SAtellite-based Signalling and Automation SysTems on Railways along with Formal Method and Moving Block validation

D1.6 - Proposed GNSS Minimum Performance Requirements

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1 Introduction

1.1 Background

The present document constitutes the final deliverable (D1.6) of the WP1 "Introducing GNSS technology in the railway sector" – in the framework of the ASTRail project, a Shift2Rail project complementary to X2Rail-1 and X2Rail-2.
ASTRail focuses on the following four workstreams:
1) Transfer the knowledge of aeronautical standard and existing integrity monitoring solutions to the application of fail-safe moving block location by performing an assessment of local error modelling, hazard analysis and verification activities before proposing minimum performance standards for such equipment for use in the rail domain;
2) Perform Hazard Analysis of the railway system examining safety level of Moving Block Signalling System operating without trackside detection, from technical and operational point of view, along with the hazard identification in the most significant operative conditions defined by the use cases;
3) Identify the most suitable technologies to be implemented in the railway field for performing automated driving;
4) Based on the state of the art, on the past experiences of the partners and on ad-hoc experiments, it will identify the most promising formal and semi-formal methods for the different development phases of railway equipment, and, particularly, for the signalling solutions targeted by ASTRail.

The WP1 corresponds to the first work-stream that focuses on the introduction of GNSS technology into Railway applications by borrowing experience from aeronautical sector. This work stream contributes to the X2Rail-2 WP3 "Fail-Safe Train Positioning (including satellite technology)" that aims to develop a fail-safe, multi-sensor train positioning system by applying GNSS technology to the current ERTMS/ETCS core and by using new technologies (e.g. inertial measurement units) or other on-board existing sensors (e.g. accelerometers, odometer sensors).

Task 1.8 "GNSS Minimum Performance Requirements for Rail" will propose a set of minimum performance requirements for the use of GNSS (and other sensors) in rail. This will include hardware, software, equipment test procedures and operational requirements based on the analysis for Tasks 1.1-1.5 and the design and simulation activities of Tasks 1.6-1.7.
Subtask 1.8.1 "Drafting and feedback of rail MOPS" will be led by SIRTI to ensure rail protocols are followed with regards to standards, whilst significant effort will be performed by ENAC to propose requirements akin to those of aviation yet respecting the analysis undertaken, the rail industry framework and the results obtained in Tasks 1.1-1.7.
Subtask 1.8.2 "Finalization of the Draft Rail MOPS" will involve the completion of a formal document for external dissemination namely the D1.6

The D1.6 is the output of the Tasks 1.8 with the definition of the GNSS Minimum Performance Requirements suitable for the Railways Domain also based on different railways mission operational profiles.
The results of the previous work, done during the analysis of performance of GNSS system in Tasks 1.1-1.5 and the design and simulation activities of Tasks 1.6-1.7, that are documented in the deliverables D1.1-D1.5, will be the base to define a set of minimum performance requirements for the use of GNSS in railways, in combination with the other sensors identified in D1.4,according to the results of WP2 "Safety analysis of Moving block signalling system", in particular the task 2.3 "Hazard identification and risk analysis evaluation", provided with D2.2 "Moving Block signalling system Hazard Analysis".

1.2 Purpose and Scope

The present deliverable responds to the following objectives:

1) To ensure the compliance with rail protocols whilst using GNSS in Moving Block signalling system operating without trackside train detection.
2) To propose minimum performance requirements for the use of GNSS, in combination with the other sensors identified in D1.4, in Moving Block signalling system operating without trackside train detection.

1.3 Related documents

ID	Title	Reference	Version	Date
[RD.1]	D1.1 – Aeronautical Assumptions and Requirements	D1.1 ASTRAIL	5.0	2019-02-01
[RD.2]	D1.3 – The ERTMS hazards associated with GNSS faults	D1.3 ASTRAIL	2.0	2019-01-29
[RD.3]	D1.4 – GNSS Algorithms Design	D1.4 ASTRAIL	1.15	2019-01-18
[RD.4]	D1.5 – GNSS Solutions Report	D1.5 ASTRAIL	1.7	2019-02-28
[RD.5]	D2.1 – Modelling of the moving block signalling system	D2.1 ASTRAIL	2.0	2019-01-29
[RD.6]	D3.2 – Automatic Train Operations: implementation, operation characteristics and technologies for the Railway field	D3.2 ASTRAIL	1.0	2018-02-28

1.4 Deliverable structure

The present deliverable is structured in the following way:

Chapter 2 GNSS based positioning system in VB based architecture gives an overview of the GNSS based position system according to [RD.3] and [RD.4].

Chapter 3 Minimum performance requirements for GNSS in railways presents a set of requirements for the use of Global Navigation Satellite System (GNSS) augmented by the Satellite-Based Augmentation System (SBAS) which in Europe is the European Geostationary Navigation Overlay Service (EGNOS) and based on [RD.1] and [RD.2].

Chapter 4 Localization system in railways summarizes the needs associated to GNSS to fulfill rail specifications.

Chapter 5 Conclusions summarize the main issues of the present deliverable.

2 GNSS Based Localisation System (GBLS)

In the ASTRail project we analysed a GNSS-Based Localisation System for the Moving Block Signalling system according to ERTMS lev.3. In [RD.5] the functional description of moving block system is provided, introducing the Virtual Balise (VB) concept. The existing Physical Balises (PBs) are replaced by GNSS-based virtual balises, that provide the reference location. Furthermore, it has been established that in challenging signal environments, positioning under the VB concept may not be optimal and difficulties arise with respect to proving the safety of the system. An alternative solution is therefore proposed based on hybridisation which may be used under these challenging environments.

Importantly, the use of virtual balises has to enable backward compatibility with existing architectures supporting physical balises to accelerate and simplify their adoption. The system shall detect when the train reaches a virtual balise previously identified and recorded in the map database. Safety related issues emerge in relation to Virtual Balise concept, that are analysed in [RD.2].

2.1 GNSS reference architecture

The reference architecture here shall incorporate the GNSS-Based Localisation System (GBLS) which acts under some conditions like the *virtual balise reader* addressed in previous ASTRail work [RD.2], [RD.3] and [RD.4]. Recall that the virtual balise based positioning system works by setting a VB point on the railway track and determining the passage of the VB point using the position solution from the GNSS receiver. However, as mentioned above and established within the proposed MOPS statements given in section 3 a practical way to address the challenges of the difficult urban environments which impact negatively GNSS signals is for the GBLS to function under different modes. These modes are given as follows:

1. Legacy Mode: The use of the existing physical balises with existing odometry sensors. Under this mode, the localisation of the train is performed using the green boxes as shown in Figure 1. However, through the provision of the PB detection, linking information and track data (which will include reference to the environment i.e. tunnel) provided to the GBLS, it is aware of the environment and will thus not provide positioning information to the central positioning block.
2. Virtual Balise Mode: The use of GNSS positioning is employed to output a message, in the same format as that from the Physical Balise Reader (PBR) but based on a virtual GNSS position. This mode is used in open sky and light suburban locations and is supported by an odometry based threat diagnosis in addition to the inherent SBAS monitoring and an autonomous integrity solution based on Advanced RAIM.
3. Enhanced Odometry Mode: In the enhanced odometry mode, the legacy odometry function is unchanged and from the point of view of the positioning module the input appears very much like the VB mode, except in the fact that very frequent VB messages are provided. Internal to the GBLS however, the function differs to the Virtual Balise Mode in that the existing legacy odometry sensors and GNSS measurements are used to provide an updated position with respect to the previous PB position (note the input from the PBR). This enhanced geometry function is less dependent upon the number of measurements, can place greater weight on Doppler GNSS measurements whose error distributions are less difficult to manage than the code pseudorange.

The global architecture is shown in Figure 1, where the Ground Based Localisation System (GBLS) on-board component contains a GNSS receiver (GNSS RX) to obtain code pseudorange, carrier phase, Doppler and signal strength measurements. A means to obtain Satellite-Based Augmentation System (SBAS) messages either via geostationary satellite (GEO) or through ground data communications is considered as given. Furthermore, the GBLS on-board component has inputs providing track data, for mapping the obtained position solution and aiding threat diagnosis [RD.3], as well as input from the odometry sensors and knowledge of the reading of physical balises (in the diagram shown as passed on through the positioning module but this may equally be directly from the balise reader as a second output). The positioning module itself would not require modification in this case and the system is thus backward compatible to the legacy solution.

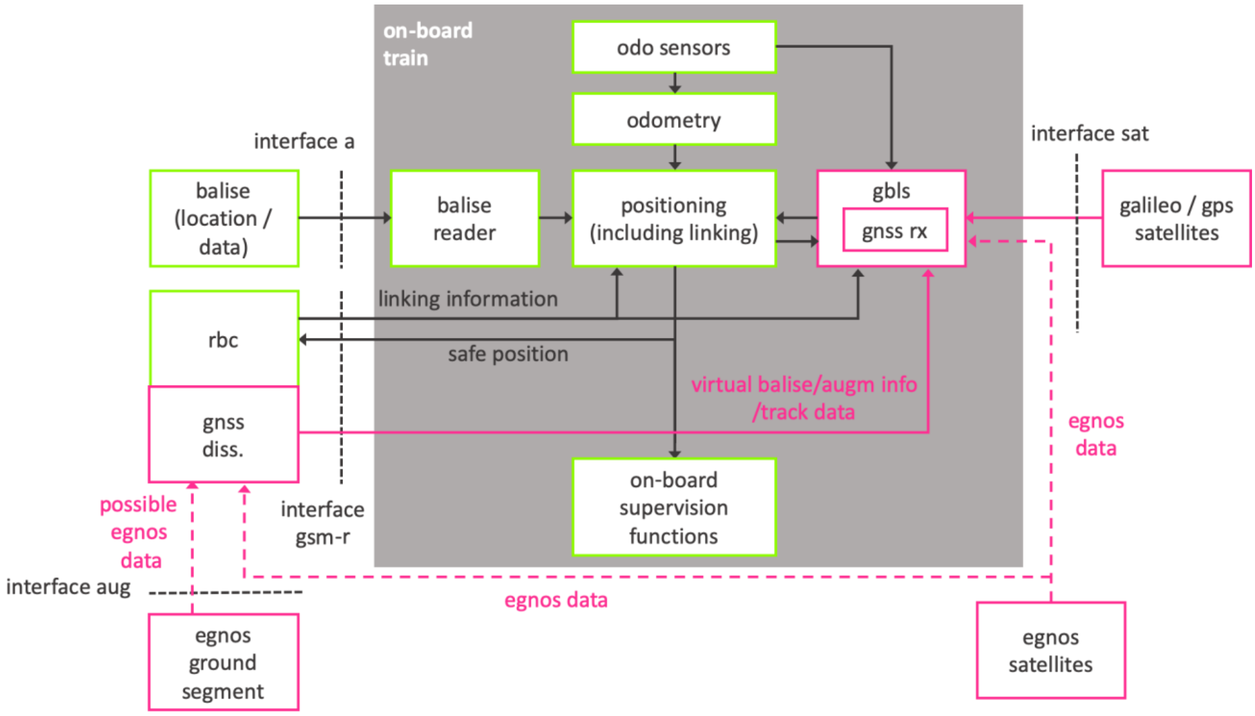


Figure 1 – Reference architecture for localization unit of train

2.1.1 Modal Architectures

In Figure 2, the GBLS architecture elements when in VB mode are highlighted (the actual physical architecture will be a combination of Figure 2 and Figure 3 with the addition of higher level control functions for mode selection and input management). The GNSS receiver performs the measurements before a (weighted) Least Squares Estimation (LSE) which is mapping to the track. Threat diagnosis using in part the odometry is performed as well as an Advanced Receiver Autonomous Integrity Monitoring (ARAIM) scheme. Once the solution is verified and the associated confidence bounds with respect to the position and velocity obtained as computed, the VB message is determined for output to the positioning module.

