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# High Accuracy Positioning Engine with an Integrity Layer for Safety Autonomous Vehicles

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## BIOGRAPHY

**Enrique Domínguez Tijero** received a M.Sc. degree in Telecommunications Engineering in 2000 and a Master in Space Technologies in 2009, both from the Polytechnic University of Madrid. He joined GMV in 2000 working first in the development of EGNOS and Galileo and since 2009 in GNSS software receivers, multi-sensor fusion algorithms and integrity algorithms.

**L. Martínez Fernández** holds a Degree in Aerospace Engineering from the Polytechnic University of Valencia, specialty in Aero-navigation, and an MSc in Aeronautical Engineering from Polytechnic University of Catalonia, specialty in Space. She joined the GMV as a GNSS engineer working in activities related with *magicGNSS*: precise orbit determination, precise positioning and integrity algorithms.

**J. I. Herrero Zarzosa** holds a Bachelor and Master Degree of Applied Science (BASc) from the University of Valladolid. He has been working for GMV in the automotive sector for more than 15 years. As a product development manager in the GMV automotive aftermarket division he has been involved in ESCAPE during the first half of the project.

**Jessica García** obtained her degree in Telecommunication Engineering from the Universitat Politècnica de Catalunya in 2010. She started as a firmware engineer working on security systems and developed her career on different sectors. In 2014 she got in the automotive sector, where she currently works from the research area of the international company FICOSA.

**Javier Ibañez-Guzmán** obtained his Ph.D. at the University of Reading and his MSEE at the University of Pennsylvania (USA) as a Fulbright scholar. In 2011, he was visiting scholar at the University of California, Berkeley (CITRIS). He is member of the technical staff at Renault S.A., working on autonomous vehicle navigation technologies. Formerly he was senior scientist at a national research institute in Singapore, where he spearheaded work on autonomous ground vehicles. Dr. Ibañez-Guzmán has

several publications and patents in the robotics and automotive domains.

**Emmanuel Stawiarski** obtained a degree in Signal Processing from the École Supérieure d'Électricité in France in 1999. He joined Renault in 2003, working first in the electrical development of instrument clusters, then navigation systems. He is currently working in Research department on localisation systems for autonomous driving vehicle projects.

**Philippe Xu** graduated from the Ecole Normale Supérieure de Cachan, France, in 2011. He received his Ph.D. degree from the Université de Technologie de Compiègne, Heudiasyc UMR CNRS 7253, France, in 2014 and is an associate professor in this same university since 2015. His research interests cover information fusion, computer vision and machine learning applied to autonomous vehicles.

**Giuseppe Avellone** (Master in Electronics, Università di Palermo, 1996) is with the Functional Safety Management Office of Automotive Product Group at STMicroelectronics. He was previously involved in development of RF IC's, algorithms and applications mainly for GNSS receivers and CDMA/UMTS receivers. His research interests include Functional Safety and signal processing for GNSS receivers and wireless communication systems.

**Fabio Pisoni** (Master in electronics, Politecnico di Milano, 1994) is leading the GNSS System and Software Team at STMicroelectronics. He was previously with the GNSS System Team in Nemerix SA and has earlier experience in communications. His research interests include DSP and navigation algorithms for embedded GNSS receivers, observables generation and integrity, functional safety.

**Emanuela Falletti** (Ph. D. in electrical and communications engineering, 2004) is the head of the GNSS Core Algorithms unit in the Navigation Technologies research area of the Istituto Superiore Mario Boella (ISMB), Torino, Italy. Her research activity focuses on digital signal processing algorithms for advanced GNSS software receivers, interference detection

and mitigation, multi-antenna processing, and signal simulation.

**Miguel Ortiz** works as a geolocation research engineer at the COSYS department in the Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR).

