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On-board positioning strategies based on GNSS low-cost receivers for rail freight transport

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Abstract

The European initiative Shift2Rail (S2R) joins efforts for smart and sustainable growth in the railway sector by fostering research and innovation. Specifically, the project FR8RAIL within the Innovation Programme 5 (IP5)'rail freight' of S2R aims to remove limiting factors of rail freight transportation. The work presented here is part of FR8RAIL and addresses the use and implementation of positioning strategies for rail freight transportation. Freight localization services based on on-board positioning, for example, can facilitate logistic optimization schemes that rely on continuous position and speed information. No extra trackside infrastructure is required, which reduces implementation and maintenance costs. The paper describes the challenges and requirements of on-board positioning strategies for the use in rail freight transportation and presents solution concepts (positioning requirements, hardware architecture, algorithms) for a more competitive rail freight.

Keywords: Freight Transport; GNSS; Localization Services.

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Nomenclature

EGNOS	European Geostationary Navigation Overlay Service
EoT	End of Train
EU	European Union
GLONASS	Global'naya Navigatsionnaya Sputnikovaya Sistema
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GSM-R	GSM-Railway
IMU	Inertial Measurement Unit
IP	Innovation Programme
KF	Kalman Filter
KPI	Key Performance Indicators
LOBU	Locomotive On-Board Unit
NLOS	Non Line of Sight
PF	Particle Filter
PU	Processing Unit
RANSS	Railway Advanced Navigation System Simulator
RTK	Real Time Kinematic
S2R	Shift2Rail
SBAS	Satellite Based Augmentation System
TBD	To Be Defined
TMS	Traffic Management System
UMTS	Universal Mobile Telecommunication System
wOBU	Wagon On-Board Unit
WP	Work Package
WSN	Wireless Sensors Network

1. Introduction

The EU is fostering rail freight transportation to increase its market share in the freight sector. In order to increase the use of rail freight, competitiveness has to be improved. Freight services need to address the following main issues: cost and reliability. The work presented here is part of the project FR8RAIL within the IP 5 of S2R, where the following points must be addressed:

- Reduction of the infrastructure maintenance cost.
- Missing electrification of freight wagons.
- Increase of logistic and infrastructure capacity.
- Generation of a freight data model.
- Accurate train position estimation and reliable integrity.

Particularly, the objective of FR8RAIL's work package 3 (WP3) is the development of telematics technologies (including hardware, software and algorithms), which will provide essential input information for different applications such as condition based and predictive maintenance, logistic services, traffic management, real-time network management and intelligent gate terminals. The development comprises a wagon on-board unit (wOBU), different modules of a wagon and cargo monitoring system for maintenance and logistic purposes, and systems for on board and wayside communication. The wOBU and the referenced components specified here form the basis for being able to implement applications, such as automatic train set-up functionalities as well as a technical solution to provide information about the train (train integrity and end of train (EoT)) to the Traffic Management System (TMS).

Enhancing freight localization services solves directly or indirectly some of the previously presented points. Freight localization services require a cost-effective and reliable position estimation that allows real-time monitoring to improve the efficient use of infrastructure. The advantages of on-board positioning systems are the reduction of the trackside infrastructure, which directly reduces the trackside maintenance costs. Additionally, it provides continuous position and speed monitoring, which enables new logistic optimization schemes based on this information.

The first challenge is the definition of the requirements for the freight location services. Furthermore, it is important to address the lack of electrification of freight wagons that challenges the operation of autonomous on-board systems. The next challenge is the heterogeneous shape of freight wagons, which complicates the positioning system antenna setup. Due to the shape differences and in order to have a unique system capable to be adjusted to every freight wagon, the receiver's antenna is limited to certain locations on the wagon. In some cases, the GNSS signals cannot be properly acquired due to these constraints. Thus, it is mandatory to take advantage of all the possible techniques to reduce/mitigate undesirable effects, use of augmentation systems, realize collaborative positioning and improve integrity assessment capabilities.
After the analysis, the selected on-board positioning system solution is defined with the aim of providing a low-cost architecture where the selected position algorithm and position enhancement techniques can be applied. The goal is to provide an adaptable on-board positioning system for its future use on real rail freight transport addressing the different constraints and making rail freight more attractive in terms of cost and reliability.