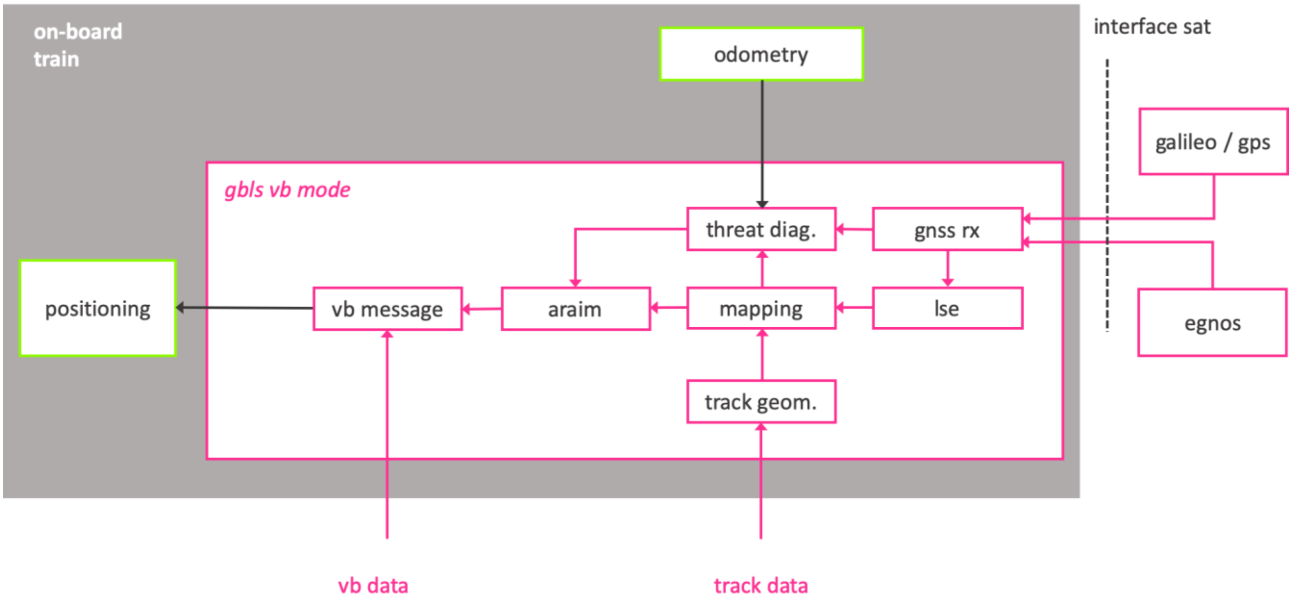


Figure 2 – GBLS Virtual Balise Mode

In Figure 3, the GBLS architecture elements when in Enhanced Odometry (EO) mode are highlighted. In [RD.3] different categories of hybridization between GNSS positioning and complementary systems are classified into three main solutions, namely loose integration, tight integration, ultra-tight integration. The different solutions imply a trade-off between performances and ease of implementation: Due to the limitations of the tight integration (high data rate involved and quality of the data) and ultra-tight integration (specific GNSS receivers needed), the loose integration scheme has been selected.

The physical balise data is used in combination with doppler radar velocity measurements to generate the nominal trajectory. Incremental observations from the tachometer (wheel speed sensor) and GNSS are used to difference from the nominal state as input to the Kalman Filter which then provides the differential states to update the trajectory and output a new message (frequently) to the positioning module.

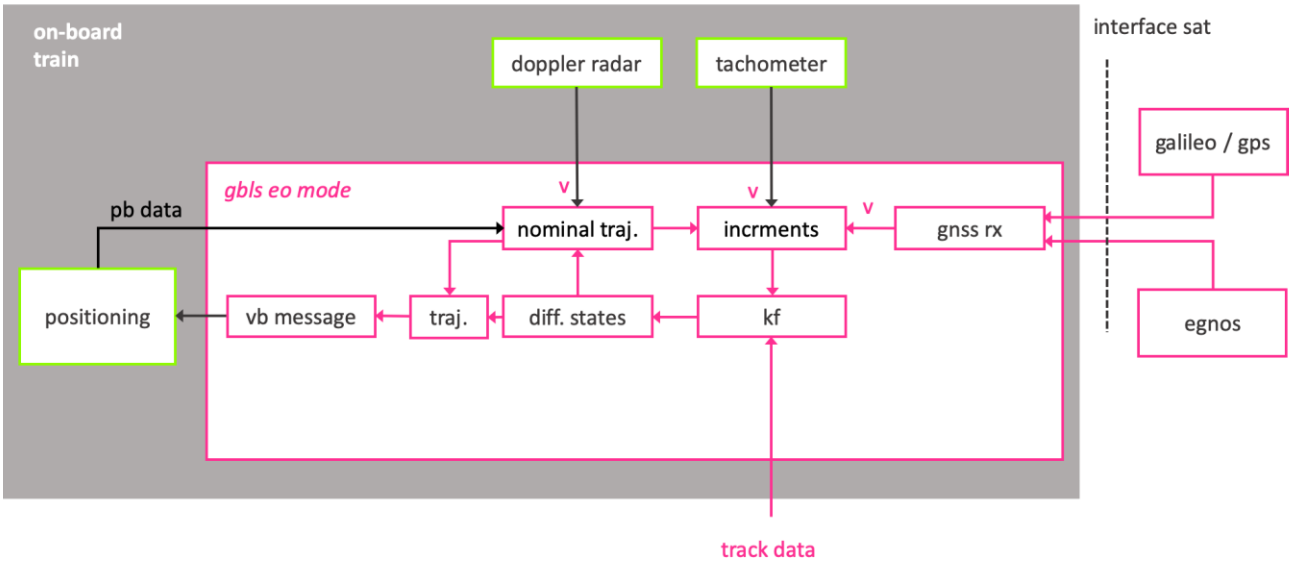


Figure 3 – GBLS Enhanced Odometry Mode

In [RD.4] the loosely coupled integration has been implemented to increase the availability and the precision of the GNSS positioning in the presence of a GNSS impaired environment as described in [RD.3]. To aid the GNSS receiver, two complementary positioning systems based on dead reckoning technology have been analysed, taking into account the state-of-the-art analysis presented in [RD.6].

Name	Description	Issues
Doppler radar	The Doppler Radar-based sensor can measure the speed of a vehicle by measuring the shift in frequency that is observed when the emitted signals from a moving vehicle reflect on the surface. Doppler Radar sensors can measure the speed without being affected by errors due to the wheel slippage or to the ground conditions and they may improve position accuracy if included in the GNSS-centric architecture.	Occasional signal drop outs, noise bursts, snowy weather, extremely smooth surface, vehicle pitch motion, vibrations impact on the accuracy
Wheel odometer	The wheel odometry is based on the measurement of the number of revolutions of the wheels. The motion of the vehicle can be computed using vehicle kinematic equation starting from the number of wheels' revolution.	The odometry is currently exploited for train positioning and is among the ETCS safety on-board interfaces.

Table 1 – Complementary technologies for GNSS system

Tests performed according to the following Figure 4 are described in [RD.4].

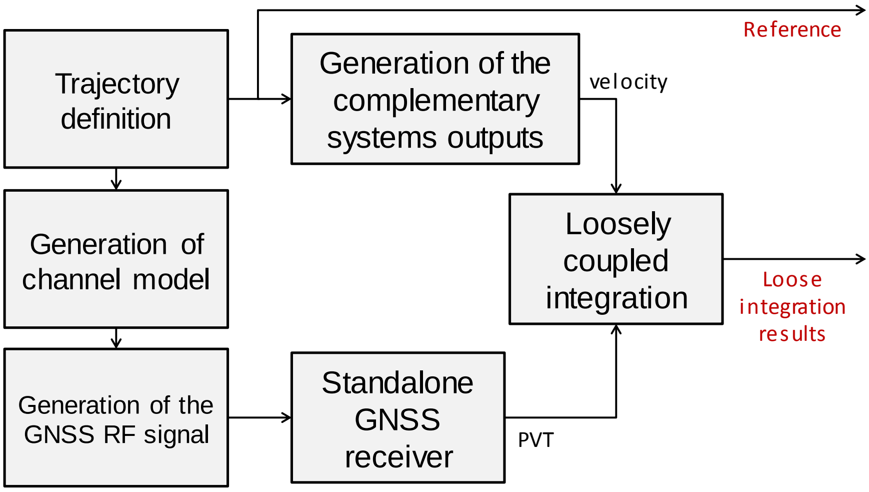


Figure 4 – How the tests are performed on the loose integration algorithm

The tests lead to the following remarks:

- the integration of Doppler radar and odometer is needed to cope with outages of the GNSS signal;
- the integration of Doppler radar and odometer greatly helps to limit the positioning errors which affect the GNSS receiver;
- the use of GNSS helps to prevent the drifting of the position which characterizes the dead reckoning system when the position is got from the use of the Doppler radar alone;
- the presence of a physical balise is much useful to limit the positioning errors in the start of mission conditions.

2.2 Environments

In the GBLS, the on-board subsystem determines which mode to operate under, based on the track data which contains an index to the environment classification described in the standards proposed in section 3. Since trains move from favourable GNSS conditions, known as open-sky conditions, through urban canyons which are areas in which signals are susceptible to disturbances leading to significant errors and into tunnels for which signals are entirely blocked. This differs from aeronautical standards in which only classifications with respect to equipment types relating to the level of integration of displays and controls are needed.

An alternative to the proposed classification would be for the railway infrastructure manager to separate the network into areas in which the legacy solution (based on physical balises and odometry) applies and areas in which GNSS may be used. However, whilst this could account for tunnels, it would not take into consideration the strong variation in performance between open-sky and urban environments. In any case there would need to be some mechanism within the on-board system to determine whether to use the legacy approach or the GNSS-based solution.

An attempt has been made therefore to classify the local environment. This classification could be invariant with respect to time or a function of it. The latter; however, presents in the view of ASTRail an unnecessarily complex solution that would require significant data collection, analysis offline prior to rail operations as well as heavy communication during operations. Whilst this approach was studied and is not ruled out as a potential future aspect of a GNSS Based Localisation System (GBLS), a fixed classification was preferred in this work and is used in the proposed MOPS. Environments are split into seven categories as a function of the minimum, average and maximum number of visible and blocked satellites over the combined constellation (GPS and Galileo) cycle with respect to the local terrain and infrastructure topographic databases. Each location along the track (at distances of 10m in this work) is assigned an environment class through this offline work, that would be provided in the form of a database or through communication to the train. An example of such a classification is shown below (the details to how this classification is arrived at are given in section 3.11.