## ABSTRACT

Autonomous vehicles are becoming a reality. One of the most critical functions of an autonomous vehicle is to be able to obtain an accurate and reliable estimation of the position and attitude of the vehicle. This is even more critical when operating without human supervision as for the SAE Level 4. This paper presents an innovative positioning engine capable of providing highly accurate real-time position and attitude estimations along with an integrity layer consisting of Protection Levels (PL), which bound the error of each estimated value with a certain confidence level.

The position and attitude estimated by the engine are based on the measurements provided by an intelligent off-the-shelf automotive camera, a mass market dual-frequency GNSS receiver, low-cost inertial sensors, vehicle odometry and lane-level navigation maps. Highly accurate positions are computed by means of a real time PPP hybrid algorithm that employs dual-frequency GPS and Galileo measurements, inertial sensors and PPP corrections obtained from a web server when the connection is available through the cellular network. Another robust hybrid standard positioning algorithm runs in parallel allowing consistency checks. Last but not least, the automotive intelligent camera provides lateral distance measurements to the road lane marks which are employed to improve the accuracy by means of the lane-level accurate maps and also to provide an accurate position relative to the map.

The position and attitude values provided by the engine (including the position computed relative to the map) are complemented with the estimation of the associated integrity Protection Levels (PL), computed for multiple target integrity risks. The implementation of an integrity layer is crucial since in safety-critical applications it can be more important to know whether the information is reliable than the precise information itself. This integrity layer determines the degree of usability of the location and attitude estimations, which is used as part of autonomous vehicle architecture to ensure that the vehicle operates safely.

This engine has been developed within the ESCAPE project ([1]) and is being integrated and tested with an autonomous car. ESCAPE (European Safety Critical Applications Positioning Engine) is a project co-funded under the Fundamental Elements program of the European GNSS Agency (GSA). It started on October 2016 with a

duration of 3 years and with the main objective of developing a localisation system that provides the vehicle position and attitude estimations to be employed in safety critical applications like Autonomous Driving (AD) or Advanced Driving Assistance Systems (ADAS). The project is led by the Spanish company FICOSA in collaboration with partners from across Europe: Renault, IFSSTAR and the University of Technology of Compiègne from France, STMicroelectronics and Instituto Superiore Mario Boella from Italy and GMV from Spain.

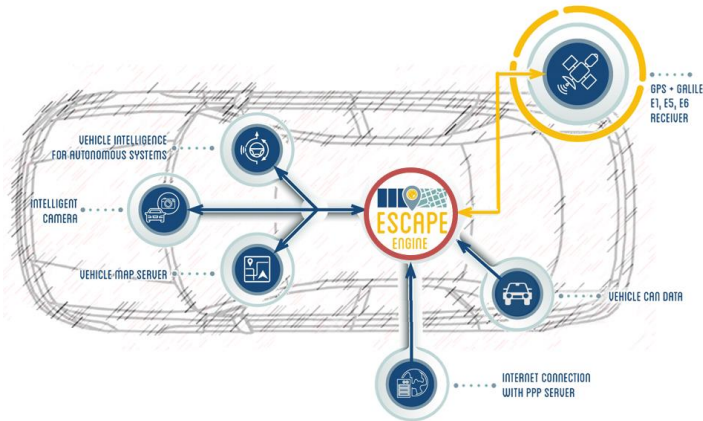
ESCAPE enables a high-grade of data fusion (GNSS, inertial sensors, cameras and vehicle sensors) and the exploitation of several key technological differentiators such as the precise point positioning service (PPP), the potential use of the Galileo signal authentication and the provision of an integrity layer to assess the degree of trust one can associate to the position information provided by the device. Therefore, the three key pillars of the ESCAPE positioning engine are:

- The smart exploitation of different localization data sources to provide a highly accurate navigation solution, including GPS and Galileo dual-frequency measurements, intelligent cameras providing lateral distance to road lane-marks, inertial measurement units, vehicle odometry, PPP corrections and high definition maps;
- The unique provision of real-time integrity protection levels associated to the location estimates, which express the “degree of usability” of the positioning information for safety-critical applications. The PLs associated to the positions computed relative to the map are fundamental for autonomous driving applications;
- The full integration of the ESCAPE engine into a vehicle with autonomous driving capabilities, and its test on several different reference paths and environmental conditions.