This paper first introduces the topic of the rail freight as addressed in FR8RAIL WP3. Requirements for freight railway location services are presented in Section 2. After that, Section 3 describes the low-cost architectures analysis for on-board positioning systems. Section 4 describes the selected architecture. Section 5 presents the positioning algorithms to be implemented. Section 6 shows the conclusions of this work and the next steps within FR8RAIL WP3.

2. Requirements of the freight location services

Specifying reasonable requirements for railway freight location services is a complex task. This is because the requirements are critical for the verification and validation process of the system. It is important to understand the objectives of the location services to adequately define the corresponding requirements. Freight location services objectives highlighted in FR8RAIL are the cargo monitoring system for maintenance and logistic. This means that time constrains and position estimate requirements compared with safe-critical requirements can differ (Wiss et al. 2000).

In this case, requirements are going to be split in two main blocks. On one hand, the functional requirements are described, which are more related with the general system requirements. On the other hand the positioning performance requirements are detailed.

Functional requirements of the system must be fulfilled with the architecture design. The following list gathers the three most important functional requirements:
- Autonomous electrification for wagons on-board systems.
- Low-cost hardware.
- Location estimate for every wagon.

Regarding the performance requirements, GNSS Rail User Forum (Wiss et al. 2000) defined requirements for different type of rail location services. The performance requirements are accuracy, availability, integrity, service interrupt threshold, continuity, coverage and fix rate. Most of the terms are inherited from GNSS and intend to cover all the different location service type for railway. The most important ones for the operational applications are accuracy, availability and fix rate (see Table 1).

Table 1. GNSS Rail Advisory Forum Requirements (Wiss et al. 2000)

Operational applications	Accuracy	Integrity		Availability	Fix rate
	Horizontal (m)	Alert limit (m)	Maximum time to alarm (s)	% of mission time	seconds (s)
Tracing & Tracking of vehicles	50	125	<10	99.9	TBD
Cargo monitoring	100	250	<30	99.5	TBD
Dispatching	50	125	<5	99.9	TBD
Passenger information	100	250	<30	99.5	TBD

FR8RAIL reviewed the performance requirements based on the request carried out by the railway infrastructure operators. The main objective is having a track selective on-board positioning system able to provide a position estimate autonomously even on harsh scenarios where GNSS performance is reduced or not available. However, it is important to remark that these values are under discussion. The agreement of a common framework regarding the performance requirements between GNSS and railway is not achieved (Filip et al. 2008, Beugin et al. 20010). Additionally, the proposed values must be discussed to have a trade-off between position performances for safety-critical applications using low-cost architectures (see Table 2).

Table 2. FR8RAIL requirements

Operational applications	Accuracy	Integrity		Availability	Fix rate
	Horizontal (m)	Alert limit (m)	Maximum time to alarm (s)	% of mission time	seconds (s)
FR8RAIL Location service	2	TBD	TBD	95	Max 120

As mentioned, the functional requirements are fulfilled mainly by the hardware design whereas the performance requirements have to take advantage of synergies of the architecture used and the positioning algorithms and techniques.

3. Low-cost architecture analysis

In the low-cost architecture analysis, it is important to determine which the possible alternatives are in order to select those that will be part of the solution viable positioning solution. The analysed architecture components are the following: on-board system power supply alternatives, available positioning technologies and antenna placement in freight wagons.

3.1. Electrification alternatives

The lack of electrification in freight wagons is one of the main problems when trying to include an on-board positioning system. In order to have an autonomous solution for each wagon, the alternative of having an electrified coupling system that is capable of providing electricity to the positioning system is discarded. The following alternatives have been studied in order to fulfill the system requirement.

- Battery powered: The system can be powered by batteries. Choosing this supply type has the drawback of being dependent on the time that the batteries could last powering the system. They must be recharged periodically.
- Solar panel powered: This technology takes advantage of the solar radiation to generate energy. The autonomy of this system is directly linked to the exposition of the solar panels to the radiation. This means that situations where this radiation is blocked, such as in tunnels, under certain weather conditions, at night, etc., this power generation systems will not be valid. In order to guarantee enough energy to the connected systems additional rechargeable batteries must be installed. Another point to take into account is the solar panel system placement. As the efficiency of the system is directly linked with the relative orientation towards the sun, the typical installation is carried out on the roof. Extrapolating this situation to the freight wagon, the different freight wagon shape will have a negative effect regarding the installation. In some case, the solar panels should be continuously being installed and removed every time the wagon arrives to the destination. All these points make this system time cost inefficient and complex to be used as a scalable solution.
- Contact-less power supply generator: The third power supply option for the system is an autonomous power supply generator using the movement of the train in order to obtain sufficient energy for the system. However, problems of autonomy could appear in every time the train is not in motion. To avoid running out energy support batteries must be installed in addition to the contactless systems. This system is able to generate energy by taking advantage of the electromagnetic waves generated in the systems installed in the wheel axis. In order to handle the energy power supply properly, support batteries could manage the exceeding generated energy in addition to provide a solution to the situation where the wagon is static.