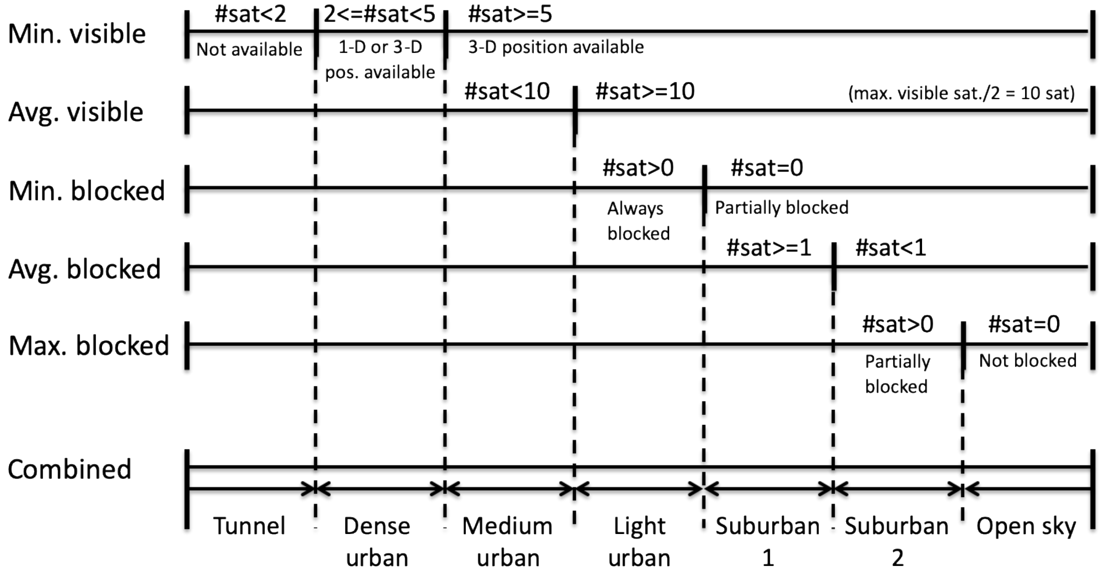


Figure 5 - Environment Classes

2.3 Operational scenarios

In [RD.3] the operational scenarios that mostly benefit from the introduction of complementary technologies are identified on the following specific situations and conditions, taken from Implementation Characteristics (ICs) and Operation Conditions (OCs) described in [RD.6]:

- Environmental Implementation Characteristics (ICEs):
  - *ICE-3 – GNSS availability and reliability*: defining the more likely environment characteristics having an impact on the GNSS system, i.e. open-space/restricted/urban scenarios
- Positioning Operation Conditions (OCPs):
  - OCP-2 – *Start of mission*: demanding for the initialization of the absolute position of the train at the start of the trip
  - OCP-3 – *Stop at the station*: demanding for precise positioning of the train at a station stop to avoid any potentially dangerous situations
  - OCP-4 – *Positioning in closed environment*: where the GNSS system's unavailability has to be compensated with other positioning sources, such as radio signal based systems, dead reckoning methods, landmarks positioning, cooperative positioning, etc…

The operational scenarios examined for the GNSS positioning are resumed in the following table from [RD.3].

Operational scenario	Positioning issues and challenges	Reference IC and OC
In station	- GNSS localization in station could be difficult because of a *poor or blocked sky visibility and the presence of multipath*. - At the start of mission, on-board odometry and/or inertial systems are useless in the absence of an absolute position - The localization in station is required to be especially precise.	ICE-3 OCP-2 OCP-3
	- GNSS localization in tunnels is impossible because of the	ICE-3

	absence of satellite signals (outage) - Inertial systems and/or on-board odometry, combined with digital maps, provide availability of the position estimate, but the inertial solution may drift and such drift is dependent on the length of the tunnel.	OCP-4
In proximity of major railway exchanges and parallel branches	- GNSS standalone could have difficulty in achieving the necessary accuracy to discriminate among several close tracks.	ICE-3 No specific OC for ATO

Table 2 – Target operational scenarios

2.4 High-Level Requirements

As eluded to in the previous section, requirements are not general across all rail operational scenarios and environments. Significant previous work has been undertaken on capturing attempts to define GNSS requirements for the rail sector [1]. The high integrity requirements of the railway sector are difficult to satisfy with a stand-alone GNSS receiver: the signals are affected by the ground environment such as terrain, buildings and tunnels and the requirements extend below the 10^{-9} level. Furthermore, at such a safety integrity level, rail requirements must be met through the provision of multiple functions. Table 3 shows a selection of high-level requirements from [1]. Continuity requirements are omitted since they ultimately derive from availability requirements.

Operation	Accuracy	Integrity	TTA	Availability (%)
Start-Of-Mission	N/A	10^{-9}/hr	<10s	99.99
Low-Density/Speed	25	10^{-9}/hr	<1s	99.99
Medium-Density/Speed	10	10^{-9}/hr	<1s	99.99
High-Density/Speed	1	10^{-9}/hr	<1s	99.99
Station	1	10^{-9}/hr	<10s	99.99

Table 3 – GNSS requirements for rail

It is also noted that alert limit requirements are further omitted from Table 3. It is envisaged in this solution that the train's processing of the movement authority takes in to consideration the obtained protection level. This approach optimises performance because it does not heavily restrict and penalise the localisation system when under more challenging conditions. Instead, under such challenging conditions, a larger protection level is computed which ultimately leads to a lower speed of operation or greater separation between trains under the moving block. Further details are given in section 3.10.

Accuracy requirements are generally expected to apply in an average risk sense, whilst integrity requirements are safety critical and apply in a specific risk manner (i.e. reasonable worst cases are assumed).

There may be multiple monitoring and diagnostic steps. The solution proposed in this report assumes monitoring within the SBAS ground segment, on board the train with both ARAIM and an odometry based diagnostics. The combination of the outcome of the monitoring and the true system state determines which of the operational states the system is in. Figure 6 shows the results of this offline hypothetical analysis. A positioning failure as defined above occurs when the position error (PE) exceeds the protection level (PL). Under this event and corresponding lack of detect, an integrity event occurs which is equally a lack of safety. The detection of a fault by the monitoring solution, employing the various elements (SBAS, ARAIM, Odometry), leads to a lack of continuity as shown in Figure 6. As described in section 3, ARAIM contains an exclusion capability than can allow the system to return to normal operation in the event of a detected fault. The figure is thus a simplification of Figure 9.

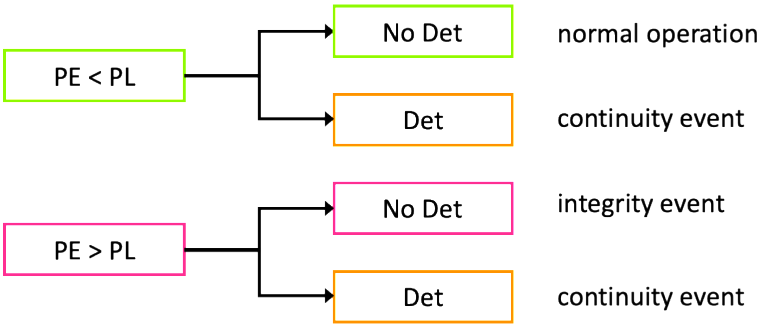


Figure 6 – Integrity/Continuity States

Detection is no longer specified as a simple function of GNSS parameters as a requirement to be met. Rather, the task will be to determine at principally what speed the train may operate at a particular location for 99.9% of the time. The train may always operate at a lower speed due to an increased protection level.

Figure 7 below shows the various contributors to the protection level which determines the availability at a certain operational speed. Protection levels are partly determined by the available satellites (as well as the error models and high level requirements, integrity allocation) which may be subject to the effect of signal loss due to a variety of causes, both predictable and not, and also subject to the detection and subsequent exclusion of satellites from faults or false detection of faults.

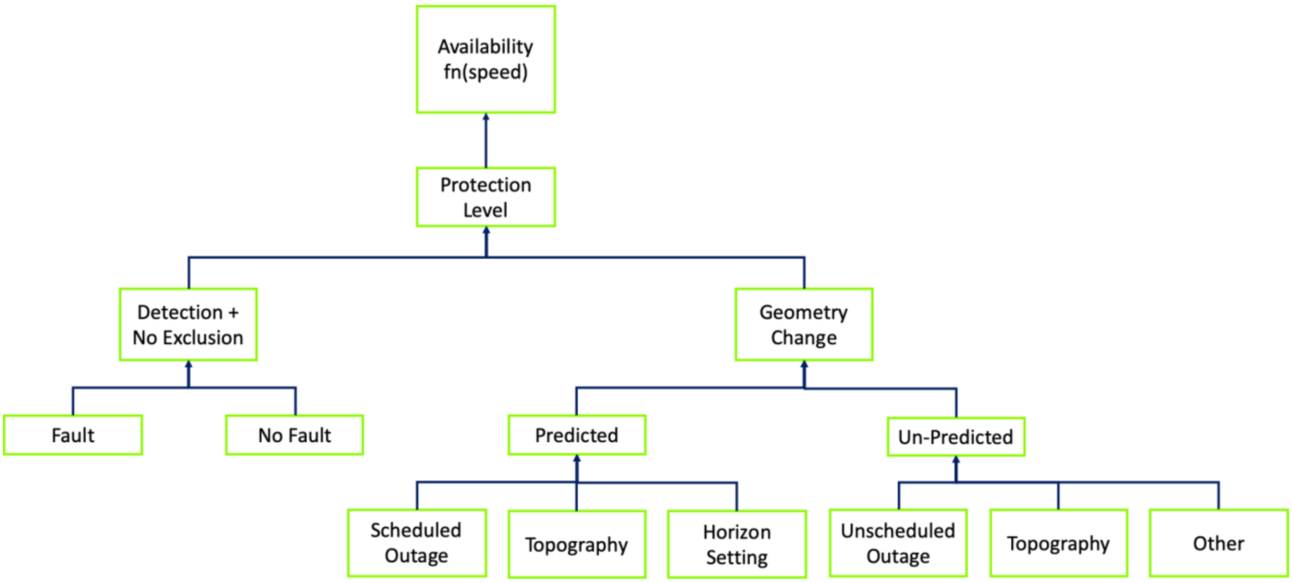


Figure 7 – Availability

3 Minimum performance requirements for GNSS in railways

In this chapter an initial set of Minimum Performance Requirements are proposed for the GNSS Based Localisation System (GBLS) for rail.

3.1 Scope

This Chapter contains minimum performance standards (MOPS) for localisation equipment using the Global Navigation Satellite System (GNSS) augmented by the Satellite-Based Augmentation System (SBAS) which in Europe is the European Geostationary Navigation Overlay Service (EGNOS). Requirements in this document are stated with a ‘shall’ statement whilst recommendations are identified with a ‘should’ statement.

Paragraph 3.2 contains an overview of the localization system and the role of the GNSS constellations, SBAS and additional sensors.
Paragraph 3.3 contains the key terms and definitions employed within the standards.
Paragraph 3.4 contains the high-level operational goals and relations to the high-level requirements.
Paragraph 3.5 specifies the environment classes critical to the development of these standards.
Paragraph 3.6 provides the considerations related to mapping the rail network to the environment classes.
Paragraph 3.7 provides test considerations.
Paragraph 3.8 presents the assumptions taken and the methods to be implemented within the solution.
Paragraph 3.9 provides the bulk of the requirements.
Test procedures are given in paragraph 3.10.

3.2 System Overview

The GNSS Based Localisation System (GBLS) is a multiple layer GNSS augmentation to the core constellations (GPS, Galileo,...) that with the aid of SBAS corrections provides integrity and performance information to support rail localisation operations. SBAS implementations (WAAS, EGNOS,…) are safety critical systems consisting of a reference receiver network and integrity monitoring sites to assess GNSS constellation performance.

SBAS reference stations are widely dispersed and contain GNSS/SBAS ranging receivers that monitor signals from the core constellations. The measurements are used by the central data processing facilities to determine differential corrections relating to the orbit and clock errors of the satellites, and ionospheric delay information in the original Single Frequency (SF) formulation. Furthermore, they verify the quality of the corrections through bounding.

GNSS is a world-wide position and time determination system that uses satellite ranging signals to determine user location. It encompasses all satellite-based positioning systems including GPS and Galileo.