The innovative ESCAPE GNSS Engine (EGE) is close-to-market, its components are organized in a modular architecture and has safety at its core as its specification and design are based on the ISO 26262 recommendations ([2]). The EGE includes the following main components:

- GNSS receiver chipset: an automotive-grade multi-band and multi-constellation GNSS receiver.
- Inertial Measurements Unit (IMU)
- Communication peripherals needed for the communications of the board with the vehicle and with the cellular network.
- Main processor running the EGE algorithms:
  - GNSS+Sensors Positioning&Integrity algorithm, where GNSS measurements are integrated with those provided by an inertial measurement unit (IMU) in order to provide a GNSS pose with integrity.
  - Camera-based Positioning&Integrity algorithm. The accurate maps containing road lane-marks along with the intelligent camera measurements allow a second positioning service with accuracies

that can reach a few centimeters in the cross direction, thus complementing and enhancing the positions provided by the GNSS+Sensors Positioning&Integrity algorithm.



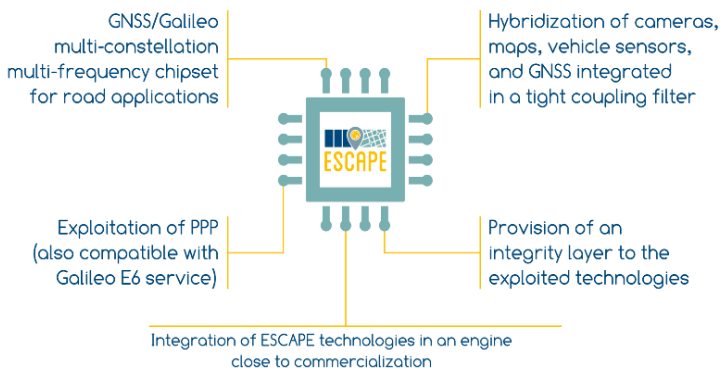
**Figure 1 – Conceptual block diagram of the in-car system including the ESCAPE GNSS Engine**

The paper includes a description of the engine architecture and the design of the algorithms along with the algorithm performance results obtained with real data under different environments (performances are assessed in three different operating conditions associated to open-sky, sub-urban and deep urban environments).

**ESCAPE OBJECTIVES**

These are the main objectives of ESCAPE project [1]:

- Development of a positioning engine for safety critical applications
- Exploration of European GNSS differentiators
- Autonomous driving as the target application
- Provision of integrity as the most relevant performance feature

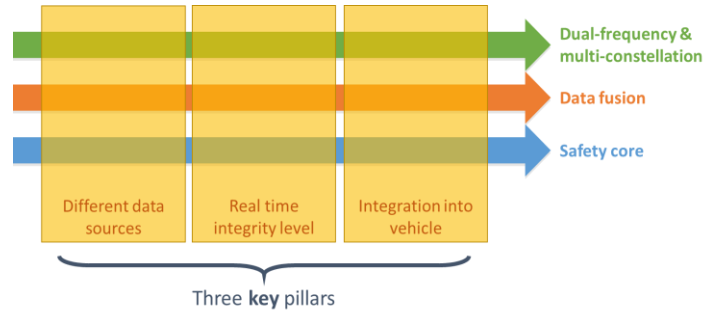


**Figure 2 – ESCAPE Innovation Aspects**

**SYSTEM DESIGN**

The design of the ESCAPE GNSS Engine (EGE) is based on three key pillars:

- Use of different data sources
- Provision of real-time integrity level
- Integration into vehicle



