Map-Aided Software Enhancement for Autonomous GNSS Complementary Positioning System for Railway

Gorka de Miguel, Jon Goya, Nerea Fernández, Saioa Arrizabalaga, Jaizki Mendizabal, and Iñigo Adin

***Abstract*—Independently on the business case addressed, one of the main drawbacks of the railway use cases that need continuous Global Navigation Satellite Systems data is the lack of availability for the 100% of the time of the journey. Additionally, the integrity assessment of the position estimation given is also mandatory for safety critical applications. Thus, tunnels and multipath effects are one of the most challenging situations for the continuous positioning systems. In this context, an autonomous on-board Complementary Positioning System has been proposed to overcome the limitation of Global Navigation Satellite System based positioning systems. This paper proposes a positioning enhancement solution by means of fusing data from the satellite navigation system and inertial measurement units. That hybrid solution provides higher availability and accuracy to the positioning specially on known blocked scenarios, such as tunnels, or urban canyons, by means of a novel environment aware map aided software technique named Known Blocked Scenarios algorithm… This paper describes the Complementary Positioning System and the field test carried out in a challenging environment to validate the enhancement proposed by the authors, which demonstrate the benefits that this system has in known harsh environments for railways.**

***Index Terms*—Availability, CPS, GNSS, IMU, KBS, Multi-Sensor, On-Board Positioning, Positioning, Railway.**

I. Introduction

THE EUROPEAN Union (EU) aims at making railway a more attractive transportation method by improving its efficiency and reducing its costs. The European Rail Research Advisory Council (ERRAC) has defined some goals in order to increase the efficiency of the current railway infrastructure by means of track capacity augmentation [1].

In this context, SHIFT2RAIL, the main railway innovation initiative in EU plans to increase the attractiveness of the railway transportation by means of doubling the railway capacity, cutting the life-cycle costs of railway transports by as much as 50% and increasing reliability and punctuality by as much as 50% [2]. This could be applied to, at least, two of the Innovation Programs: IP2 and IP5 of this initiative dealing with control and communication systems and freight rail respectively. In the former, control, command and communication systems will go beyond merely being a contributor to the control and safe separation of trains, and become a flexible, real-time, intelligent traffic management and decision support system. And in the latter, the main challenge is to acquire a new service-oriented profile for rail freight services based on excellence in on-time delivery at competitive prices, interweaving its operations with other transport modes, addressing end-user needs by incorporating innovative value-added services, among others. In both cases, one of the enablers is the on-board Global Navigation Satellite System (GNSS) based positioning system and the improvement of their performance in order to reach every business' case requirements. For instance, these new services resulting from IP2 and IP5 roadmap will have an important impact in the migration from ETCS level 2 to ETCS level 3. This migration will allow a descent in the infrastructure costs up to 25% to regional and freight dedicated lines and efficiency improvements of more than 50% [3].

As a base, the suitability of GNSS systems for railway applications is being or has been analyzed by several European projects such as:

- GRAIL2 [4]–[7] aimed at developing and validating an ETCS odometry system prototype based on GNSS technology.
- SATLOC [8]–[10] aimed at developing and validating the use of GNSS in low traffic lines signaling and train control. The usefulness of the presented system on a real line was shown. However, the use of complementary positioning techniques was presented as essential. A future use of route maps and virtual balises was proposed.
- GaLoROI [9]–[14] project obtained the position estimation using GNSS (including Galileo technology), Eddy Current Sensors (ECS) and track-matching techniques. The tests performed in order to analyze the Reliability, Availability, Maintainability and Safety (RAMS) showed that GNSS performance was not good enough to meet railway requirements in harsh environment, showing the need of additional sensor fusion in order to increase the availability of the system.
- 3InSat [15]–[17] developed a Localization Determination System (LDS). The LDS is a fusion of GNSS systems with

Manuscript received February 1, 2019; revised May 30, 2019; accepted August 27, 2019. Date of publication October 14, 2019; date of current version December 17, 2019. This work was supported by SIA project as part of the European H2020 framework of projects, funded by European Commission (EC) and managed by European GNSS Agency (GSA), under contract number 776402. The review of this article was coordinated by Guest Editors of the Special Section on Smart Rail Mobility. *(Corresponding author: Gorka de Miguel.)*

The authors are with the CEIT-IK4 Research Centre, 20018 Donostia-San Sebastián, Spain, and also with the TECNUN, Universidad de Navarra, 20018 Donostia-San Sebastián, Spain (e-mail: gdemiguel@ceit.es; jgoya@ceit.es; nfernandez@ceit.es; sarrizabalaga@ceit.es; jmendizabal@ceit.es; iadin@ceit.es).

Digital Object Identifier 10.1109/TVT.2019.2940621

augmentation techniques and integrity detection solutions. The project aimed to reach the requirements of the European Rail Traffic Management System (ERTMS)/ETCS level 2 trackside balise. This project gave as a result a GNSS solution and a theoretical modeling concerning the Safety Integrity Level (SIL). The results wanted to integrate the satellite based localization systems in ERTMS-ETCS environment.
- ERSAT-EAV [18] aimed to reuse the ETCS odometry and the virtual balise concept in order to eliminate fixed balises. Augmentation networks such as EGNOS (European Geostationary Navigation Overlay Service) are also used to verify and validate different GNSS solutions in order to guarantee the positioning functions in areas in which GNSS signal is not accurate enough.
- RHINOS [19], [20] aimed to increase the use of EGNSS (European Global Navigation Satellite System) to support safety critical train localization functions for train control. RHINOS pillar was the GNSS infrastructure used for aviation with additional layer to meet the railway requirements.
- STARS [21], [22] developed an approach to characterize the GNSS performance in the railway environment. The project also quantified the economic benefits of using GNSS in ERTMS.
- X2RAIL-2 [23] aims to improve the performance at a railway system level by introducing new functionalities that should revolutionize the signaling and automation concepts in the future. The key technologies cover GNSS application in railway and advanced technologies for implementing new signaling functionalities.
- ERSAT-GCC [24], [25] aims to speed up the certification process of EGNSS according to ERTMS rules. The main goal is to define and certify a standard process, methodology and the related toolset for classifying track areas as suitable for locating Virtual Balises (VB), and to launch an operational line with integrated satellite technology by 2020.