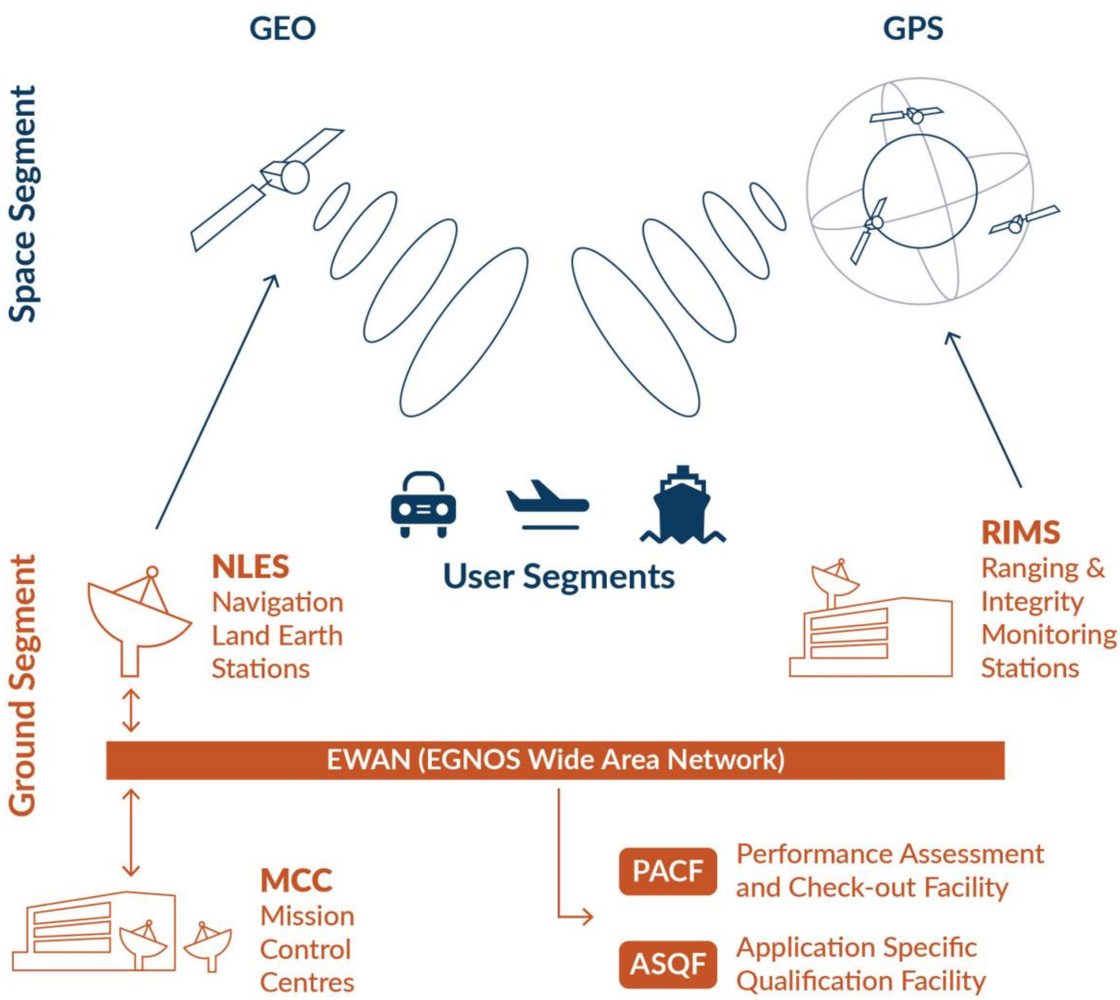


Figure 8 – EGNOS Architecture [2]

3.2.1 GPS Signals

GPS ranging signals are generated on multiple carrier frequencies including the GPS L1 frequency (1575.42 MHz) and L5 frequency (1176.45) which both lie in ARNS protected frequency bands. Pseudo-random noise (PRN) codes are modulated onto the carrier, the L1C/A code at a rate of 1.023 MHz and the L5 code at a rate of 10.23MHz. The user receiver computes a pseudorange to the satellite by the travel time of the signal. Low rate navigation data messages are modulated (50 symbols per second on the L1C/A signal) which define the satellite orbit, system time, clock corrections, health and accuracy of the measurements obtained. The receiver is then able to compute its position in the relevant coordinate frame (World Geodetic System 1984 – WGS-84 for GPS) in addition to a receiver clock offset.

3.2.2 Galileo Signals

Galileo ranging signals are generated on multiple carrier frequencies including the E1 frequency (1575.42 MHz) and E5a frequency (1176.45) which both lie in ARNS protected frequency bands. Pseudo-random

noise (PRN) codes, are modulated onto the carrier, the E1 code at a rate of 1.023 MHz and the E5a code at a rate of 10.23MHz. The user receiver computes a pseudorange to the satellite by the travel time of the signal. Low rate navigation data messages are modulated (250 symbols per second on the E1 signal and 50 symbols per second on the E5a signal) which define the satellite orbit, system time, clock corrections, health and accuracy of the measurements obtained. The receiver is then able to compute its position in the relevant coordinate frame (Galileo
Terrestrial Reference Frame - GTRF) in addition to a receiver clock offset.

3.2.3 SBAS Signals

The SBAS signal is transmitted from geostationary satellites on the L1/E1 frequency (1575.42 MHz) band at 500 symbols per second.

3.3 Definition of Key Terms

A glossary of terms and acronyms is provided at the end of the document. This paragraph expands on some key terms.

3.3.1 General

Availability: The availability of the localisation system is the proportion of time for which it has the ability to provide the required function and performance. It is an indication of the ability of the system to provide a usable service at a specific point on the network.

Continuity: Continuity is the ability of the localisation system to provide a continuous solution over a specified period of time without interruption.

Misleading Information: Misleading information is defined to be any localisation solution that is output containing an error larger than the relevant alert limit or protection level, without any indication of the fault within the time-to-alert

Localisation mode: The localisation mode refers to the equipment operating to meet requirements for a type of rail operation (start of mission, station parking, high speed line,…) and under certain environmental conditions designated by the respective classification as described in §3.5.

SBAS Sigmas: Parameters derived from SBAS messages including the SBAS UDREI which specifies the quality of the error bounding related to satellite position and clock errors.

3.3.2 Alert Limits and Protection Levels

Along-Track Alert Limit: The along-track alert limit (ATAL) is the interval in the tangential along track direction which its midpoint at the true position, that must contain the estimated position with the required probability specified for the localisation mode.

Cross-Track Alert Limit: The cross-track alert limit (XTAL) is the interval in the normal cross-track direction which its midpoint at the true position, that must contain the estimated position with the required probability specified for the localisation mode.
Along-Track Protection Limit: The along-track protection level (ATPL) is the interval in the tangential along track direction which its midpoint at the true position, that is assured to contain the estimated position with the required probability specified for the localisation mode. It is the interval for which the missed alert and false alert requirements are met for the localisation mode.

Cross-Track Protection Limit: The cross-track protection level (XTPL) is the interval in the normal cross track direction which its midpoint at the true position, that is assured to contain the estimated position with the required probability specified for the localisation mode. It is the interval for which the missed alert and false alert requirements are met for the localisation mode.

3.3.3 Fault Detection and Exclusion (FDE) Terms

Fault Detection and Exclusion: Fault detection and exclusion is a receiver process that autonomously provides an element of integrity monitoring for the localisation solution though the use of redundant measurements. FDE is composed of a fault detection function and in the event of detection of a fault, fault exclusion is attempted. By excluding the fault, the localisation system may return to a nominal state without interruption to the service. Figure 9 shows the possible FDE conditions.

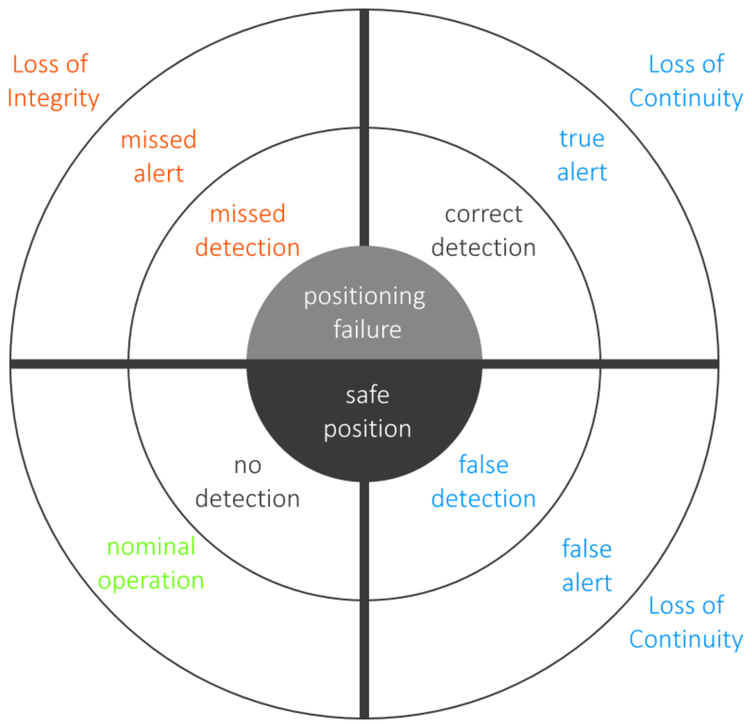


Figure 9 – FDE Conditions

Alert: An alert is an indication to the higher level train functions that the localisation performance does not meet the necessary requirements.

Localisation Failure: A localisation failure is defined to occur whenever the difference in the true position and the estimated position exceeds the applicable alert limit in any of the relevant directions.

Missed Detection: A missed detection is defined to occur when a localisation failure is not detected.

Time-To-Alert: Time-to-Alert (TTA) is the maximum allowable elapsed time from the onset of a localisation failure until the equipment annunciates the alert.

Failed Exclusion: A failed exclusion is defined to occur when a true localisation failure is detected but the detection condition cannot be removed.

Wrong Exclusion: A wrong exclusion is defined to occur following a detection and exclusion, whereby the localisation failure condition remains.

Missed Alert: Localisation failures which are not alerted as a result of a missed detection or wrong exclusion

False Detection: A false detection is defined to occur when a localisation failure is detected although a true localisation failure has not occurred.

False Alert: A false alert is defined to occur when an alert is issued following a detection although a true localisation failure has not occurred.

3.3.4 Localisation Terms

Virtual Balise: A Virtual Balise is based on using GNSS for the detection of position reference. The Virtual Balise Reader is the on-board equipment, that provides continuous train positioning using GNSS and detects Virtual Balises based on pre-known Virtual Balise positions and the train position.

Enhanced Odometry: Enhanced odometry refers to the use of GNSS potentially hybridised with other odometry sensors in order to provide velocity or difference of position updates.

3.4 Operational Goals

We consider the virtual balise concept in a moving block system without trackside detection (see [RD.5]). The ETCS on-board kernel receives from the Virtual Balise reader a time or odometer stamp of the detected virtual balise with the dynamic detection accuracy for resetting of the confidence interval of the train position and the balise information for the detected virtual balise.
Further the Virtual Balise reader has to guarantee the detection of virtual balises in the correct sequence on the track, using the Linking Information for operational modes with a Movement Authority. Linking information provides an advanced list of balise groups that are expected along the route associated with the Movement Authority, including the distance between the groups and their orientation.

An important aspect that we have to take into account is that by means of the virtual balises we are not able to determine the track of the train considering the performance of GNSS receiver in terms of accuracy and integrity. For this reason, we have to consider the need of the presence of physical balises to fulfill the procedures in some operational modes, as start of mission when the train is in the stations or in presence of switches.

The localisation of the train is one of the key functions related to the balise transmission system. In ERTMS the train position is estimated by the distance from the last relevant balise group (LRBG) to the front end of the train measured using ETCS train odometry. Considering the odometer accuracy and the error in the balise group location reference, in ERTMS the accuracy of distances measured on-board shall be better or equal to ±(5m + 5% s), as requested in Subset-041.