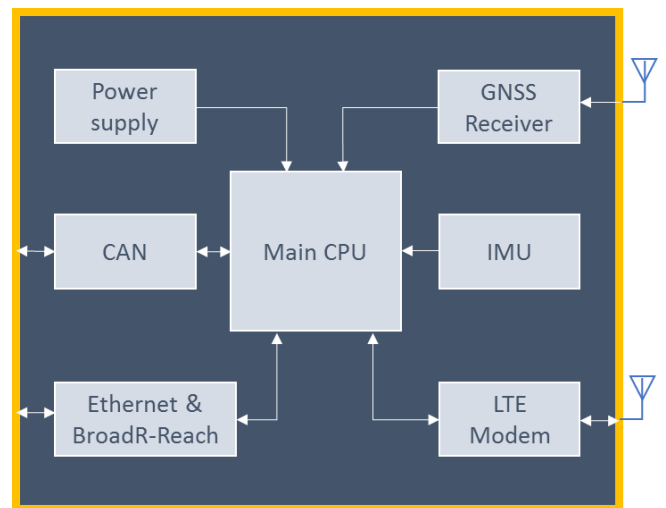
**Figure 3 – System Engine**

**HW DESIGN**

The design of the ESCAPE GNSS Engine (EGE) addresses several major components as well as the safety analysis of all its elements. The EGE hardware includes the following main components:

- The GNSS receiver chipset,
- The Inertial Measurements Unit (IMU)
- The main processor,
- The peripherals needed for the communications of the board with the vehicle and with the cellular network.

By combining all these components and the navigation and integrity algorithms, the project develops an innovative positioning engine, which is close-to-market and has safety at its core. Such components are organized in a modular architecture, in which a main board provides access to the features supported by the EGE, while a core module implements the core processing capabilities.



**Figure 4 – EGE HW Architecture**

The whole architecture of the EGE hardware has been conceived following the most recent practices in the design of automotive electronic control units, so that all the interfaces, configurations and form factors will result compliant with widely recognized sector trends. Thus, the safety approach followed in the project during the phases of specification and design is based on the recommendations put in ISO 26262 [2].

## GNSS RECEIVER

The main distinguishing feature of the automotive-grade GNSS receiver designed within ESCAPE is its capability of processing at the same time signals from two different GNSS bands and from different satellite constellations. Although this capability is common in high-end professional receivers [3], it represents a cutting-edge industrial development in the automotive Tier-2 panorama, where it conjugates highly demanding safety requirements to high-volumes and comparatively limited costs and sizes. Indeed, one of the major challenges for the ESCAPE GNSS receiver is its capability of integrating in a unique device a high-end GNSS technology traditionally reserved for professional applications, the innovation represented by the dual-band Galileo processing, as well as all the hardware and software safety aspects that are needed to certify the component for the automotive market [2].

In addition to multi-band and multi-constellation processing, the GNSS receiver is the first-of-a-kind device on its segment that supports the new Navigation Message Authentication (NMA) service of Galileo, the additional anti-spoofing service offered by Galileo on the open E1 signal starting from 2018 [4]. The NMA allows receivers enhancing their resilience to possible counterfeit GNSS signals intentionally broadcast on-the air (spoofing), verifying the authenticity of the decoded navigation message [5]. In a moment in which the GNSS spoofing is perceived more and more as an actual risk, an authentication mechanism built in the signal-in-space and readily exploited by the receiver is a valuable differentiator in the market uptake perspective.

The multi-band GNSS receiver uses a two-chip approach, as shown in the following figure. The main chip (Teseo APP-ME STA9100MGA) hosts a first configurable RF chain for L1 signal ensemble, as well as the baseband part for all the signals in the served bands, namely L1, L2, L5, E5a/b, and E6. The secondary chip (STA5635S) is devoted to host an RF front-end configurable for receiving the non-L1 bands (GPS L2 or L5, Galileo E5a, or E5b, or E6). It provides raw (precise) measurements (e.g. pseudorange, carrier phase on each constellation and frequency/band received) for the precise positioning algorithms running on the host processor. In order to speed up "Time to First Fix" and refine the measurements, the GNSS multiband receiver can also accept assistance data from the host processor.