One of the main problems of the on-board satellite positioning systems is the reduced coverage in urban environments or in difficult orography such as tunnels or canyons. In order to solve these limitations of the GNSS only positioning systems, the positioning enhancement proposed in this paper takes into consideration the previously mentioned papers and is based on a fused GNSS and Inertial Measurement Units (IMUs) solution which helps increasing the availability of the position data.

The use of on-board satellite positioning systems in the projects listed is mainly focused on the objective of having a positioning solution suitable for Virtual Balise (VB) [26].The positioning solutions used to provide the VB usually generate a continuous Position, Velocity and Time (PVT) estimate. However, the VB solution requires only areas where the VB can be triggered and therefore only a spot positioning system is required. For that reason, the continuous positioning is not mandatory but usually considered in order to reach a reliable solution as the PVT cannot only rely on GNSS. However, there are a number of other applications and services that require continuous positioning such as the odometry service. Taking this into account, the map aided software solution presented in this article pretends to broaden the scope and to tackle the issues of the GNSS based positioning system for a continuous positioning solution that could be used not only for the VB detection.

The progress beyond the state of the art of this work is the addition of a specific environment aware map aided software technique to the GNSS and IMU positioning. This software technique, called KBS algorithm, improves the accuracy in the entrance of Known Blocked Scenarios. All has been implemented in a Complementary Positioning System (CPS).

The paper is structured as follows:
- Section II introduces the Complementary Positioning System, the technologies used and its subsystems.
- Section III describes the Complementary Positioning System including both hardware and software.
- Section IV defines the validation tests and describes the environments in which they have been performed.
- Section V shows the results obtained after the tests.
- Section VI exposes the conclusions arisen from the work presented.

II. CPS and Technologies Used

This section introduces the Complementary Positioning System (CPS) solution and the technologies used to obtain the enhanced position estimation.

CPS is an autonomous positioning system as it can perform a full available positioning operation in a standalone mode without the need of other systems already integrated in the trains. The hardware subsystems used in the CPS are low cost sensors due to the fact that it was designed to have a good cost-effectiveness for an attractive business case. Even the GNSS receiver could be a low-medium end subsystem, which is not usual on the railway applications analyzed in the introduction's projects and papers. Moreover, a wider use is enabled, as trains without GNSS on-board positioning systems could use the CPS and the ones that already had GNSS installed would only need an expansion. In case a high end GNSS system mounted on board leads to a better CPS performance to obtain the best possible positioning solution, in lines or applications in which a high performance is required.

The CPS overcomes the GNSS obscured areas thanks to the introduction of the inertial sensors, software positioning enhancement techniques and map aided environment awareness. This is achieved by using the technologies listed below:
- Global Navigation Satellite Systems (GNSS)
- Inertial Measurement Units (IMU)
- Known Blocked Scenarios (KBS)

A. GNSS

GNSS are systems that use satellites to compute a position with global coverage thanks to a GNSS receiver. They can be used for providing timing, position, navigation or tracking information. It is the main technology used for navigation and positioning services and it is widely spread in the daily life. In the near future there will be four GNSS fully operative: GPS (USA), GLONASS (Russia), GALILEO (EU) and BeiDou/COMPASS (China).

Standard GNSS receivers provide up to four observations per satellite and per frequency at a specified rate that depends on the application:

- Pseudorange: Measurement of the distance from receiver antenna to satellite antenna including receiver and satellite clock offsets, and other biases expressed in meters [27].
- Carrier Phase: Measurement of the range between a satellite and receiver expressed in units of cycles of the carrier frequency [27].
- Doppler: It is the Doppler shift with respect to the nominal signal frequency; it is positive for approaching satellites. Usually used for the calculation of the user velocity expressed in Hz [27].
- Signal Strength: Measurement of the strength of the received signal, dependent on the degree of thermal, background and intermodulation noise to which the signal has been subjected expressed in dBm [27].

B. IMU

An IMU is a device that has three gyroscopes and three accelerometers that are displaced along three mutually orthogonal axes. The main idea of inertial navigation is the Newton's First Law: "A body will continue in its state of rest, or of uniform motion in a straight line, unless an external force is applied to it". The accelerometers detect the acceleration changes due to the gravity forces and the gyroscopes the changes in the rotational attributes. An IMU is autonomous and is not dependent on other devices or signals visibility. Moreover, it has no need of an antenna so it can be mounted on-board in a stable place. However, the main drawback of the IMU is its accumulative error. The sources of the errors are mainly two:

- Bias errors: constant errors suffered by the sensors in their measurements. Knowing those errors beforehand could be a solution in order to calibrate the IMU. The static bias can be easily corrected as it is constant and a result of a wrong calibration of the sensors. On the other hand, the dynamic bias is the in-run variation and changes over the time. Even if the drift error is about the 10% of the static bias error, it is the one with the highest influence in the final implementation, as it cannot be easily corrected [28].
- Noise: another unwanted signal generated from internal electronics that interferes with measurement of the desired signal. As almost all of it is random noise (white noise), it will not be possible to predict it in advance. Nonetheless, the positive point is that in general, velocity, position, or pitch or roll error from the accelerometer or gyroscope white noise will be smaller than the other described correctable noise sources for IMU [29]. All in all, the whole sum of noises will have a lower effect than the bias errors in the IMU.

C. Known Blocked Scenarios

Known Blocked Scenarios (KBS) is a software enhancement that uses the knowledge of the zone in which the complementary positioning system is working to forecast areas in which GNSS signals are not available or could give misleading information. With this map based program, a better choice of the available positioning technologies leads to an enhanced data management and by hence to a system with a better position estimation (further details in III.C).