3.2. Available technologies

Regarding the available positioning technologies, the following have been selected for low-cost on-board positioning systems. Also a combination of technologies could be used in order to position a freight wagon and take advantage of the synergies.

- GNSS: GNSS is an affordable accurate positioning system nowadays. It is the main positioning technology in the systems available in the market. In order to achieve better availabilities and performances it can be aided or fused with some other technologies, as described in Section 5. However, railway is a harsh environment for this technology because of undesired effects such as signal blocking, multipath, etc.
- IMU: Inertial measurement units can be used as a complementary system for GNSS positioning when it is not available. IMUs can be used to compute accurate positions for short time periods of about 20-30 seconds, depending on the quality of the employed IMU.
- GSM/UMTS: Cellular networks can be used to make a triangulation and obtain a crude position estimate. The availability of the cellular networks along the track is high. However, infrastructure installation geometry is not appropriate for the triangulation. This combined with the poor accuracy performance of the current technologies relegates these two technologies to be used under more controlled environments, such us in stations, where the infrastructure geometry allow GSM/UMTS to be used to support other technologies.

3.3. Antenna number and placement

The antenna number and the mounting position(s) are critical points. There exist freight wagons of different shape and thus different antenna disposition alternatives. It is also important to remark that the antenna placement will have a direct effect on the reception of the satellite signals. GNSS is used as the main positioning technology of the system. Thus, it is important to focus on the benefits and drawbacks of the antenna position. Possible configurations include:

- Single antenna: When using a single antenna configuration mainly two possible placements are used.
  - Lateral placement: The antenna is placed in one of the sides (left and right) of the wagon. It is a standard placement valid for any freight type. Only half of the sky is visible and some satellites could be impossible to track, but it should be sufficient for positioning.
  - Top placement: The antenna is placed on the top of the container. It is the optimal place for a GNSS antenna as there it has a full sky view available, but regarding to this application, the roof could not be the best place. It would be necessary to install and uninstall the antenna every time the freight container arrives the delivery destination.
- Multiple antennas: When using multiple antennas, placing one in each side of the train would minimize the effects of seeing only half of the sky. Multi-antenna configuration can provide different positioning estimation situations (e.g. each receiver can provide a position estimate or received signal can be mixed and provide an unique position estimation).

4. Architecture proposal

The FR8RAIL architecture design is divided in two due to the differences in the freight composition (see Fig 1). This is important because the locomotive is an electrified wagon while the rest of the cargo wagons do not have a power supply. Consequently, two different systems should be developed in order to take advantage of the locomotive electrification: the on-board system included in the locomotive (LOBU) and the wagon on-board unit (wOBU). Because the power supply of the wOBU is expected to be limited, higher performance processing is restricted to the locomotive. Thus, the wOBU will provide a position estimate to the LOBU based on a limited information sources and the LOBU will be the one of taking advantage of the train composition wOBUs position estimate improving this manner the final position estimate of the train composition and of each of the cargo wagons (see Section 5).

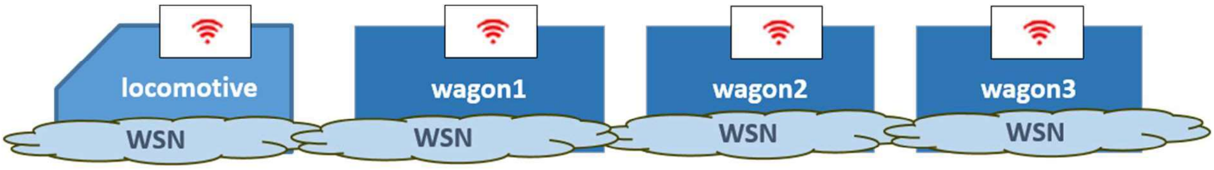

Fig. 1 On-board positioning system architecture

4.1.1. Wagon On-board Unit (wOBU)

The wOBU system is in charge of providing a position estimate to the LOBU. The wOBU system is divided in five main blocks:

- Power system: This system is in charge of generating and managing the power to the wOBU system and all the components that need to be electrified. The selected systems are contactless power supply generator providing an autonomous source of power. Contactless power systems provide inductive power obtained from a dynamo, that is, an electrical generator that produces direct current using commutators. It uses rotating coils of wire and magnetic fields in order to convert rotation into electric current according to Faraday's law of induction. As mentioned, this system has some drawbacks when the train is not moving. Auxiliary batteries are needed.
- GNSS positioning: This subsystem collects the necessary block to provide to the wOBU Processing Unit (wOBU PU) the necessary information to generate GNSS position estimate. It is important to mention that with the aim of fulfilling the requirements defined in Section 2, complementary information sources are needed.
- IMU: As support system the IMU can increase availability.
- Communication module: The communication module is the gateway to the LOBU. It allows the communication of the position estimate and the communication between the LOBU and the wOBU PU.
- wOBU Processing Unit: The wOBU PU is the core of the wOBU system and the one that manages all the information sources to generate a position estimate.

Fig. 2 depicts the architecture of the wOBU system and the five main blocks.

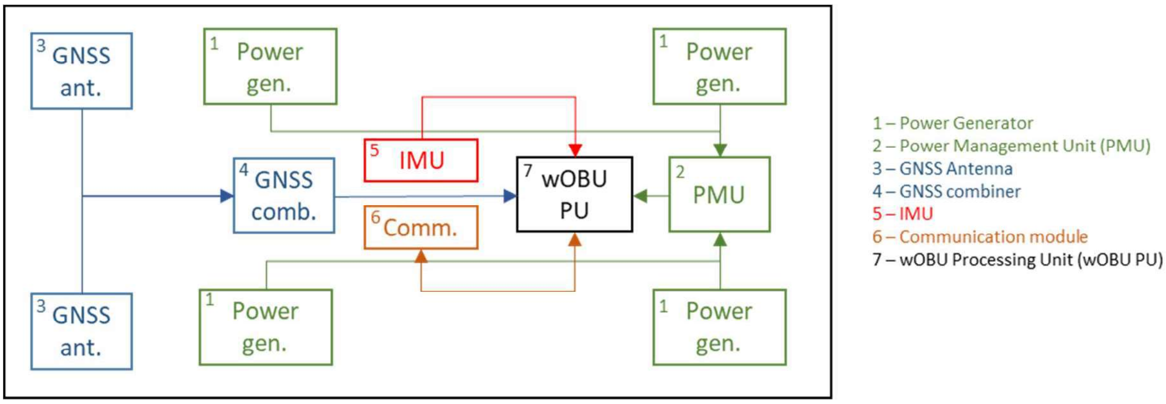

Fig. 2 wOBU on-board positioning system architecture

4.1.2. Locomotive On-board Unit (LOBU)

In contrast to the wOBU, the LOBU does not carry hardware for power generation, because locomotives are already electrified. However, the modules related to GNSS and IMU, and the communication modules are present on the LOBU too. In addition, the LOBU can be equipped with:

- A balise reader.

- A camera system and an image processing unit that can be used to detect known landmarks. Its use for track determination after switches is also conceivable.
- A LOBU processing module that is computationally stronger than the wOBU PU. The LOBU PU is used to carry and process a digital track map for positioning purposes.

Fig. 3 depicts the architecture of the LOBU system.