As defined in SUBSET-036 the bounding on the location reference of a physical balise is ±1 m for vital purposes, whereas for Virtual Balise detection using GNSS the bounding on the location reference accuracy can change depending on satellite geometry and conditions in the propagation environment. If we consider the error bound for virtual balise VBLREB, the requested accuracy of distances measured on-board becomes ±(VBLREB + 4m + 5% s), considering the same margin as in the case of physical balises and the error on the ERTMS odometry.

This uncertainty and its associated confidence is associated to the train position when we use a GNSS receiver to detect virtual balise and on board odometry, that are different form ETCS requirement for interoperability about accuracy of position and speed reported in Subset -041:

- Accuracy of distances measured on-board: for every measured distance s the accuracy shall be better or equal to ±(5m + 5% s), i.e. the over reading amount and the under reading amount shall be equal to or lower than (5m + 5% s).

- Accuracy of speed known on-board: ±2 km/h for speed lower than 30 km/h, then increasing linearly up to ±12 km/h at 500 km/h.
- Age of speed and position measurement for position report to trackside: The speed and the position of the train front indicated in a position report shall be estimated less than 1 sec before the beginning of the corresponding position report.

3.5 Environment Classes

The on-board train component of the GBLS shall meet requirements at all times in conformance with the local environment class. This is a lower level classification than the operational classes given in section 3.4.

Full Open-Sky: Full Open-Sky conditions are characterised by mostly good signal conditions. At least twelve satellites are visible throughout the network section, all of which are subject to EMM-B or better. All other satellites are subject to EMM-A.

Near Open-Sky: Near Open-Sky conditions are characterised by mostly good signal conditions. At least twelve satellites are visible throughout the network section. A minimum of nine satellites are subject to EMM-B or better. All other satellites are subject to EMM-A.

Light Suburban: Light suburban conditions are characterised by mostly good signal conditions. At least nine satellites are visible throughout the network section. A minimum of nine satellites are subject to EMM-B or better. All other satellites are subject to EMM-A.

Dense Suburban: Dense Suburban conditions are characterised by a mix of poor and good signal conditions. At least six satellites are visible throughout the network section. A minimum of six satellites are subject to EMM-B or better. All other satellites are subject to EMM-A.

Wide Canyon: Wide canyon conditions are characterised by a mix of poor and good signal conditions. At least six satellites are visible throughout the network section of which a minimum of three satellites are subject to EMM-B or better. All other satellites are subject to EMM-A.

Narrow Canyon: Narrow Canyon conditions are characterised by significant signal loss. In a narrow canyon environment at least one satellite is visible along the entirety of the network section and subject to multipath errors under model EMM-A. All other visible satellites are also subject to EMM-A.

Partial Tunnel: Partial Tunnel conditions are characterized by a significant lack or loss of GNSS signals. The percentage of locations for which all signals are lost is less than 20% at a single epoch and the maximum physical length of such a tunneled section is 1km. During operations in tunnel environments, on-board equipment is required to attempt signal acquisition and tracking activities only without additional requirements relating to ranging or localization outputs.

Tunnel: Tunnel conditions are characterized by the consistent lack or loss of GNSS signals. During operations in tunnel environments, on-board equipment is required to attempt signal acquisition and tracking activities only without additional requirements relating to ranging or localization outputs.

3.6 Network Environment Considerations

In order that the on-board train GBLS component is aware of the local environment, it is necessary to assess the environment for the totality of the network for which the GBLS is to be employed. Railway infrastructure management entities are free to utilise various methods including real GNSS data collection, topographic data processing, satellite imagery and LIDAR mapping amongst others. Network sections which are to be classified according to section 3.5 shall be of standard arc lengths of 100m, 1km, 10km and 100km.

The objective is to have an up-to-date database of the entire network signal environment which shall be both stored and broadcast to the on-board GBLS component at the highest data integrity levels

3.7 Localisation Modes

Legacy Mode: Localisation in the legacy mode is based on the existing physical balise and odometry solution.

Enhanced Odometry Mode: Localisation in the enhanced odometry mode is based on the existing physical balise and odometry using the available odometry specific sensors and GNSS measurements.

Virtual Balise Mode: Localisation in the Virtual Balise mode uses the GNSS-centric architecture to position the train at validated virtual balise locations.

3.8 Assumptions and Methods

3.8.1 GNSS Components

This standard is predicated on the use of GPS signals L1 C/A and L5 and Galileo signals E1 and E5a. It is assumed that GPS signals are transmitted in conformance with the GPS Interface Control Document (ICD) IS-GPS-200D [3] and that Selective Availability (SA) is inactive following U.S government policy. Such applications of the standards include assumptions on the constellation slot availabilities. It is assumed that Galileo signals are transmitted in conformance with the Galileo SIS ICD [4]. It is assumed that SBAS ground and space segments will comply with the SBAS Standards and Recommended Practices (SARPs) in International Civil Aviation Organisation (ICAO) Annex 10, Volume I through amendment 90 [5]. Any SBAS failure impacts all users of the service, in this case all trains operating GBLS on the network and in either Enhanced Odometry Mode or Virtual Balise Mode (see §3.7).

3.8.2 Applicability

These standards apply to the use of the GBLS on certified rail networks.

3.8.3 Rail Network Assumptions

We consider the use of GNSS receiver in a rail network using moving block system without trackside detection and with Virtual Balises reader on board of the train, expecting to improve network efficiency and application performance.

Moving block signalling system without trackside detection has to perform the functions of the train protection system and for this task it needs to obtain reliable information about track location and integrity, monitor track status, detect faults, maintain normal operation and carry out actions to assure safe operation in degraded situations.

The system have different limitations, parameters and requirements according to the different environments where we can specify precision, accuracy, reliability, availability and integrity for the GNSS receiver.
The CEN (Comité Européen de normalization) categorizes the rail traffic lines on the base of their services as follows:
a) Mixed traffic lines for passenger trains, speed 80-120 km/h;
b) Mixed traffic lines for passenger trains, speed 120-200 km/h;
c) Mixed traffic lines for passenger trains, speed higher than 200 km/h;
d) Mixed traffic lines for passenger trains incorporating special design characteristics;
e) Dedicated passenger lines for passenger trains, speeds greater than 250 km/h.
As illustrated in [RD.5], considering the number of trains per time interval, we distinguish
- Low density line: less or equal to 2 trains/hour in both directions.
- Medium density line: 3 -11 trains/hour in both directions
- High density line: more than 11 trains trains/hour in both directions

and regarding the type of the line, we distinguish:

- Mainline Rail (MR): principal artery of the system with branch lines, yards, sidings and spurs, operated by a high variety of trains. For capacity reasons, main lines have at least a double track and often contain multiple parallel tracks. The operation speeds correspond to types b to c, and the density is medium to high, the time intervals between running trains are heterogeneous.
- Regional Rail (RR): passenger rail services that operate between towns and cities (local trains and stopping trains). These trains operate with more stops over shorter distances than inter-city rail, but fewer stops and faster service than commuter rail. The operation speeds correspond to types a to b, and the density is low to medium, the time intervals between running trains are quite homogeneous.
- High-speed Rail (HSR): rail transport operating significantly faster than traditional rail traffic, using an integrated system of specialized rolling stock and dedicated tracks. The traffic control and signalling system must guarantee maximum safety and reliability. The main characteristic of these lines is the speed (types c and d), while the density could vary depending on the demand, the time intervals between running trains are quite homogeneous.

3.8.4 Train Automation Assumptions

The Grade of automation (GoA) of trains refers to the process by which responsibility for operation management of the trains is transferred from the driver to the train control system. GoA takes values between 0 and 4: grade of automation 0 would correspond to on-sight operation; grade of automation 4 would refer to a system in which vehicles are run fully automatically without any operating staff onboard. The following table summarize the main characteristics of each possible grade of automation, specifying the basic functions of train operation that are the responsibility of staff and the functions that are the responsibility of the system.

Basic functions of train operation		GoA0	GoA1	GoA2	GoA3	GoA4
		On-sight train operation	Non-automated train operation	Semi-automated train operation	Driverless train operation	Unattended train operation
Ensuring safe movement of trains	Ensure safe route	X (points command/control in system)	system	system	system	system
	Ensure safe separation of trains	X	system	system	system	system
	Ensure safe speed	X	X (partly supervised by system)	system	system	system
Driving	Control acceleration and braking	X	X	system	system	system
Supervising guideway	Prevent collision with obstacles	X	X	X	system	system
	Prevent collision with persons on track	X	X	X	system	system
Supervising passenger transfer	Control passengers' doors	X	X	X	X	system
	Prevent person injuries between cars or between platform and train	X	X	X	X	system
	Ensure safe starting conditions	X	X	X	X	system
Operating a train	Set in/ set off operation	X	X	X	X	system
	Supervise the status of the train	X	X	X	X	system
Ensuring detection and management of emergency situations	Perform train diagnostic	X	X	X	X	System and/or staff in OCC

Table 4 – Grades of Automation

3.8.5 Localisation Integrity Assumptions

The assumptions relating to the integrity of the localisation system are widespread and may not be given here in full. An extensive list of assumptions taken in the aviation domain are provided in [RD.1]. Instead, areas of assumptions are described.

Initially assumptions regarding the use of particular constellations and the availability of satellites within their orbits must be made. The GBLS has assumed at this stage, and based analyses upon, the use of both GPS and Galileo constellations. Further to this, assumptions regarding the long-term presence of such constellations must be taken. This is in light of the period of Glonass operation during which satellites were not replenished thus leading to a reduced constellation size. Both GPS and Galileo make long term guarantees regarding the presence of the minimum constellation and the continued replenishment of that constellation.

The baseline constellations of both GPS and Galileo consist of 24 satellites. It is assumed that this baseline constellation will be visible and operational with the slot availability probabilities as given in [3][6]. It is further assumed that the impact of satellite blockage from terrain and constructions is known to a reasonable approximation. This is not a safety issue when vowed in terms of satellite signal availability.

The GBLS utilises multiple monitoring elements, including the internal SBAS monitoring, on-board ARAIM monitoring and odometry based monitoring. In the case of SBAS, assumptions have been taken internal to the ground segment development, with regards to satellite and constellation fault probabilities. Under a future ARAIM provision, an Integrity Support Message (ISM) will be broadcast that provides verified faulty probabilities for aircraft operations with the equivalent Safety Integrity Level 3.
Assumptions regarding the error models are critical is ensuring a robust and verifiable solution with respect to safety. It is therefore assumed that sufficient validation of the error models to account for the local environment has been undertaken. A model which is a function of the local environment, for example parameterised by the local elevation mask is one manner (beyond a simple partition into urban/suburban/open sky) to improve the verifiability of such models.

3.9 Requirements

3.9.1 GBLS Train Receiver Requirements

The GBLS shall meet requirements relating to the (safety) integrity at SIL4 level. Further allocation of this high level allocation shall be undertaken by the GBLS provider in order to account for all possible sources of potential erroneous position.

The urgency of the Time-To-Alert is tied to the dynamics of the train. However, it must be noted that the movement authority communications are transmitted nominally at 5s intervals. It should be noted that whilst the requirements given in Table 5 are apparently stringent, it is possible under the train functional architecture to use odometry coasting over a few seconds thereby utilising the safe GNSS position obtained in the past.

The availability requirements include the potential outages due to false alarm and actual fault detection, in the events that following exclusion of such detected faults, the same performance level may not be met.

Further details are provided in 3.10.

Operation	Accuracy	Integrity	TTA	Availability (%)
Start-Of-Mission	N/A	10^{-9}/hr	<10s	99.99
Low-Density/Speed	25	10^{-9}/hr	<1s	99.99
Medium-Density/Speed	10	10^{-9}/hr	<1s	99.99
High-Density/Speed	1	10^{-9}/hr	<1s	99.99
Station	1	10^{-9}/hr	<10s	99.99

Table 5 – GBLS Train Receiver Requirements

3.9.2 GBLS Train Models

In this section the breakdown of sources of errors for the GNSS measurements is given. As in previous systems developed in civil aviation, the error sources are grouped into components.