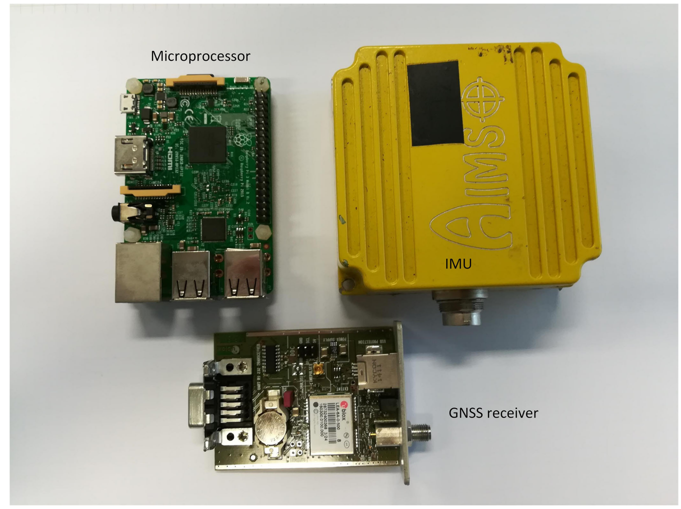

Fig. 1. Positioning and line characterization system hardware for the prototype implementation.

III. CPS Architecture

This section describes CPS architecture including both hardware and software.

A. CPS Hardware

Fig. 1 shows the hardware architecture of the CPS. Physically, it includes a multisensor equipment for location estimation that consists of the following:

- GNSS receiver (UBLOX EVK-6T-0-001): Responsible for providing an absolute position to the system. This position is used as a reference position while the GNSS system is available and its standard deviation is under a certain level. The receiver used in the CPS for the measurements, showed in the upcoming Sections IV and V, is a low-mid range GNSS receiver. The main two objectives of the receiver are the following: to record the raw data for the later assessment of the KBS threshold (Section C.1) and to perform a standalone positioning operation if there is no access to the on-board GNSS positioning system (Section C.2).
- Inertial Measurement Unit (IMU) (AIMS Navigation 0817111411): To perform a relative position estimation using the linear accelerations and angular velocities computed along with the gravity when the CPS crosses a GNSS blocked area. It is also used when a higher frequency of positioning is wanted making the availability of the system higher. The IMU employed is a low cost system.

Fig. 2. Antennas placed in ALN 668 3114 roof (Courtesy of ASTS).

- Microprocessor: The sensors used to obtain the data for positioning are connected to a microprocessor. It is the device in charge of receiving all the data from the sensors and fusing them to have a precise position estimation. The software of the positioning techniques such as the GNSS, IMU and the KBS are executed in it. The databases needed for the KBS are stored in it as well.
- AC/DC energy converter: The used sensors and microprocessor need DC power to perform their operation. Usually the power supplies available in trains are 220V AC power supplies. The introduction of this converter deals with this issue and helps with the discontinuities appearing in the power supply of the trains as it can maintain the DC power supply required for some seconds.
- GSM/UMTS Modem: CPS has also the ability to send and receive information in real time through a communication modem connected to a GSM/UMTS antenna. The data management is done through this modem, and the CPS can be remotely managed.

Excluding the IMU that needs to be placed in a stable place of the vehicle, the rest of the modules are placed into a 25 cm × 16 cm × 20.5 cm metallic container in order to make the system portable. CPS has its own GNSS receiver, and in this way it can perform stand-alone positioning.

The system uses two antennas to obtain all the needed information to work stand-alone (See Fig. 2). A dual GSM/UMTS antenna and a GNSS antenna, both compatible with the bands that are used. In the case in which the CPS is working as a complementary system to the existing on-board GNSS, the on-board GNSS antenna could be used in order to reuse the available equipment. Nevertheless, having a redundant GNSS system could help in terms of integrity due to the existence of two systems working in a similar way what gives backup to the system.

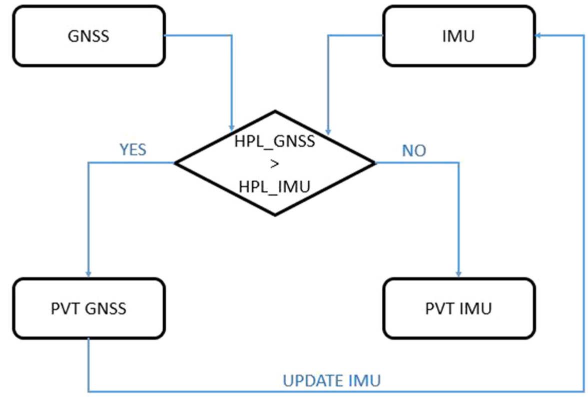

Fig. 3. GNSS+IMU integration.

B. GNSS and IMU Based Positioning Algorithm

The GNSS and IMU based positioning algorithm is the base of the CPS when providing a 100% available position. The KBS is built over this first GNSS and IMU based positioning algorithm, as an enhancement to the data that are shared by it.

This GNSS and IMU module uses the data received from a GNSS receiver in order to compute the position of the train in which it is installed. Nonetheless, taking into account that GNSS positioning has performance problems under harsh environments such as canyons or tunnels, the information received from an IMU is included in the positioning algorithm. The IMU performs a dead reckoning algorithm from a known starting point given by GNSS. This approach ensures a 100% availability in the positioning solution. However, the computed position is not always accurate enough for the system to work fulfilling the requirements of a given use case. For example, when getting into a tunnel, the last GNSS position could contain misleading information due to the degraded GNSS information obtained in the proximity of the blocking scenario. This initial misleading situation leads the IMU to give a wrong direction and position when performing the dead reckoning algorithm. IMUs have accumulative errors and having an erroneous heading direction incurs in an even bigger erroneous position estimate. That is the reason to introduce a Known Blocked Scenarios (KBS) algorithm to overcome these difficulties. Fig. 3 shows a diagram in which the situation above is explained. When doing the GNSS and IMU integration, the HPL of both technologies are compared. If the HPL of the GNSS is lower than the HPL of the IMU, the PVT obtained from the GNSS is the one given by the system. And the IMU is updated with it. In the other hand, if the HPL of the IMU is lower than the HPL of the GNSS, the PVT is obtained from the dead-reckoning of the IMU.

C. KBS

The KBS is the novel map aided software positioning enhancement proposed by this paper. It helps the GNSS and IMU positioning algorithm in terms of anticipating blocking scenarios and minimizing the use of GNSS misleading information.

