would engage the solution provider and the vehicle manufacturer.

A large part of the qualification task will benefit from simulations and integration testing platforms in realistic conditions. At the very least, a very robust final open-space validation test must take place. Car manufacturers/integrators are using private test facilities in open air to perform serious trials before proceeding to real traffic conditions. **Renault** uses a 10 square-kilometer facility in France (FIGURE 2) to perform private tests in a protected area.

New autonomous car drive tests have mandated equipment enabling measurement of the car's position on the track with an extremely high precision and repeatability. There are two competing technologies to do this:

- Install many location sensors on the test track;
- Use a general absolute positioning system.

Here we focus on an absolute positioning system that is affordable, easy to install, and low maintenance. It is based on two main assertions:

- The autonomous pilot can position accurately on the test track;
- The test track is accurately referenced to the absolute positioning system.

We focus more closely in this article on the first assertion; the second one can be covered with a specific calibration trial where equipment, as discussed further, can be used in quasi-static mode and experience consistent accuracy. Let us have a deeper look at the candidate position technologies to verify autonomous pilot accuracy.

Positioning Technologies

Many technologies have been proposed to obtain vehicle position on the course. However, they all must be compatible with a reliable mapping database. Given the lack of consistent road infrastructure equipment with alternative capabilities, GNSS positioning is the sole enabling method to fit to a map every place around the world. That is why driverless systems always include a GNSS sensor to help other data matching with the map. The versatility and low cost of GNSS positioning makes it a candidate for open-air validation as well.

Standalone Standard Positioning Service GPS. The SPS single-frequency GPS receivers are included in so many nomadic appliances today that they are a commodity. Since their introduction 20 years ago, their performance is well understood. Some trials were performed in different area profiles with satellite constellation position dilution of precision (PDOP) < 2. Worse results were obtained from deep urban canyons in downtown Seattle, Washington.

For every technology, the relevant performance for the test course is the lateral error to the expected center of the lane in the two horizontal dimensions, referred to as 2D or N/E for orientation North and East.

For standalone SPS GPS, the lateral error standard deviation in 2D can be as high as 46 meters and have peak errors up to 660 meters. Lateral error in 3D can be as high as 20 meters with peak errors up to 175 meters.

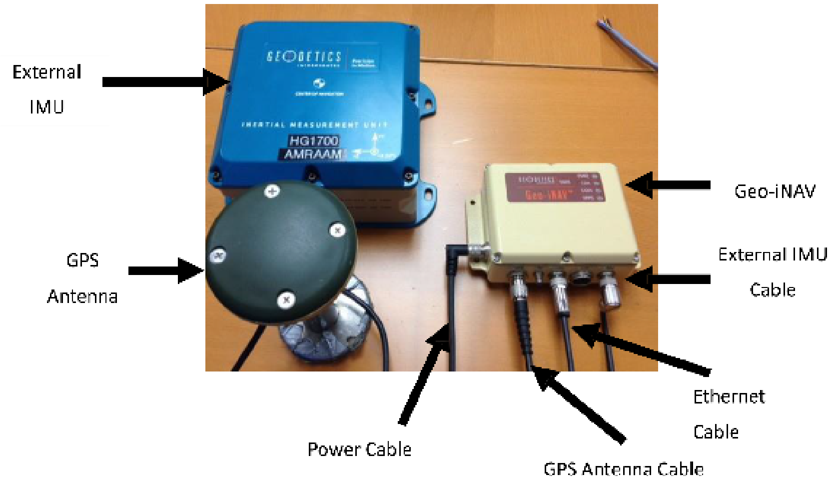
Such performances are out of range for any positioning verification. It can only deliver a rough estimate of the point on the map, but would not provide tight correlation with other sensors for the navigation system.

Hybridized IMU and SPS GPS. Coupling of an absolute navigation GPS receiver with an inertial measurement unit (IMU) can mitigate corruption of the navigation solution when intermittent GPS signal outage is encountered. The hybrid approach is beneficial on any difficult signal transmission path from the satellite that is not line-of-sight: in urban canyons, deep foliage, under bridges, tunnels and in any multipath area. It also yields benefits in the very short term (less than a few seconds) for dispersion on the position computed from the sky.

Over the last ten years, the combined benefits of micro-electro mechanical sensors (MEMS) and tight coupling algorithms have raised the bar of positioning accuracy. It enables smoothed position along track and dead reckoning (DR) in case of GNSS signal outage.

Lateral error standard deviation in 2D is lowered to 2.3 meters and peak error up to 10 meters. However, this performance is still too poor to validate a vehicle position in the lane.

Hybrid Differential Single Frequency and IMU. The next step to mitigate systematic errors of the GNSS system is to use a set of multiple reference receivers in the vicinity of the area covering the test course. The reference receivers are static. The position of the reference is



▲ **FIGURE 3** Dual-frequency differential navigation unit hybridized with external fiber-optic gyro.

determined using long-term averages to mitigate constellation errors. A minimum for a position fix of 20 minutes is commonly reported. Then the position error standard deviation in 2D is less than 2 centimeters for baselines shorter than 100 kilometers.