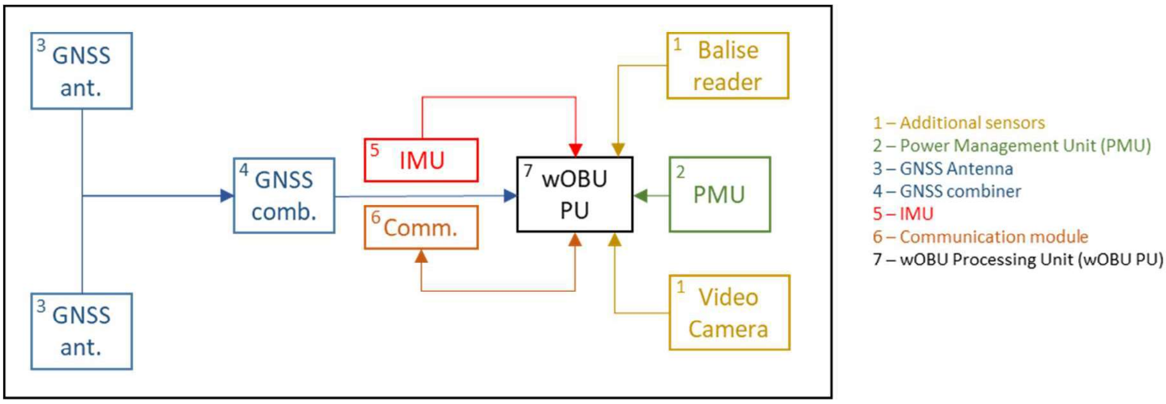

Fig. 3 LOBU on-board positioning system architecture

5. Positioning algorithms

Algorithms are required to extract the relevant position information from the raw sensor data of, e.g. GNSS receivers and inertial measurement units (IMU). In the railway context, the term position does not only refer to geographic coordinates (latitude, longitude) but also to the specific track in a railway network that the train is on, and the travelled distance on that track. Several related quantities are estimated as by-products, e.g. the speed or the position uncertainty.

5.1. Advanced GNSS processing

GNSS determine the three-dimensional receiver position from satellite signals. At least four satellites must be in view so that the position and the unknown receiver clock offset can be estimated from the transmission and reception time differences. With receivers that process signals from, e.g. the GPS, GLONASS, and Galileo systems, the number of potentially visible satellites has increased in recent years. Still, GNSS measurements are subject to errors. Advanced GNSS processing techniques can be used to reduce the effects of some error sources. Many concepts to improve GNSS measurements rely on the processing of additionally received signals, which is reflected in the umbrella term GNSS augmentation (Groves, 2013). Satellite-based augmentation systems (SBAS), e.g. the European EGNOS service (Teunissen & Montenbruck, 2017), provide correction data about the satellite clock errors. Differential GNSS set-ups with reference GNSS receivers at precisely known locations can be used to remove errors that are related to atmospheric disturbances. The position errors decrease from tens of meters to meter range. More precise statements are difficult to make because of the strong time and location dependence of GNSS errors. Further improvement of differential GNSS accuracy has been achieved with real-time kinematic (RTK) GNSS, a technique which uses not only the GNSS code but also the phase information of the carrier wave signal for satellite ranging. With a base station in the vicinity of 20 kilometers, centimeter accuracy can be achieved at the GNSS receiver (called rover in the RTK set-up). The challenge in RTK is to resolve the so-called integer ambiguities in order to determine the correct phase difference for the periodic carrier signals, which can lead to long start-up periods, also after temporary loss of satellite views. Furthermore, at least four common satellites must be in view for the RTK rover and base stations. Further GNSS advances are documented in, e.g. (Groves, 2013) or (Teunissen & Montenbruck, 2017).
Even with GNSS augmentation, some errors are difficult to eliminate. Specifically, multipath and non-line-of-sight (NLOS) situations are highly time and location dependent and difficult to handle. Scenarios without sky view altogether, e.g. tunnels, render GNSS systems temporarily useless. Often, the foliage next to a railway track is enough to leave only a small corridor for unobstructed satellite view. It is therefore essential to combine GNSS receivers with other sensors such as IMU using the multi-sensor fusion approaches described next.

5.2. Multi-sensor fusion

The exclusive use of GNSS suffers from limited availability and position errors that are difficult to characterize and predict. The combination of GNSS with IMU and other sensors, often termed integrated navigation, is an example of multi-sensor fusion and can alleviate this problem.
An established multi-sensor fusion framework that can be used to combine different measurements with train motion models is Bayesian filtering in state-space models (Roth, 2017; Särkkä, 2013). Here, the position and other quantities of interest are combined into a so-called state vector. Mathematical equations describe how the state changes over time and how it is related to the different measurements. Process and measurement noise signals account for uncertainties in the relations. The Bayesian filtering approach provides appealing conceptual solutions for estimating the state. Unfortunately, it is not possible to directly implement these solutions as computer code in most cases. Therefore, approximations based on Kalman filters (KF) are typically employed. These provide an exact solution for one special case of the Bayesian filtering problem and are simple to implement.
Multi-sensor fusion with KF accommodates GNSS and IMU measurements very well. Also further sensors can be easily included, e.g. position information from the GSM-R network, odometers, balise readers, or camera systems that detect specific landmarks. Hence, the framework is very flexible. Furthermore, KF provide probabilistic estimates of the state vector, comprising a point estimate and a covariance matrix. Hence, the uncertainty in the state estimates is quantified, which can provide valuable information for integrity monitoring. Finally, the KF framework is well-established in many navigation problems and provides practical guidelines for assessing the quality of measurements and the removal of outliers.