Having a reliable heading and position of the train is important before entering a GNSS blocked area. The orientation of the train

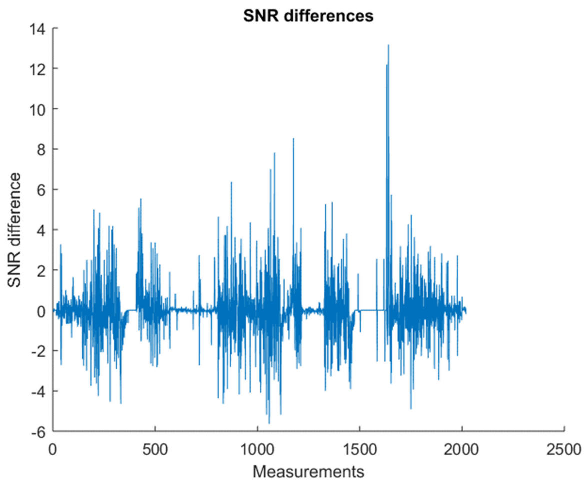

Fig. 4. Measured SNR differences in a complete scenario with different environments for GNSS.

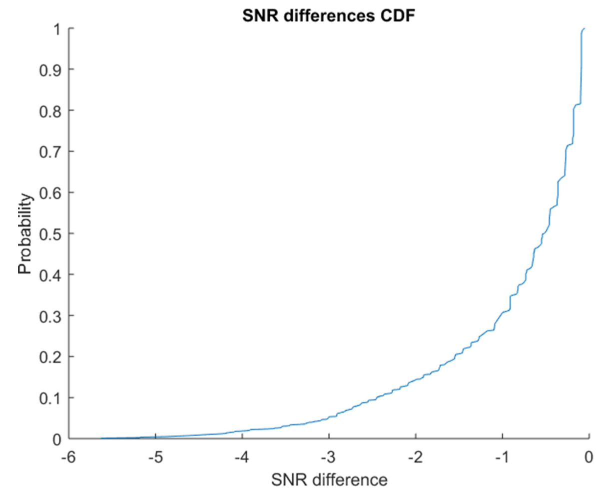

Fig. 5. CDF of SNR decreases between epochs for Threshold detection.

is computed before entering blocked scenarios in order to perform an accurate positioning operation. With a non-redundant system, the heading angle is obtained from the last "a priori" reliable position of the GNSS receiver. Thus, detecting erroneous information improves the performance of the solution in GNSS blocked areas.

Regarding the use of the KBS, two main steps are defined. The first step is the determination of known block scenarios for the determination of the KBS threshold and the second step is the KBS operation mode to enhance the position estimate in which real time positioning operation is performed.

1) Determination of the GNSS Blocked Scenarios and KBS Threshold Determination: The aim of the KBS is to improve the positioning and it is done under map located known blocked scenarios. Thus, for the KBS to be available, before starting its operation, it is necessary to first detect and create a database with these spots and sections with known blocked scenarios.

In this case, for the determination of a degraded GNSS area, the received signal to noise ratio (SNR) of the GNSS signal strengths is analyzed. Having a lower SNR increases the probability of having error in the received information [30].

Fig. 4 shows a real case for the known blocked scenarios. It shows the SNR difference between a GNSS measurement and the previous one.

Every scenario produces an attenuation based on the surrounding environment. So in the first phase, an analysis of this environment needs to be done. With that purpose, maps are consulted and the trackside is inspected with the aim of identifying the possible GNSS blockers such as urban canyons, tunnels, woods or other artificial blockers and constructions. A database with all the areas where possible GNSS outages are expected is constructed and proper position and heading values are introduced based on reliable track database information.

With the aim of reducing the computation time for the enhancement of the position estimate, the KBS is only triggered under certain conditions. Thus, based on the analysis of the SNR along these known block scenarios campaigns detection (see Fig. 4), the sensibility and the KBS threshold is calculated [31]. This threshold is highly dependent on the antenna positioning and the trackside environment. If the antenna has a full view of the sky, the threshold will be higher as the difference between blocked and non-blocked scenarios will be more elevated due to the good health of the received signal in non-blocked scenarios. This is why the authors propose to perform trips in different times of the day, with different satellite constellations in view and different weather to have a reliable threshold configuration.

In a railway with very differentiated parts, in which the train has line of sight with the satellites every moment apart from the blocked scenarios, 2 runs will be enough to build an accurate database as the satellite architecture and the surrounding environment will not have a big influence. In the case in which the surroundings of the blocked scenarios are GNSS challenging areas, more runs are needed in order to differ between blocked and no-blocked areas as the SNR decreases are lower, and the threshold must be calculated more carefully. Runs in different times of the day are recommended in order to evaluate the performance with different satellite architectures.

The sensibility of the KBS is triggered based on the SNR decreases. This means that a SNR fall down compared with the previous epoch determines that GNSS signals are not trustful anymore unless the SNR shortfall is recovered. This allows complementary positioning sensors to have a trustful position once GNSS signals are not available, which improves the position estimation results. The KBS system allows detecting the entrance of the tunnels or other blocking structures where the complementary positioning sensors take the key role regarding to the position estimation. Summing up, the KBS threshold is set-up based on the SNR decreases.

For the particular case of the test campaign shown in Fig. 4, the selected threshold to trigger the software enhancement tool was −2.5 dB between two consecutive SNR measurements. To select that threshold, a Cumulative Density Function (CDF) is used. The threshold is selected to be the one which marks the 10% of probability (Fig. 5).

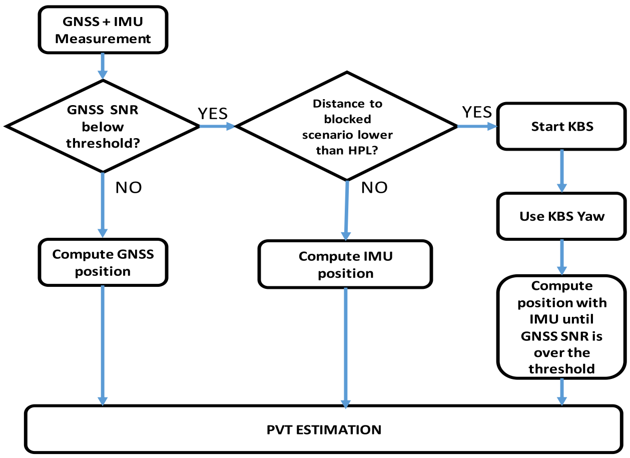

Fig. 6. KBS operation.

Fig. 7. General environment in EuskoTren Lane.

Fig. 8. Section of Eusko Trenbide Sarea (ETS) network.