The variance of the pseudorange error is given by:

$$\sigma_i^2 = \sigma_{i,SBAS}^2 + \sigma_{i,train}^2 + \sigma_{i,tropo}^2 \qquad \text{(eq.1)}$$

The variance of the SBAS corrections is given by $\sigma_{i,SBAS}^2$ which may be computed from the SBAS messages based on the relevant standards. The variance associated to the train receiver accounting for the local effects of interference, multipath and noise is given by $\sigma_{i,train}^2$.

$$\sigma_{i,train}^2 = \sigma_{i,noise}^2 + \sigma_{i,multipath}^2 \qquad \text{(eq.2)}$$

The multipath model follows the form:

$$\sigma_{i,multpath} = a_0 + a_1 e^{-a_2\theta} \qquad \text{(eq.3)}$$

Where a_0, a_1 and a_2 are parameters describing the difficulty of the environment. The parameter θ may be the elevation or C/N0 of the satellite signal and a_2 will be set accordingly. The multipath model parameters are as yet to be determined.

	A	B	C
a_0	TBD	TBD	TBD
a_1	TBD	TBD	TBD
a_2	TBD	TBD	TBD

Table 6 - Multipath Model

3.10 GNSS Based Localisation System (GBLS) Foundations

In this section the integrity concept for the GBLS is outlined, avoiding the need for strict alert limits.

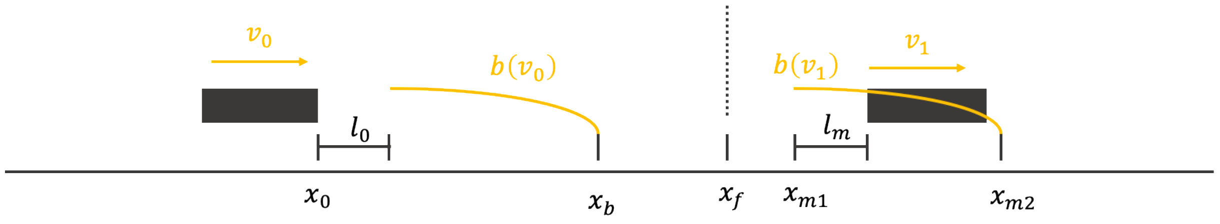


Figure 10 - Fixed and Moving Block

The train on the left of Figure 10 with train head position estimated to be at x_0, is the train whose MA is under question. It is moving with estimated speed of v_0 (to the right) and the along-track protection level (APL) for the position is denoted by l_0 which is guaranteed to bound the true head position in the positive direction with an allocated proportion of the required safety integrity risk (see Figure 12). The velocity protection level l_{v0} is guaranteed to bound the velocity with an allocated proportion of the required safety integrity risk. The braking curve is represented by b and is a function of numerous parameters including the velocity of the train.

Under a fixed block system, the next fixed block into which it is unsafe to move into is defined by the end point x_f. Under the moving block system either, the unsafe zone tail endpoint is defined by x_{m1} which is the estimated tail point of the preceding train x_t minus the along track protection level (APL) of this train l_m. Alternatively, the continued motion and braking curve of the preceding train may be account for leading to x_{m2}.

In order for the train to continue at the current speed under the current MA it must be sure that in the following time interval it is not possible for:

$$\boldsymbol{x_b > x_m} \quad \textbf{(eq.4)}$$

Where either:

$x_m = x_f$ fixed block

$x_m = x_{m1}$ moving block

$x_m = x_{m2}$ advanced moving block with braking

The position x_b may be computed as:

$$\boldsymbol{x_b = x_0 + l_0 + b_{min}(v_0 + l_{v0}; params)} \quad \textbf{(eq.5)}$$

Here the braking curve is the minimum efficiency curve (longest braking distance) given the operational and environmental conditions of the train and as a function of the maximum bounded velocity $v_0 + l_{v0}$.

The other positions are computed as.

$$\boldsymbol{x_{m1} = x_t - l_m} \quad \textbf{(eq.6)}$$

$$\boldsymbol{x_{m2} = x_t - l_m + b_{max}(v_1 + l_{v1}; params)} \quad \textbf{(eq.7)}$$

Here the braking curve is the maximum efficiency curve (shortest braking distance) given the operational and environmental conditions of the train and as a function of the maximum bounded velocity $v_1 + l_{v1}$.

In the above analysis timing has been omitted and the system has thus been analysed assuming both instantaneous communication and MA update intervals.

Consider now a system which has a communication interval Δt. This might be the European standard 5s, or some national standards (e.g. 7s) or also include the possibility of missed communications from either the train in question or the preceding train.

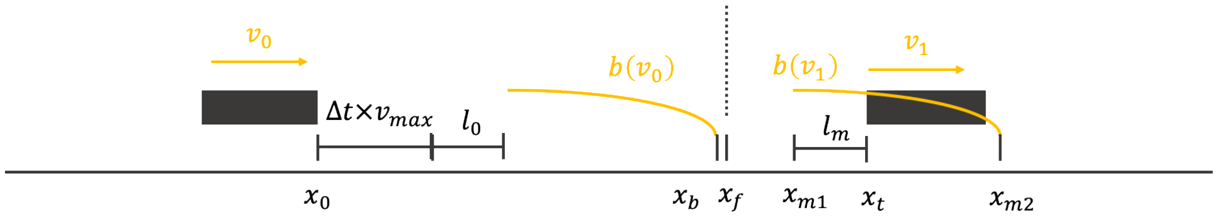


Figure 11 - Fixed and Moving Block with Communication Delay

The updated bound of x_b is then

$$\boldsymbol{x_b = x_0 + l_0 + (\Delta t \times v_{max}) + b_{min}(v_0 + l_{v0}; params)} \quad \textbf{(eq.8)}$$

Where:

$$\boldsymbol{v_{max} = v_{\max\_MA} + l_v} \quad \textbf{(eq.9)}$$

For high-speed trains, with $v_{\max\_MA}$ up to 350km/hr and using $\Delta t = 5s$, the system delays alone are up to 500m and braking distances maybe be several kilometres. A protection level of the order of 100m, or even 500m will not be the primary determining factor in restricting the headway between trains and the capacity of the lines.

It remains now to determine an integrity concept in order to obtain the protection levels discussed above. Such an integrity model should be addressed for both the Virtual Balise (VB) mode and the Enhanced Odometry (EO) mode. Firstly, the VB mode is treated. Figure 12 below shows part of an integrity allocation for the VB mode using a default risk value of 10^{-9} per hour. This risk may be modified as the top level requirement. It is understood as a rate (λ_{IR}), meaning that it applies to any hourly period and operations which are shorter or longer than this requirement would be allocated a risk value in accordance.

$$\boldsymbol{IR_{\Delta t} = 1 - e^{-\lambda_{IR}\Delta t} \cong \lambda_{IR}\Delta t} \quad \textbf{(eq.10)}$$

The risk is allocated between the fault-free case and the faulty case. Under the fault-free state, no constellation, ground segment or satellite failures are left undetected by the SBAS monitoring capability for longer than the required Time-To-Alert which is addressed below. This also applies to faults with a cause originating within the SBAS augmentation itself. A default allocation of 50% of the total budget is assigned to the fault-free case. Under the fault-free hypothesis

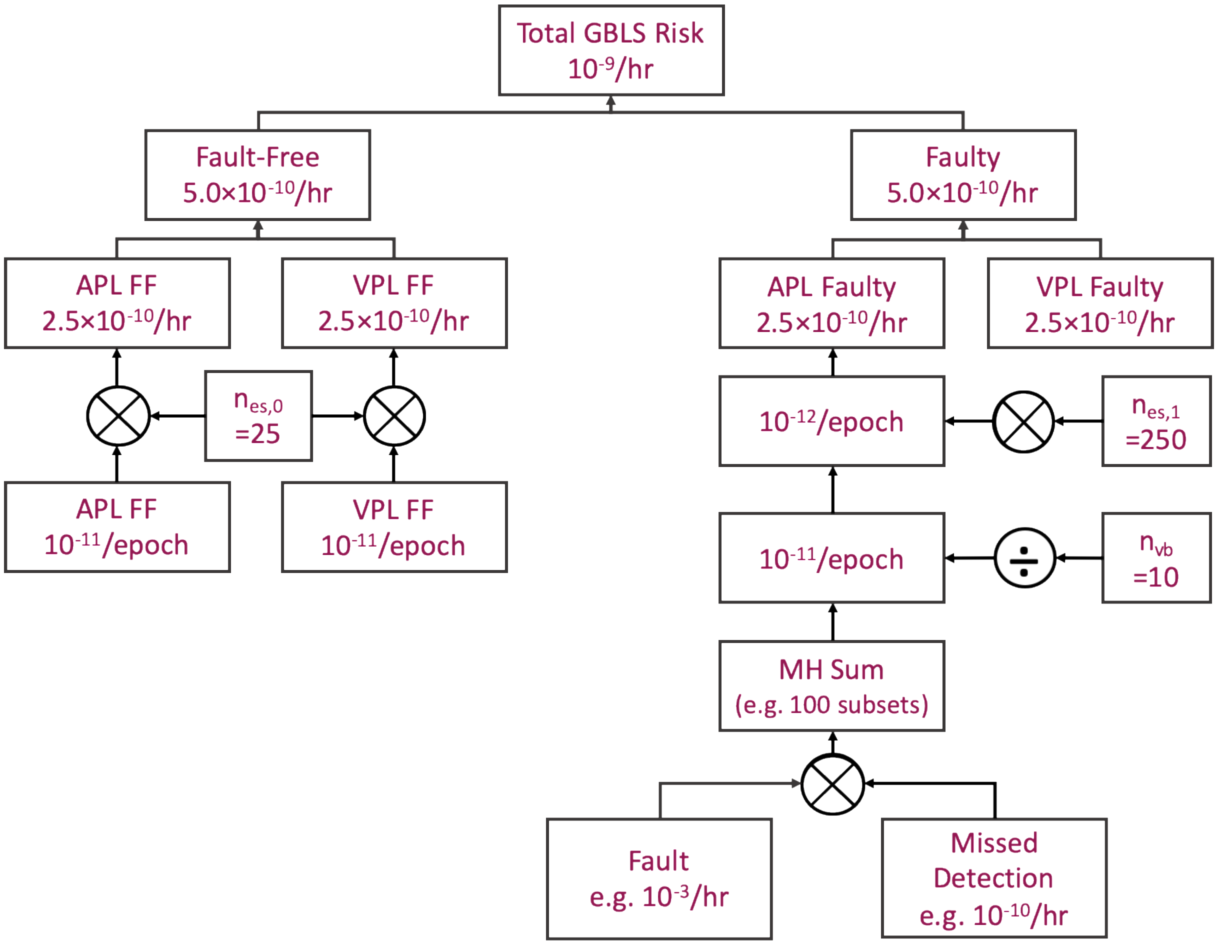


Figure 12 - Safety Integrity Allocation

For the fault free case, the analysis is simple:

$$l_a = k_{ff\_a}\sigma_a \quad \text{(eq.11)}$$

$$l_v = k_{ff\_v}\sigma_v \quad \text{(eq.12)}$$

$$k_{ff\_a} = k_{ff\_v} = Q^{-1}(1.25 \times 10^{-10}) = 6.33 \quad \text{(eq.13)}$$

$$\sigma_a{}^2 = \sum_{i=1}^{i=n} s_{ai}^2\sigma_i^2 \quad \text{(eq.14)}$$

$$\sigma_v{}^2 = \sum_{i=1}^{i=n} s_{vi}^2\sigma_i^2 \quad \text{(eq.15)}$$

$$s_a = e_a{}^T S = e_a{}^T(G^T W G)^{-1} G^T W \quad \text{(eq.16)}$$

$$W = \Sigma^{-1} = \begin{pmatrix} \sigma_1^2 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \sigma_n^2 \end{pmatrix} \quad \text{(eq.17)}$$

$$\sigma_i^2 = \sigma_{udre}^2 + \sigma_{iuve}^2 + \sigma_{tropo}^2 + \sigma_{local}^2 \quad \text{(eq.18)}$$

Or with iono-free DF SBAS

$$\sigma_i^2 = \sigma_{udre\_df}^2 + \sigma_{tropo}^2 + \sigma_{local\_df}^2 \quad \text{(eq.19)}$$

For the faulty case apply an SBAS-ARAIM concept with prior probabilities for each satellite fault event as follows:

$$P_{fail} = P_{sbas} + P_{local} \quad \text{(eq.20)}$$

$$P_{sbas} = 10^{-7} \quad \text{(eq.21)}$$

$$P_{local} = f(C/N_0, env) \quad \text{(eq.22)}$$

Constellation failures are rendered negligible by the SBAS monitoring.