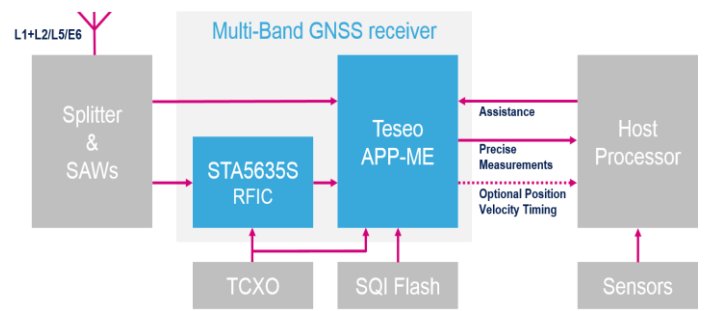


Figure 5 – GNSS Receiver Architecture

## SW DESIGN

The EGE software architecture is organized in three layers:

1. The lower layer is the Board Support Package: it is responsible of managing HW-specific drivers and OS resources that make the EGE hardware to be functional;
2. Middleware: this layer acts as an interface between the interfaces to the vehicle sensors and the application layer, in order to obtain the vehicle measurements and make them available to the positioning applications;
3. Algorithm Facility: this is the application layer, i.e., the software in charge of computing the pose estimations from all the available sensors measurements and the associated protection levels.

The software is hosted in a multi-processor System-On-Chip, chosen to guarantee the availability of the necessary computational resources at a competitive cost.

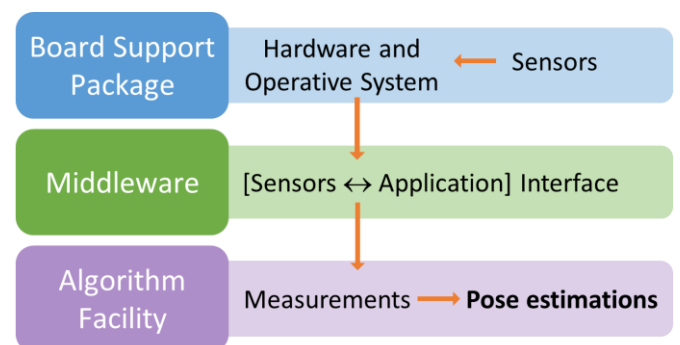
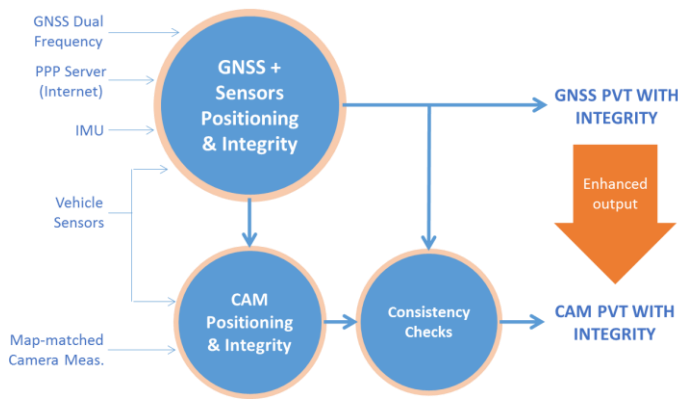


Figure 6 – EGE SW Elements

## EGE POSITION&INTEGRITY ALGORITHMS

The following figure provides a graphical representation of the algorithmic architecture.