2) KBS Operation: Once the KBS threshold is properly selected, the positioning algorithm is able to enhance the positioning in these blocked scenarios. Fig. 6 shows the KBS algorithm methods which relies on having a more accurate starting point which leads to a more accurate position estimate.

The KBS determines not the valid GNSS, but the degraded GNSS information based on the strong SNR decreases between epochs. The KBS takes advantage of the detection of strong blocking areas, which are mainly tunnels. Tunnels are the main blocking areas, due to their strong effect and their limitation to a defined area. At this point, apart from detecting and discarding the GNSS information a "database" is set up to reduce the errors of the next time epochs where GNSS is not available by resetting the yaw information of the algorithm.

The positioning system proceeds in the same manner every time that it receives a GNSS information. First of all, it compares if the selected triggering option is reached. If not, the GNSS is considered reliable and the algorithm computes the position estimate. If the KBS is triggered, the KBS takes a look up into the KBS database and based in the information of the previous reliable estimate and the distance to the different known blocked scenarios entries, it uses the stored information to correct it. The distance to use an entry from the database is, as maximum, the HPL (Horizontal Protection Level). The HPL is the statistical error bound obtained during the real time operation of the positioning algorithm.

This methodology is repeated until the KBS detects a valid GNSS.

IV. Test Definition

This section shows the tests proposed and the measurements done in order to validate the CPS algorithms. A demanding environment near Donostia / San Sebastian (Spain), was selected. In this section the track and train selection and ground truth generation are introduced.

A. Track and Train Selection

The chosen railway is placed between Hendaia and Donostia, in a regional train that puts together France and Spain operated by Eusko Trenbide Sarea (ETS). This railway has a difficult orography since GNSS blockers appear in more than 50% of the track analysed. Most of the journey is done inside tunnels or canyons; both urban or natural (see Fig. 7).

The trial track is mostly set in an urban environment inside the city of Donostia and the villages near it. However, there are also suburban and rural areas in the more than 20km of track. The rural areas are mountainous areas in which the signal reception is not direct in all the cases. The environment in which the algorithm was tested can be considered a GNSS demanding zone in which long periods of lack of signal were recorded.

The tests took place in service during approximately 30 days, in which the full operation of the trains during their usual journeys were recorded. In this way, different satellite constellations in view were tested, and the collected data was more realistic.

The route going from Fanderia station to Errenteria station (Fig. 8) has been chosen for the tests as it is a representative part of the journey because the track is surrounded by buildings and the train travels through a tunnel (see Fig. 8 (green area)). The degradation of the signal prior to the entrance to the tunnel affects the performance of the positioning system. The surroundings

Fig. 9. EuskoTren Serie 900 Locomotive.

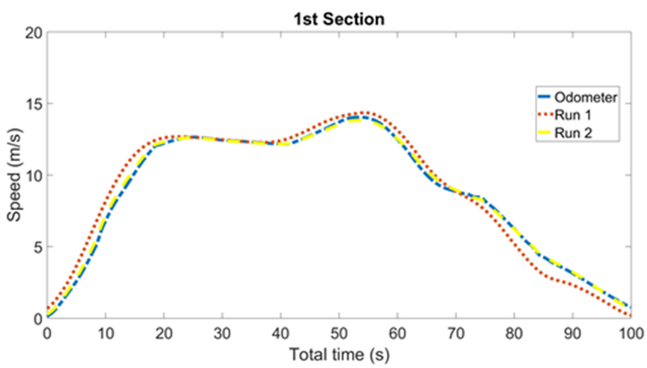

Fig. 10. Speed profile comparison.

and the fact that the tunnel is preceded by a curve also influences the result without the software enhancement proposed by this paper.

The vehicle used was an electric locomotive Serie 900 from Euskotren. (See Fig. 9).

B. Ground Truth Generation

For this measurement campaign, the ground truth is obtained using independent sensors installed on-board. In this case, the Euskotren on-board odometer [32] has been used.

First, the information source for this ground truth was independent to the information used by the CPS in order to ensure a non-dependent behaviour of the error.

The odometer data were interpolated to obtain a smoother speed profile. Additionally, in order to check the proper behaviour of this profile it has been compared and validated with other GNSS based speed profiles from other journeys carried out during this period. (see Fig. 10) and used to determine the starting point of the journey.

The obtained accuracy after interpolating the information and smoothing the behaviour depicts a representative and consistent behaviour compared with other runs. Afterwards, this speed profile is projected into positions in combination with a track database composed by the geolocated information (x,y,z and travelled distance) to obtain the set of timestamped trustful positions which are considered as the ground truth, in order to compare them with the PVT estimates obtained using the CPS [33]. The section under study in this work is 100 seconds long so the drift error of the odometer is affecting the accuracy of the ground truth less than the order of magnitude of the resulting data from the CPS solution shown in the results section. For the measurement campaign shown here, no slope and no slippery effects are reported in the section under study at a 10m/s average speed, so a speed error margin of 0.333% could be applied for the 100 seconds from one stop to the other. That represents a maximum error of $+/-$ 3.33m of error with the odometer algorithm, which is lower than the order of magnitude of the error computed by CPS.

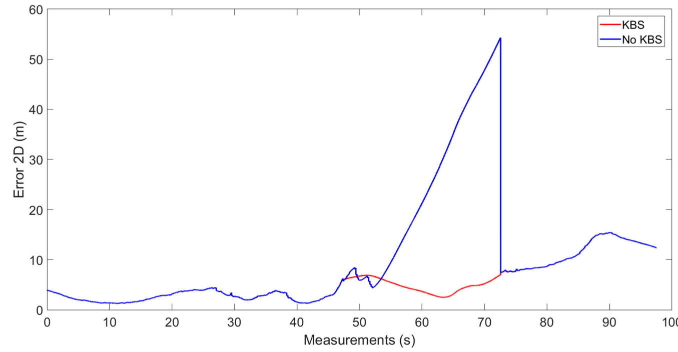

Fig. 11. Error 2D full journey.

V. Results

This section presents the obtained results. The results here shown have been obtained from a 1 month 20h/day run on a CAF 900 series train, operated by Euskotren over Eusko Trenbide Sareak infrastructure.