The P_{local} is a function of the environment and the signal power. In this respect, various NLOS and extreme multipath mitigation strategies would be put in place that would enable a reduction in the obtain values. These include:

- C/N0 weighting
- C/N0 cutoff
- MF C/N0 comparison

3.11 Environment Classification Studies

In this section, supporting work on practical ways to define different environment classes are given. Traditionally, GNSS environments have been classified into Open Sky, Suburban and Urban Canyon environments, often in an ad hoc manner. In this work, a new scheme is proposed based on the number of visible and blocked satellites when considering the GPS and Galileo constellations. The method could be extended in a simple manner to other constellations or three or more constellations in use.

The first decision taken in this approach is to consider each location (such points are separated by 10m) over the cycle of the constellation geometries, rather than defining environment classes per time point or per satellite. Differences with respect to the error and fault models as a function of satellite and time will be accounted for by C/N0.

The methodology proposed here is demonstrated through application to a main line passing through Ile-de-France, the greater Parisian region of France. Figure 13 shows the region's rail networks and county borders whilst Figure 14 and Figure 15 show the sections within Google maps.

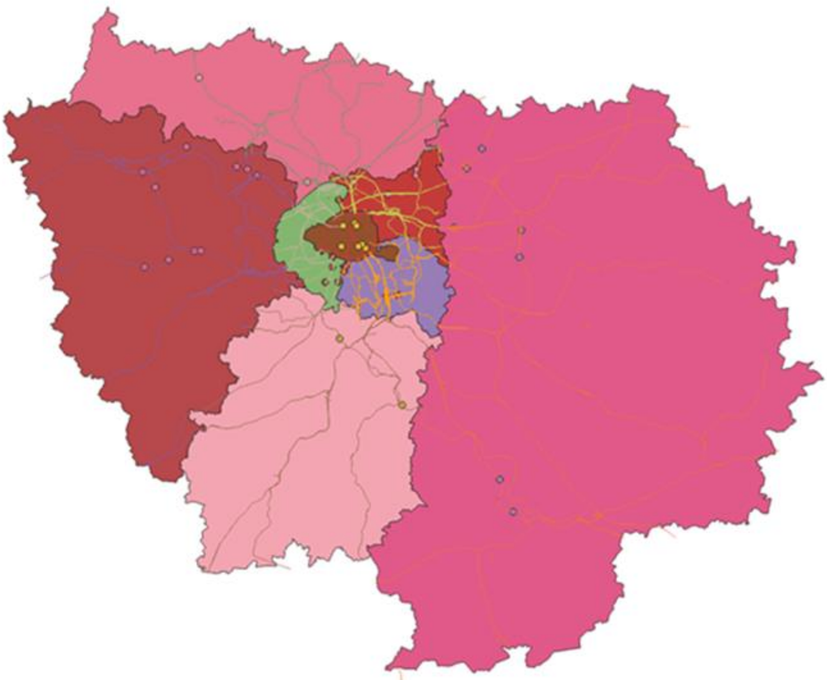


Figure 13 - Ile de France Rail Network

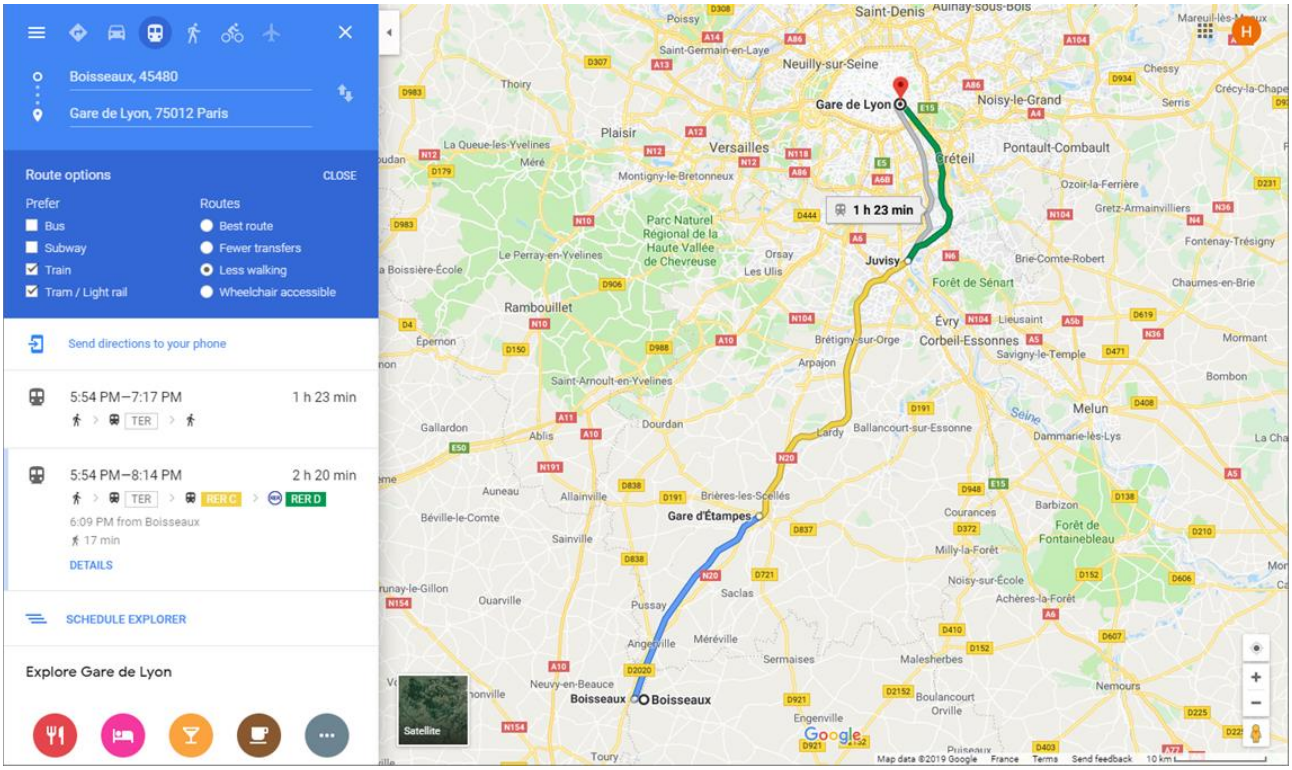


Figure 14 - Selected Route

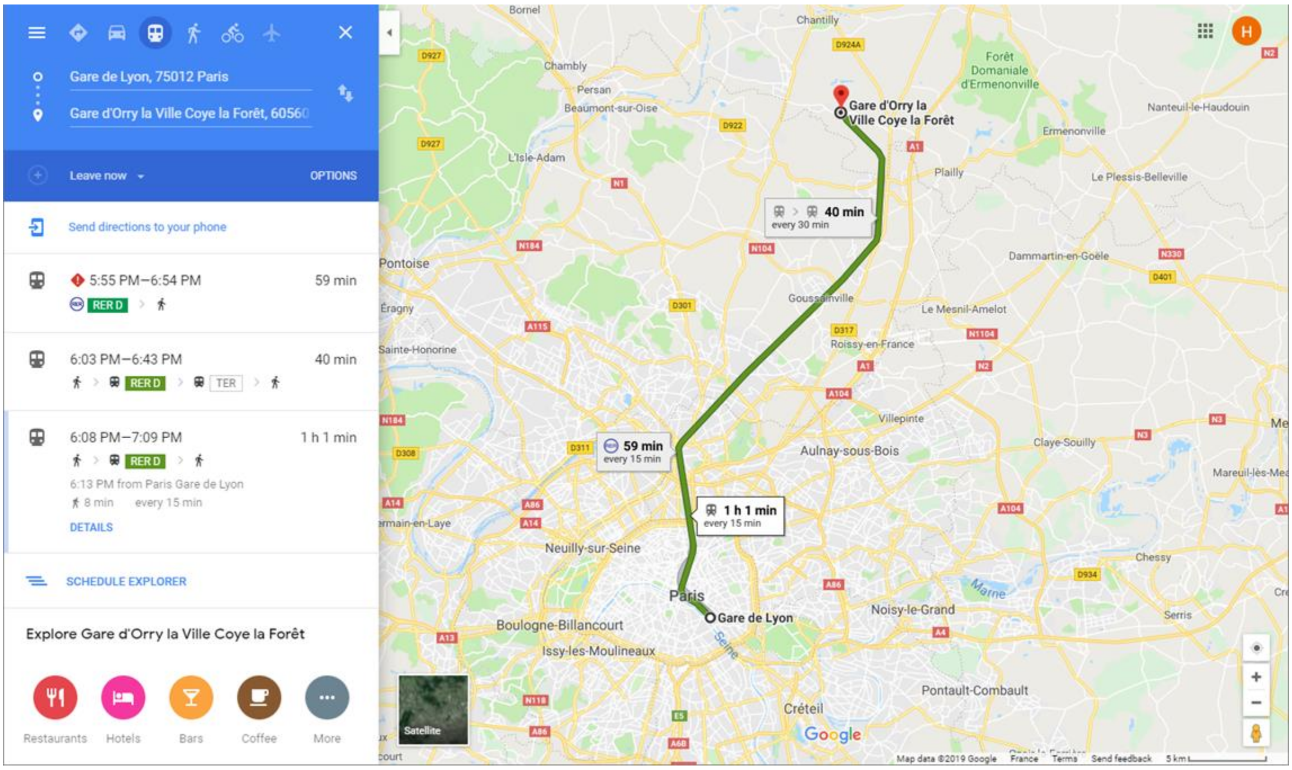


Figure 15 - Selected Route

This route was selected in order to provide a wide range of environments, including significant satellite signal blockage and likely extreme multipath. The route also contains a tunneled section which is highlighted in Figure 17. In Figure 18 the height of the track is given which shows a lack of continuous data through the tunneled section. In Figure 19 the GIS data is presented also showing the tunneled location.