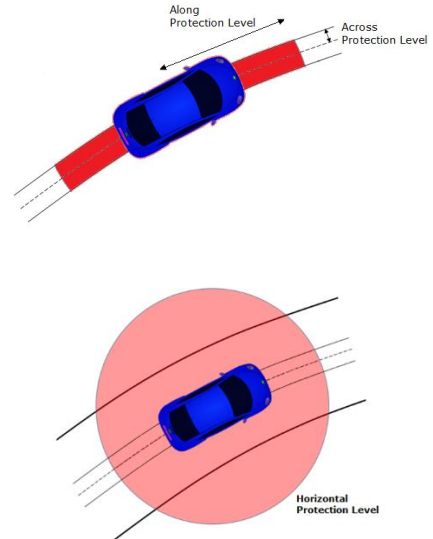
**Figure 7 – EGE Position&Integrity Algorithms Architecture**

The main algorithms at the core of the engine are:

- The GNSS+Sensors Positioning&Integrity algorithm, where GNSS measurements are integrated with those provided by an inertial measurement unit (IMU) in order to provide a GNSS pose with integrity. This position is computed by combining Standard Point Positioning (SPP) and Precise Point Positioning (PPP) algorithms. The PPP algorithm exploits an Internet connection to a remote server to get sets of precise corrections for the GNSS navigation: when available, the PPP service is able to reach decimeter-level positioning accuracy [6]. The PPP algorithm is based on the real-time *magicPPP* ([7]).
- The Camera-based Positioning&Integrity algorithm, enabled by the availability of accurate maps containing road lane-marks. These maps along with the intelligent camera measurements allow a second positioning service with accuracies that can reach a few centimeters in the cross direction, thus complementing and enhancing the positions provided by the GNSS+Sensors Positioning&Integrity algorithm. Also measurements from vehicle sensors that provide – among others – speed and yaw rate, are used to reach the maximum possible accuracy.

Integrity Layer: Protection Levels

The integrity of a certain estimate refers to the confidence one can give to the correctness of the estimate with respect to the true (but unknown) quantity. This confidence is expressed in the language of GNSS positioning with the concepts of protection level (PL) and integrity risk (IR). The PL should bound the error with a certain confidence level and the IR is the probability that the error exceeds the protection level [8]. A well-established and trustable framework to set integrity risks and compute protection levels is mandatory for any applications wants to use an estimated position as an input for operations involving safety of life (as well as economical transactions or any kind of law enforcement, though with different levels of risk).



**Figure 8 – Protection Level concept associated to an estimated position**

For this reason, the EGE provides each position estimate, whatever service is used to compute it, with a protection level. The protection levels, provided by the “GNSS+Sensors Positioning&Integrity” and the “CAM Positioning&Integrity” algorithms, are computed with a technique known as KIPL (Kalman Integrated Protection Level), based on the idea of dynamically modelling the different components of the positioning error with a properly parameterized error probability distribution ([9], [10] and [11]). Each distribution is processed and updated separately and provides a contribution to the total error probability. Finally, the protection level is computed as the maximum error level whose probability is below a given integrity risk. Thus, the integrity module forwards the integrity solution in form of a set of protection levels corresponding to different target integrity risks (TIRs).

**EGE SAFETY ANALYSIS**

The objective of safety engineering is to ensure that all safety risks associated with the design, development, production and operation of a system are adequately assessed, minimised, controlled, and accepted. It attempts to reduce the frequency and impact of failures, and ensure that when failures do occur, the consequences are not life-threatening.

The approach for safety assurance in ESCAPE aims at covering the following aspects:

- Ensuring functional safety of the EGE, that provides a positioning service based on the hybridizing of the GNSS technology with the vision/maps-based technology, plus vehicle sensors;
- Deriving technical and functional safety requirements for achieving an acceptable level of residual risk, due

to hazards caused by malfunctioning behaviour of the engine.