First of all, the results obtained without the use of the KBS will be presented to later on be compared with the results when the KBS enhancement technique is applied. During this performance evaluation, accuracy and availability results are going to be discussed as they are the main drivers for the railway applications, as presented in the introduction. The accuracy error is assessed by the Euclidean distance in the horizontal plane between the ground truth position and the position estimate.

It is important to mention that the analyzed sector is part of a longer journey and the initial errors are dependent on the previous position estimations. However, the tunnel is reached between the 50^{th} and 70^{th} second. A change of behavior in the error can be observed during the mentioned seconds in Fig. 11.

A. Measurement Campaign Analysis

To be able to make a good comparison between both systems, it is important to use the same observables generated during the test runs when using KBS and when not. Fig. 11 shows the 2D errors computed for both KBS and non KBS operation modes during the whole journey.

However, to analyse the whole journey could quit the focus from the important part of the paper. That is the reason to show

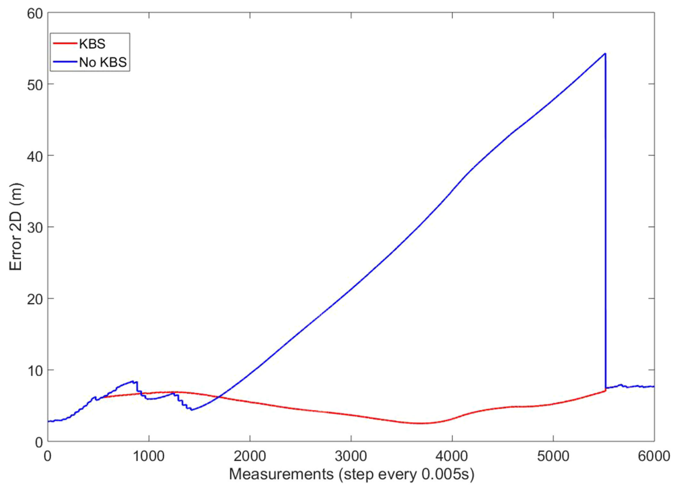

Fig. 12. Error 2D in KBS operation zone.

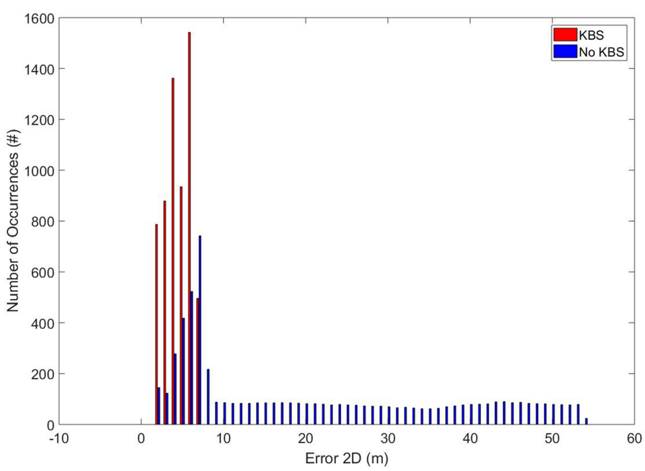

Fig. 13. Histogram of the error 2D.

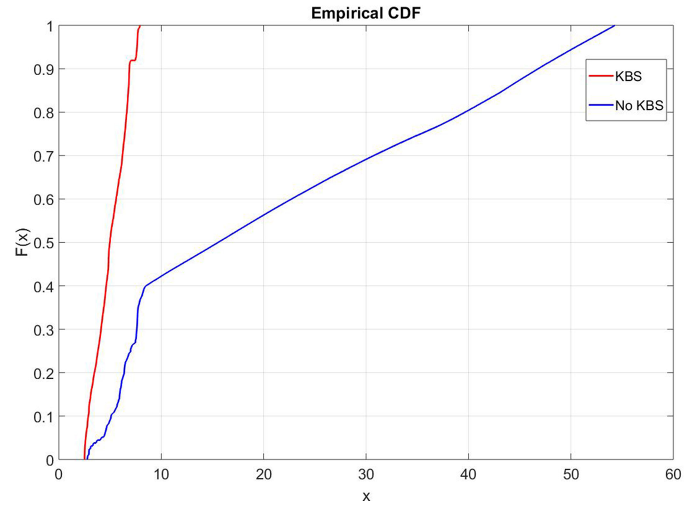

Fig. 14. CDF of the empirical error 2D.

the graphs in the area in which the KBS enters in operation. The focus will show the real improvement of the KBS. Fig. 12 shows the KBS operation zone that is analysed.

The accuracy results of the CPS systems without the KBS, showed an error peak that reached 54.29 meters. It is important to remark that even if the tunnel is almost straight using misleading information can lead to this undesired effects (see Fig. 12). The mean error of this section is 21.15 meters.

In the other hand, when using KBS, the accuracy is significantly better. The maximum error peak is lower than 7.96 meters and the main improvement is that the mean error is reduced to 5.07 meters (See Fig. 12).

Fig. 13 analyses the frequency of the different error during this journey. The error is mainly spread at low error distances; however, when KBS is not being used, there is a long tail with error that reach the aforementioned value of more than 50 meters.

When using KBS, the error is also mainly spread at low error distances; but the maximum error reaches a value of 8 meters, which is smaller than the maximum error obtained without using the KBS.

Having the error as a distribution function, the CDF presents the probability that the error will take a value lower than x. And here it is based on the empirical data obtained. It can be stated that the CDF (95%) is around 50 meters (see Fig. 14). This means that the 95 percent of the time the error is lower or equal to 50 meters.

The CDF obtained from the error information when the KBS is used, bounds the error at 95% in 8 meters (See Fig. 14).

As the graphs show, when the KBS is not used, the error obtained in the tunnel environment decreases the performance significantly and thus improving this matter will have a great impact on the overall picture.

The performance of the KBS improves significantly the performance of the GNSS and IMU dead reckoning algorithm by detecting misleading information of the GNSS.

VI. Conclusion

This paper presents a progress for the positioning systems in the railway sector. One of the key aspects that is important to remark is the need of complementary information sources, on top of GNSS, for the continuous position to provide fully availability at the expense of the accuracy error performance. For most of the railway applications, the availability of the systems is as important as the accuracy. It is necessary to have access to the position of the train during the whole journey. So as to overcome these limitations, the Complementary Positioning System (CPS) has been introduced in this paper with a map aid enhancement software called KBS algorithm.