5.3. Inclusion of digital maps

Trains are constrained to move on railway tracks. Therefore, maps of the railway infrastructure can provide valuable information about the train position. Unfortunately, the inclusion of map information is difficult in a KF framework because of the highly nonlinear relations in track-constrained motion models. Therefore, more advanced concepts must be employed.
One option is to replace the KF of most integrated navigation approaches with more flexible particle filters (PF). Such an approach is documented in (Heirich, 2016). Although PF are appealing because of their theoretical properties (Särkkä, 2013), they have several practical drawbacks. For instance, accurate PF require a large number of so-called particles, which entails a large computation load. Furthermore, PF work only well for low-dimensional state vectors and face divergence issues in higher dimensions.
An alternative option that preserves the use of KF is to first determine the most likely track segments that the train is on. For each of the track hypotheses, on-track state estimates can be computed using a track-constrained KF in a second step. The here employed motion models work with the one-dimensional position on the track as state variable. In the course of the estimation process, unlikely track hypotheses can be removed. Here, extra sensor input from, e.g. balise readers or camera systems for switch detection can be useful. Because of a lower computational demand in comparison to PF and promising first experimental results, the on-track KF approach will be pursued in this project.

5.4. Collaborative positioning and integrity assessment

The wagon positions in a train obey distance constraints that are determined by the wagon lengths. This information can be exploited to improve the overall train positioning. Similar to the inclusion of map information, however, the handling of distance constraints goes beyond the KF sensor fusion methodology. Therefore, novel approaches must be developed.
A promising idea is to combine the position estimates that are independently computed by each wOBU and transmitted to the LOBU into a single position measurement. Together with the distance constraints, all wOBU positions can be used to formulate an optimization problem with the on-track train position as decision variable. Because of the scalar decision variable, such an optimization problem can be easily solved numerically. wOBU measurements that are in conflict with the distance constraints can be removed from the computations and flagged as suspicious. This provides the means for integrity monitoring of the wOBU positioning modules. Finally, the solution of the optimization problem can be easily included in an on-track KF in the LOBU positioning module.

5.5. Positioning algorithm proposal

In order to keep the hardware costs and computation efforts low, KF-based positioning using GNSS and IMU will be implemented for the wOBU. Via the wOBU commination modules, the KF output is send to the LOBU with a frequency of about 1 Hz.

The LOBU is electrified and can hence provide more computing capabilities, which allows for the implementation of the inclusion of digital maps and the collaborative position using the wOBU input. Moreover, access to additional sensors, e.g. balise readers, odometers, camera-landmark detection systems, and GSM-R receivers, is conceivable for the LOBU. The multi-sensor fusion will be realized using a KF approach that works with a changing number of track hypotheses, as described in Section 5.3.

6. Conclusions and future work

Based on the analysis of the requirements, the state-of-the-art technologies and the positioning techniques, a positioning system is proposed to achieve to fulfil all the positioning related performance requests that can come up in the future. Prior to deployment and validation in the field, the theoretical performance of the algorithms, the environment, and the observables for the algorithms could be modelled in the simulation platform called RANSS (Goya et al., 2015). This would evaluate the performance of the proposed system in terms of accuracy, reliability and continuity, indicators similar to the GNSS system. Detecting in advance all the possible gaps or problems avoiding unsuccessful and costly field-test, reducing the amount of effort to reach to a final solution.

These are the next steps that are going to be followed:

- Generation of the reference scenarios ground truth for each of the subsystem included in the proposed system architecture.
- Generation of the observables that each subsystem involved into the positioning estimate, including error model to perform realistic observables.
- Proposed algorithm development to fulfil the request performance levels to later on compare the results of the position estimate.
- Comparison and discussion of the obtained results to detect the strengths and weaknesses of the proposed architecture and algorithm solution.

Once all these steps are followed the development of the system could be carried out having reduced significantly the development time and cost.

Acknowledgements

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