The safety approach followed in the project during the phases of specification and design is based on the recommendations put in ISO 26262 [2], resulting in the definition of the following sequence of steps:

- 1) Execution of the Hazard Analysis and Risk Assessment (HARA), according to ISO 26262. The analysis considers behavioural concepts focused on operational scenarios (e.g., lane merges, visibility conditions, GNSS operational scenarios or highway infrastructure conditions) and covers the analysis of the safety impact of the accuracy of digital road maps;
- 2) Assessment of Automotive Safety Integrity Level (ASIL) to all hazardous events by estimating severity, probability and controllability of hazards;
- 3) Identification of safety goals for each hazardous event;
- 4) Derivation of functional and technical safety requirements. Following a deductive top-down approach, safety requirements are identified for hardware and software components of the EGE, starting from the safety goals down to the lowest level of functional and technical architecture.



Figure 9 – Adopted safety methodology

The traceability between the safety goals and the derived requirements passes through the use of the EGE estimate and the check of the associated protection level by the ADCC. Before using the pose estimate provided by the EGE, the autonomous vehicle must check that the size of the protection level is below a safety threshold, determined depending on the current vehicle state, on the manoeuvre the vehicle is required to execute, and on the status of the other on-board systems involved in the automation.

Therefore, from the safety point of view, the only risk associated to the EGE is the miscalculation or corruption of the computed protection levels. Then, the requirements are focused on two main goals:

- i) to ensure that the calculation of protection levels is correct, and
- ii) to avoid their use in those cases where the protection levels are too high.

If the protection levels are consistent with the integrity risk and the system is used only where they are below the safety threshold, then no safety hazards can take place. Before using the position estimate, the vehicle must check that the size of the protection level is below a safety threshold.

## EGE FIRST RESULTS

The developed EGE is currently being integrated in the autonomous car and tested at the University of Technology of Compiègne (UTC).



Figure 10 – Autonomous Car employed in ESCAPE tests



Figure 11 – ESCAPE Integration Tests at the University of Technology of Compiègne

The first results obtained from this integration campaign are promising. The following table shows the errors obtained processing the GNSS data collected in a sub-urban scenario with a certain level of multipath.

	RMS Horizontal Error (m)	RMS Vertical Error (m)
Static Part	0.29	0.91
Kinematic Part	0.49	0.92

Table 1 – EGE Integration Test – GNSS in sub-urban – RMS Horizontal Error

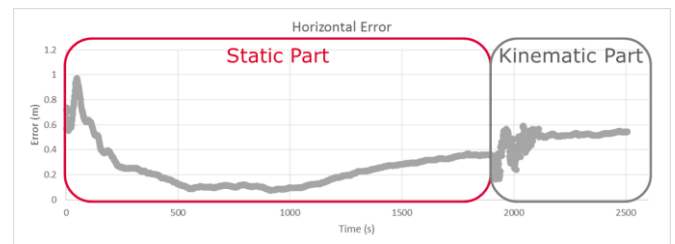


Figure 12 – EGE Integration Test – GNSS in sub-urban – Evolution of the Horizontal Error

Once the integration activities will finish in the following months, the system tests and a performance assessment test campaign will be carried out at Renault during the first half of 2019.

## CONCLUSIONS

The ESCAPE project is developing an innovative positioning engine that enables automated driving functions up to a SAE automation level 4 and creates a new paradigm of safety-oriented navigation technology on the road.

The crucial aspect of automated manoeuvring is safety so the three key and innovative aspects of the safety-oriented navigation technology provided by ESCAPE engine are:

- The smart exploitation of different localization data sources to provide a highly accurate navigation solution, including GPS and Galileo dual-frequency measurements, intelligent cameras providing lateral distance to road lane-marks, inertial measurement units, vehicle odometry, PPP corrections and high definition maps;
- The unique provision of real-time integrity protection levels associated to the location estimates, which express the “degree of usability” of the positioning information for safety-critical applications. The PLs associated to the positions computed relative to the map are fundamental for autonomous driving applications;
- The full integration of the ESCAPE engine into a vehicle with autonomous driving capabilities, and its test on several different reference paths and environmental conditions.



**Figure 13 – New paradigm of safety-oriented road navigation technology**

## ACKNOWLEDGMENTS

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