The CPS gives a positioning alternative to overcome the use of degrade GNSS position due to the introduction of a Known Blocking Scenario software module combined with GNSS and IMU algorithm.

The system presented in this work provides a step forward in railway positioning with a low cost solution approach that allows the discrimination of all the GNSS degraded situations enhancing the availability and overall performance in harsh environments.

The use of the CPS system and its software enhancement modules improves the existing on-board systems and can lead the way to eliminate the trackside equipment which can be useful for applications such as regional train lines or freight tracking in which the requirements are more relaxed than for ETCS level 3.

During the measurement campaign in EuskoTren, the suitability of the KBS to detect and mitigate GNSS shadowed areas in demanding environments is proved with the data of the improvement shown in section V. The maximum error reached is more than six times lower and the mean error is four times lower when the KBS is used. Taking into account the introduced results, the KBS gives the possibility to a positioning system to go through larger tunnels without having to change the existing alert limits. Moreover, the KBS opens the possibility to have better operation limits in the existing positioning systems.

Acknowledgment

The authors would like to express special thanks to their colleagues from EuskoTrenbide Sarea (ETS) and EuskoTren who allowed both measuring campaigns in the project's framework and the use of their infrastructure.

References

[1] ERRAC, "Rail route 2050: The sustainable backbone of the single European transport area," Eur. Rail Res. Advisory Council, Paris, France, Tech. Rep., 2013. [Online]. Available: http://www.errac.org/wp-content/uploads/2013/11/D9-SRRA-RAILROUTE2050.pdf

[2] "Shift2Rail mission and objectives." [Online]. Available: https://shift2rail.org/about-shift2rail/mission-and-objectives/. Accessed on: Oct. 28, 2019.

[3] V. Amdas, T. Bradbury, S. Denniss, D. Chapman, R. Bloomfield, and D. Fisher, "ERTMS level 3 risks and benefits to UK railways (final report)," Transp. Res. Lab., Eur. Railway Traffic Manage. Syst., France, Paris, Tech. Rep. PPCA09094, 2010.

[4] L. Marradi *et al.*, "GNSS for enhanced odometry: The GRAIL-2 results," in *Proc. NAVITEC 2012 Eur. Workshop GNSS Signals Signal Process.*, pp. 1–7.

[5] E. González, C. Prados, V. Antón, and B. Kennes, "GRAIL-2: Enhanced odometry based on GNSS," *Procedia - Social Behavioral Sci. Transp. Res. Arena 2012*, vol. 48, pp. 880–887, 2012.

[6] "GSA. GRAIL-2—Summary," 2012. [Online]. Available: http://grail2.ineco.es/Grail2/html/main.jsp. Accessed on: Oct. 28, 2019.

[7] A. Urech, *GNSS in Rail Safety Applications*. Madrid, Spain: I Rail Technological Forum For Internationalization, 2011

[8] G. Barbu and J. Marais, *The SATLOC Project*, Paris, France: *Transport Research Arena*, 2014.

[9] "GSA. GRAIL-2—Summary." [Online]. Available: https://www.gsa.europa.eu/satellite-based-operation-and-management-local-low-traffic-lines. Accessed on: Oct. 28, 2019.

[10] J. Marais, C. Meurie, A. Flancquart, S. Lithgow, and G. Barbu, "SATLOC. Demonstration of an innovative concept specification and results of simulation tools applied on photographed geo-referenced particular route environment," 2014. [Online]. Available: http://hal.univ-smb.fr/IFSTTAR/hal-01061356. Accessed on: Jan. 22, 2019.

[11] T. P. K. Nguyen, J. Beugin, and J. Marais, "Dependability evaluation of a GNSS and ECS based localisation unit for railway vehicles," in *Proc. 13th Int. Conf. ITS Telecommun.*, pp. 474–479.

[12] "GSC. GaLoROI—Summary," 2014. [Online]. Available: https://www.gsc-europa.eu/markets/rd/fp7-3rd-call-projects/galoroi-galileo-localization-for-railway-operation-innovation. Accessed on: Jan. 22, 2019.

[13] D. Lu and E. Schnieder, "Performance evaluation of GNSS for train localization," *IEEE Trans. Intell. Transp. Syst.* vol. 16, no. 2, pp. 154–1059, Apr. 2015.

[14] "GSA. GaLoROI—Summary." [Online]. Available: https://www.gsa.europa.eu/galileo-localisation-railway-operation-innovation. Accessed on: Oct. 28, 2019.

[15] A. Neri, A. Filip, F. Rispoli, and A. M. Vegni, "An analytical evaluation for hazardous failure rate in a satellite-based train positioning system with reference to the ERTMS train control systems," in *Proc. 25th Int. Tech. Meeting Satell. Division Inst. Navigation*, pp. 2770–2784.

[16] F. Rispoli, M. Castorina, A. Neri, A. Filip, and G. Di Mambro, F. Senesi, "Recent progress in application of GNSS and advanced communications for railway signaling," in *Proc. 23rd Int. Conf. Radioelektronika*, 2013, pp. 13–22.

[17] N. Kassabian, L. L. Presti, and F. Rispoli, "Augmented GNSS differential corrections minimum meansquare error estimation sensitivity to spatial correlationmodeling errors," *Open Access Sensors*, vol. 14, pp. 10258–10272, Jun. 2014.

[18] "ERSAT EAV grant agreement No 640747," [Online]. Available: http://www.ersat-eav.eu/. Accessed on: Jan. 22, 2019.

[19] "RHINOS project summary," [Online]. Available: https://cordis.europa.eu/project/rcn/199612_es.html/. Accessed on: Jan. 22, 2019.

[20] P. Salvatori, C. Stallo, S. Pullen, S. Lo, and P. Enge, "Use of SBAS corrections with local-area monitoring for railway guidance and control applications," in *Proc. IEEE/ION Position, Location Navigation Symp.*, Apr. 2018, pp. 23–26.

[21] STARS Project. [Online]. Available: http://www.stars-rail.eu/project/. Accessed on: Jan. 22, 2019.