For a MEMS integrated with a standard SPS GPS single-frequency receiver with DGPS correction on a mobile platform moving at less than 70 km/hour with HDOP < 1.4, **TABLE 1** compares performance in a 2013 test.

Hybrid Differential Dual-Frequency Carrier Phase and IMU. The GNSS solution can be further improved taking into account both L1 and L2 frequencies to mitigate propagation error and carrier phase to achieve ultimate signal accuracy. The combination of both helps solve ambiguities associated with the carrier-phase technique. When combined with a MEMS IMU, accuracy confirmed with HDOP < 1.6 is:

- Lateral error standard deviation down to 0.18 meters
- Peak error of 0.6 meter.

However, this is still insufficient accuracy when compared to 0.1 meter required for verification testing.

With such low-cost IMU, GPS outages produce a rapidly increasing lateral error over elapsed time. The lower the speed, the poorer the position result.

Another limitation common to many differential solutions is the turn-on delay for the solution. It is also a repetitive issue in case of disruption of the GNSS solution. It extends the delay to recover from DR situation.

Epoch-by-Epoch

Highly skilled navigation experts have developed a new class of

Geo-iNav	Parameter	Accelerometer	Gyroscope
Tactical (internal MEMS Epson M- G362)	Measurement range	±3 g	±150 °/s
	Biais (in-run) stability	< 0.1 mg	3 °/h
	Random walk	0.04 m/s/h$^{0.5}$	0.2 °/h$^{0.5}$
Advanced (external FOG KVH 1750)	Measurement range	±10 g	±490 °/s
	Biais (in-run) stability	7.5 mg	0.05 °/h
	Random walk	0.07 m/s/h$^{0.5}$	< 0.012 °/h$^{0.5}$

▲ **TABLE 1** IMU performance grades.

instantaneous, real-time precise GPS positioning and navigation algorithms, referred to as epoch-by-epoch (EBE), and employing hybridiized dual-frequency differential GPS with a high-performance IMU.

Compared to conventional real-time kinematic (RTK), integer-cycle phase ambiguities are independently estimated for each and every observation epoch. Therefore, complications due to cycle slips, receiver loss-of-lock, power and communications outages, and constellation changes are minimized. There is no need for the initialization period (several seconds to several minutes) required by conventional RTK methods.

More importantly, there is no need for re-initialization immediately following loss-of-lock problems such as those that occur when a mobile GPS receiver passes under a bridge or other obstruction, or when it loses satellite visibility during a shaded portion of road. In addition, EBE provides precise positioning estimates over longer reference receiver-to-user receiver baselines than conventional RTK.

This feature supports testing for long-range operations, for example, like positioning a vehicle on a lane. The reference receiver is set in the vicinity of the test center track.

EBE requires the use of a minimum of two receivers, each of which is tracking a common set of five or more satellites and providing simultaneous dual-frequency phase data. Typically, one of the receivers is stationary but this is not a requirement.

EBE has been proven utilizing dual-frequency receivers and operating at distances of up to 50 kilometers from the nearest base station in unaided mode. Additionally, the EBE algorithms operate in a network environment and make optimal use of all GPS measurement data at each epoch, gracefully degrading the position accuracies when some measurement data are not available. Furthermore, the system will make use of an IMU system, compensating for outages when line-of-sight to the satellites is blocked. This produces a robust and more reliable system.

Epoch-by-epoch can deliver several benefits including:

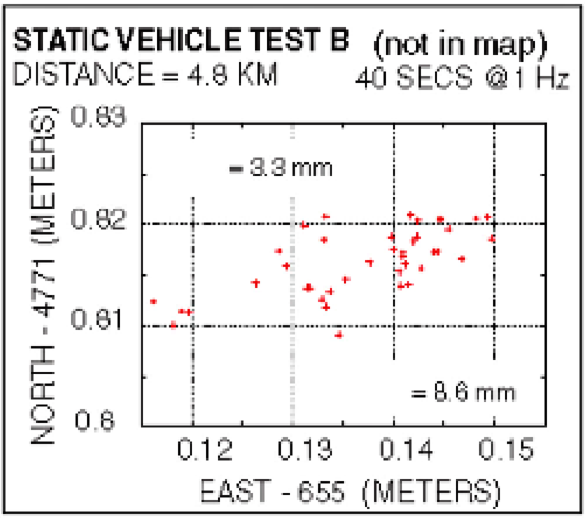
- Computationally efficient algorithms that provide a position estimate based on a single epoch in several milliseconds. This allows the real-time position estimate to be computed on the user platform (assuming reference station data is sent to the user platform).
- An initialization period is not required. Since RTK requires some period of time (that can be measured in seconds to minutes) to perform ambiguity resolution, this is an important capability for platforms that:
  - Require high accuracy (for example, for end-game scoring);
  - Cannot see the satellites until launch;
  - Have short flight or test course duration;
- A re-initialization period following loss-of-lock is not required, unlike RTK, which needs to restart the integer-cycle phase ambiguity resolution process. This is another important capability because vehicle monitoring is considering EBE for dynamic applications where loss-of-lock and loss-of-data are likely.