[22] B. Stamm and P. Gurnik, "STARS project—Satellite technology for advanced railway signalling," [Online]. Available: http://www.stars-rail.eu/wp-content/uploads/2017/05/STARS-project-Satellite-technology-for-advanced-railway-signalling.pdf. Accessed on: Jan. 22, 2019.

[23] "X2RAIL-2 – Objectives," 2018. [Online]. Available: http://projects.shift2rail.org/s2r_ip2_n.aspx?p=X2RAIL-2. Accessed on: Jan. 22, 2019.

[24] "ERTMS on SATELLITE galileo game changer," Periodic Rep. for period 1. [Online]. Available: https://cordis.europa.eu/project/rcn/212900_en.html. Accessed on: Jan. 22, 2019.

[25] J. Marais, R. Hmida, A. Flancquart, S. Sabina, and M. Ciaffi, "Video-based classification of railway track areas for GNSS-based virtual balise solutions in the ERSAT GGC project," in *Proc. Int. Tech. Meeting Inst. Navigation*, Reston, VA, USA, Jan. 2018, pp. 196–205.

[26] J. Goya, L. Zamora-Cadenas, S. Arrizabalaga, A. Brazález, J. Meléndez, and J. Mendizabal, "Advanced train location simulator (ATLAS) for developing, testing and validating on-board railway location systems," *Eur. Transp. Res. Rev.*, vol. 7, 2015, Art. no. 24.

[27] D.E. Wells *et al.*, *Guide to GPS Positioning*. Fredericton, NB, Canada: Canadian GPS Associates, 1986

[28] A. Noureldin, T. B. Karamat, and J. Georgy, *Fundamentals of Inertial Navigation, Satellite-Based Positioning and Their Integration*. Berlin, Germany: Springer-Verlag, 2013.

[29] R. Chow, *Evaluating Inertial Measurement Units*. Long Beach, CA, USA: Epson Electron. Amer., Nov. 2011.

[30] G. De Miguel, J. Goya, J. Uranga, I. Adin, and J. Mendizabal, "GNSS complementary positioning system performance in railway domain," in *Proc. 15th Int. Conf. ITS Telecommun.*, May 2017, pp. 1–7.

[31] S. Arrizabalaga, I. Adín, G. De Miguel, J. Goya, L. Zamora-Cadenas, and J. Mendizabal, "Data acquisition for complementary positioning system in GNSS denied areas," in *Proc. World Congr. Railway Res.*, 2016, Milan, Italy, pp. 4562–4571.

[32] European Railway Agency, "Performance requirements for interoperability," European Railway Agency, Valenciennes, France, Subset-041, Jun. 2016.

[33] J. Goya, G. D. Miguel, S. Arrizabalaga, L. Zamora-Cadenas, I. Adin and J. Mendizabal, "Methodology and key performance indicators (KPIs) for railway on-board positioning systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 19. no. 12. pp. 4035–4042, Dec. 2018.

Gorka de Miguel received the M.Sc. degree in telecommunications engineering from TECNUN (School of Engineering of San Sebastián), University of Navarra, Donostia-San Sebastián, Spain, in 2015. In 2015, he joined the CEIT-IK4 Research Centre, Donostia-San Sebastián, Spain, where he is currently a Research Assistant and a Ph.D. Student within the Transport and Sustainable Mobility Group. He is also an Assistant Lecturer in Electronic Fabrication Systems with TECNUN. His research interests include the field of positioning and software development. He is now actively participating in H2020 European funded projects in Railway signaling and positioning topics.

Jon Goya received the M.Sc. degree in telecommunications engineering in 2011 and the Ph.D. degree in 2016 from the University of Navarra, Donostia-San Sebastián, Spain. He is currently a Lecturer with TECNUN, University of Navarra, and a Researcher with CEIT-IK4 Research Centre, Donostia-San Sebastián, Spain. His professional research interests include the simulation of on-board positioning system and performance analysis for railway. He has participated in FP7 projects coordinated by CEIT (EATS) and is now actively participating in H2020 European funded and Shift2Rail projects in railway signaling and positioning topics: ERSAT-EAV and FR8RAIL.

Nerea Fernández received the M.Sc. degree in telecommunications engineering from the Faculty of Engineering in Bilbao, University of the Basque Country, Bilbao, Spain, in 2016. In 2017, she joined the CEIT-IK4 Research Centre, Donostia-San Sebastián, Spain, where she is currently a Research Assistant within the Transport and Sustainable Mobility Group. Her research interests include the field of railway signaling specially in zero on-site testing and adaptable communication systems.

Saioa Arrizabalaga received the M.Sc. degree in telecommunication engineering from the Faculty of Engineering in Bilbao, University of the Basque Country, Bilbao, Spain, in 2003, and the Ph.D. degree in engineering from TECNUN, University of Navarra, Donostia-San Sebastián, Spain, in 2009. She is currently a Lecturer with TECNUN and a Researcher with CEIT-IK4 Research Centre, Donostia-San Sebastián, Spain. She is involved in the participation of European research projects, direction of doctoral theses, scientific and technical publications in national and international journals and conferences. She is the Author of the book *Multi-Service QoS Architecture for a Multi-Dwelling Gateway*.

Jaizki Mendizabal received the M.Sc. and Ph.D. degrees in electrical engineering from TECNUN, University of Navarra, Donostia-San Sebastián, Spain, in 2000 and 2006, respectively. He was with Fraunhofer Institut für Integrierte Schaltungen, Erlangen, Germany, and SANYO Electric Ltd, Gifu, Japan, as an RF-IC Designer. He is currently with CEIT-IK4 Research Centre, Donostia-San Sebastián, Spain. He is also a Lecturer of Communications Electronics and Communications via Radio with TECNUN. His research interests include communications and signaling systems for the railway industry.

Iñigo Adin received the M.Sc. degree in electronics engineering in 2003 and the Ph.D. degree in 2007 from the University of Navarra, Donostia-San Sebastián, Spain. He is the Author or Co-Author of one patent, two technical books, an invited chapter, and 40 articles in journals and international conferences. His research interests include safety-critical designs, with special interest in positioning, communications, electromagnetic compatibility, and transport interoperability. He was the Coordinator of the FP7 European Project TREND and now coordinates the H2020 AIOSAT for GSA.