However, it must be mentioned that many of the GPS receivers in use by the test (and training) community today do not support this dual-frequency requirement. Hence, those systems could not realize the maximum benefit.

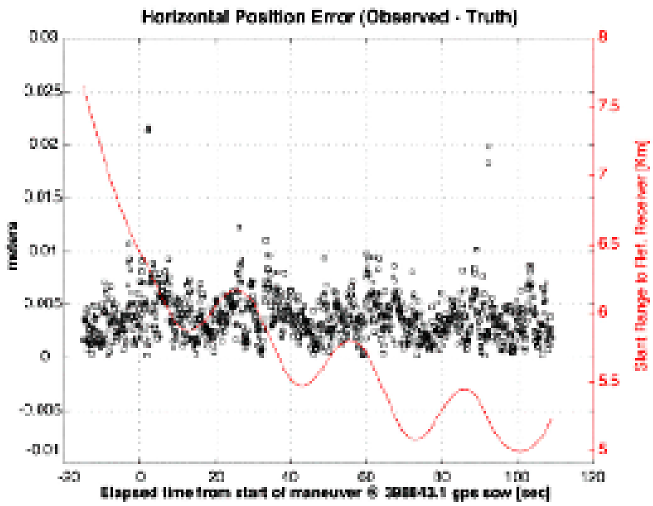
This technology is implemented in a rugged modular platform (**FIGURE 3**) with three main units:

- A dual-frequency GPS antenna
- An integrated INS coupling GPS receiver with either an internal MEMS IMU or external IMU
- An external fiber-optic gyroscope (FOG) IMU for high-end accuracy and reliability. The external IMU is optional and dedicated to increasing the DR capability.

Performance. Tests have been performed in conditions close to the land-vehicle navigation validation. It is based



▲ **FIGURE 4** Single point error when rover is static



▲ **FIGURE 5** Dynamic trial test single point error

on measurements on- the-fly with no post-processing except for evaluation of the error.

The first case is a static position of the rover 4.8 kilometers away from the reference receiver. Positions are updated once per second. The system includes a FOG IMU. the lateral error peak is less than 4 centimeters. Bias error is less than 1 centimeter. See **FIGURE 4**.

The second test case is with a high-dynamic mobile platform, moving at a speed of 200 km/h, with an average distance from the reference to the rover of 6 kilometers. Lateral error standard deviation is 0.5 centimeters, peak error is less than 2.2 centimeters. Bias error is lower than 0.2 centimeters (**FIGURE 5**).

The performance in these test cases meets the expected accuracy for validation of autonomous navigation.

One last method to increase accuracy is to switch a different class of IMU performance, from tactical grade to advanced. When in the line-of-sight of the GNSS sky-view, the performance is the nearly the same.

Conclusion

A real-time, differential epoch-by-epoch, dual-frequency carrier-phase GPS receiver, tightly hybridized with a high performance IMU can provide absolute error lower than 5 centimeters in the 10-kilometer baseline range of the reference static receiver. This is fully adapted to the qualification of driverless auto-pilot systems for the targeted year of 2020. It can avoid the need to use complex theodolite and vision calibration systems. It provides maximum flexibility and minimum sustaining costs.

Acknowledgement

This study has been made possible thanks to materials provided by Geodetics Inc. and the advice of Jeffrey A. Fayman, vice president of Geodetics Inc. The results displayed in Figures 4 and 5 are from a test with medium-size UAV from Allied Drones, model EF44 high-endurance quad.

Geo-iNAV grade L1/L2	Horizontal Position Accuracy (RMS)	
	Autonomous	Differential
Tactical	1.5 m	5 cm
Advanced	1.0 m	5 cm

▲ **TABLE 2** Horizontal error performance.

Manufacturers

The Geo-iNAV platform consists of please cite makes and models of the GPS antenna, IMU, receiver, FOG, etc. please cite makes and models of the GPS antenna, IMU, receiver, FOG, etc. please cite makes and models of the GPS antenna, IMU, receiver, FOG, etc.

GILLES BOIME is is chief scientist for Spectracom. He is involved in GNSS signal generator, hybridized navigation platforms, GNSS timing and synchronization inovative solutions build-up. He holds an engineering diploma in telecommunication from Institut Superieur d'Electronique de Paris.

EMMANUEL SICSIK-PARE is strategic product manager for Spectracom. He is involved in timing and navigation products and systems definition and application market monitoring. He holds a M.Sc degree from Telecom Bretagne.

JOHN FISCHER is CTO of Spectracom. He has more than 30 years experience creating navigation and communications systems, received his Masters in electrical engineering from SUNY at Buffalo and has worked in radar, command and control, and wireless systems prior to joining Spectracom.