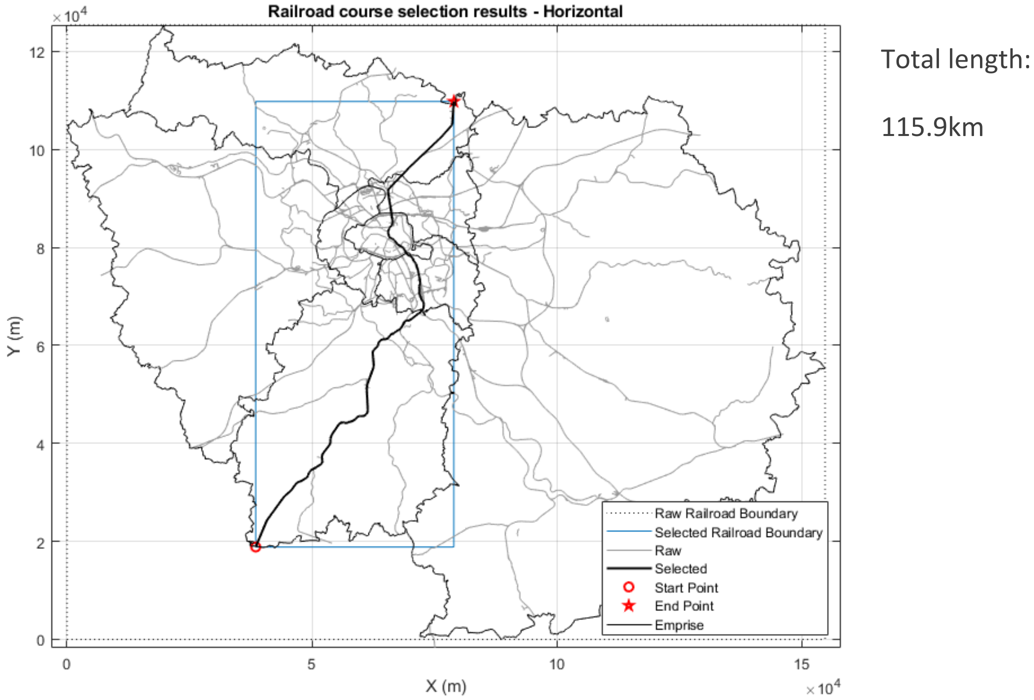


Figure 16 - Track of Interest

X (m) $\times 10^4$

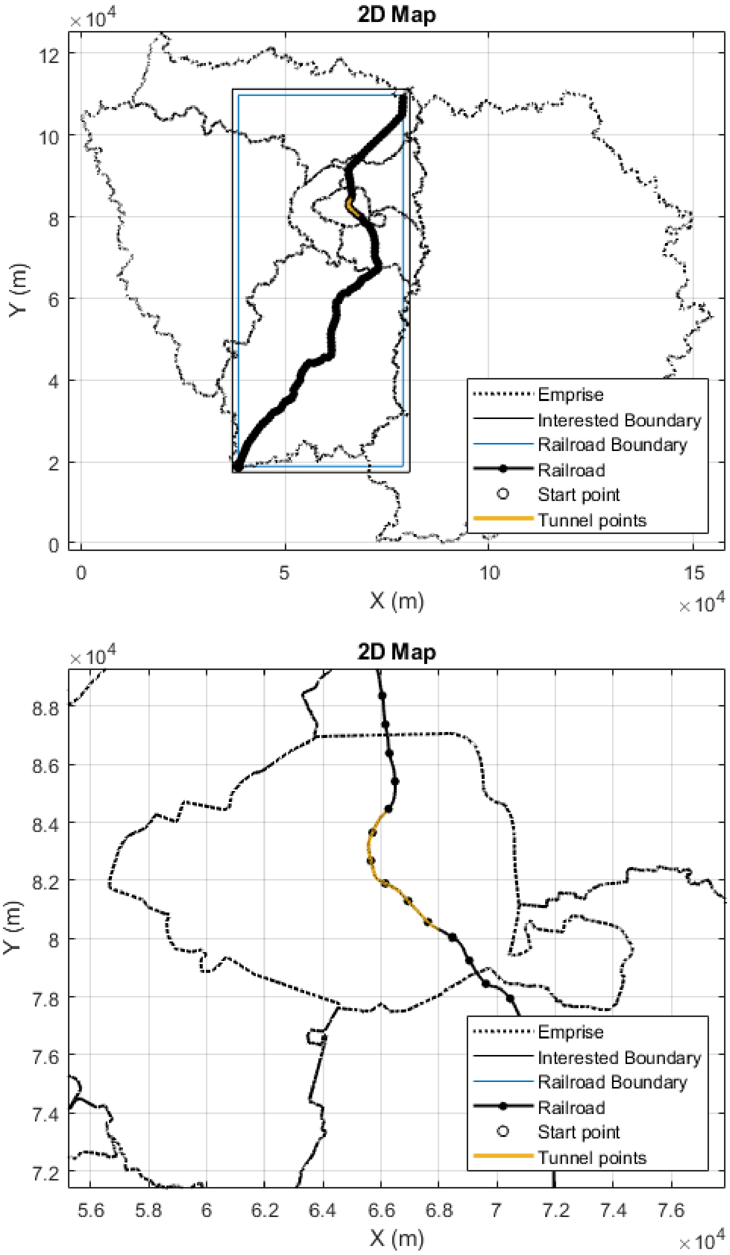


Figure 17 - Tunnel Location and Zoom

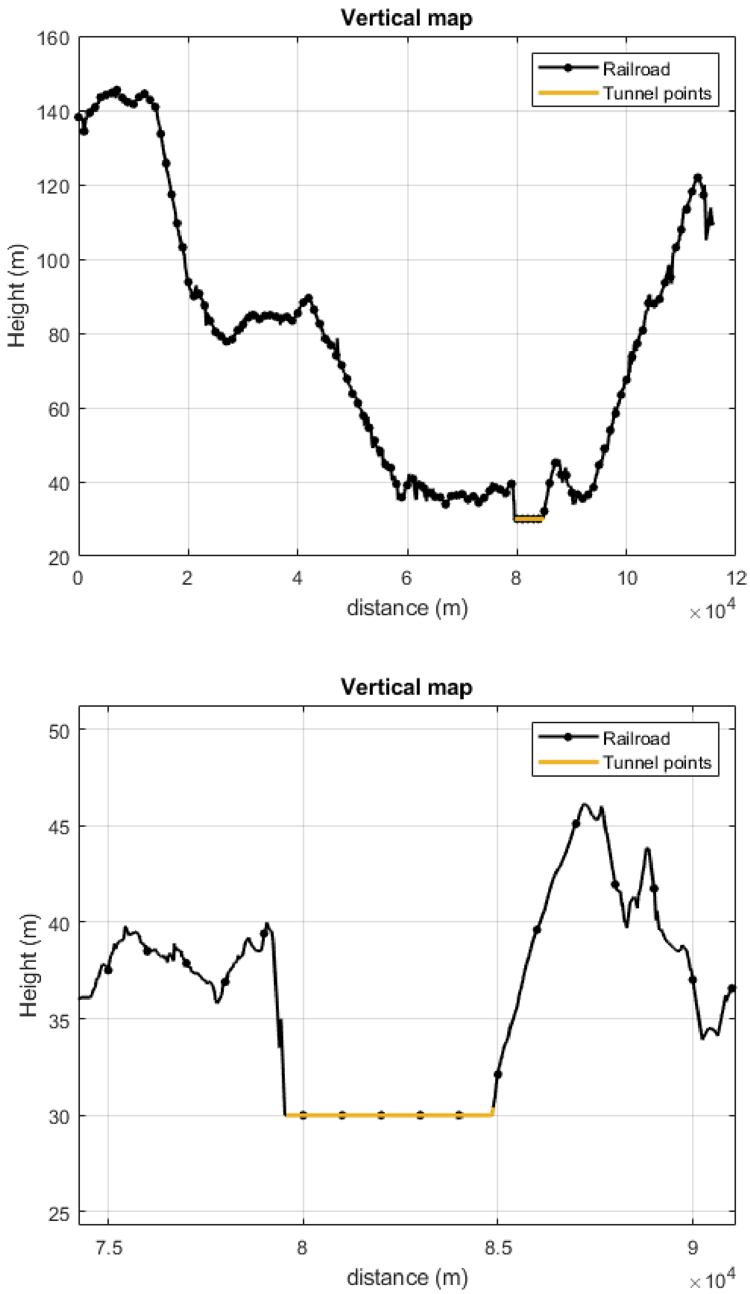


Figure 18 - Tunnel Location Height and Zoom

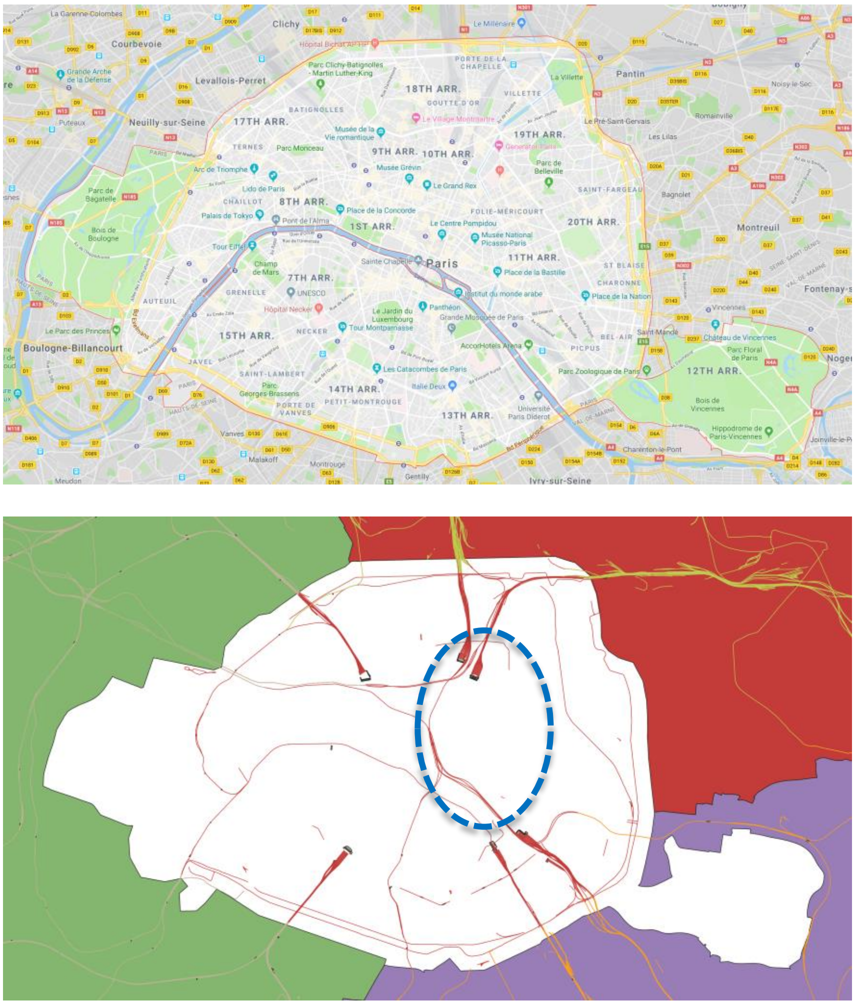


Figure 19 - Tunnel Location GIS

In order to determine the type of environment at each location along the track, a number of metrics could be used. One option would be to utilise real data to assess the error distributions of localised error sources, however, the results vary greatly with the time of day of data collections and leads to complex analysis of the results. Such error distribution analysis is needed, but is proposed here as a second phase of assessment to determine the models to be used for each classification, the actual classification should rely on a simpler means. Satellite geometry parameters such as the along-track Dilution of Precision were also considered but in comparing to the basic quantities of numbers of visible and blocked satellites, a simpler partition using the latter method was evident.

Figure 20 shows the minimum, average and maximum of the number of visible and blocked satellites over the 48 hour cycle expressed as cumulative distributions over the spatial points along the track. These 6 statistics are used to partition the different points into a set of environment classes. Note that a mask angle of 5 degrees is used such that only satellites nominally above this mask are considered visible or blocked. Figure 21 shows a zoom of Figure 20 over the first (worst) 10% of the data. Note that each curve is determined with respect to its own sorting function and thus individual locations do not occur at exactly the same percentile in each of the curves. Since the partitions are sufficiently wide (only a small number of classes), this avoids any ambiguities.

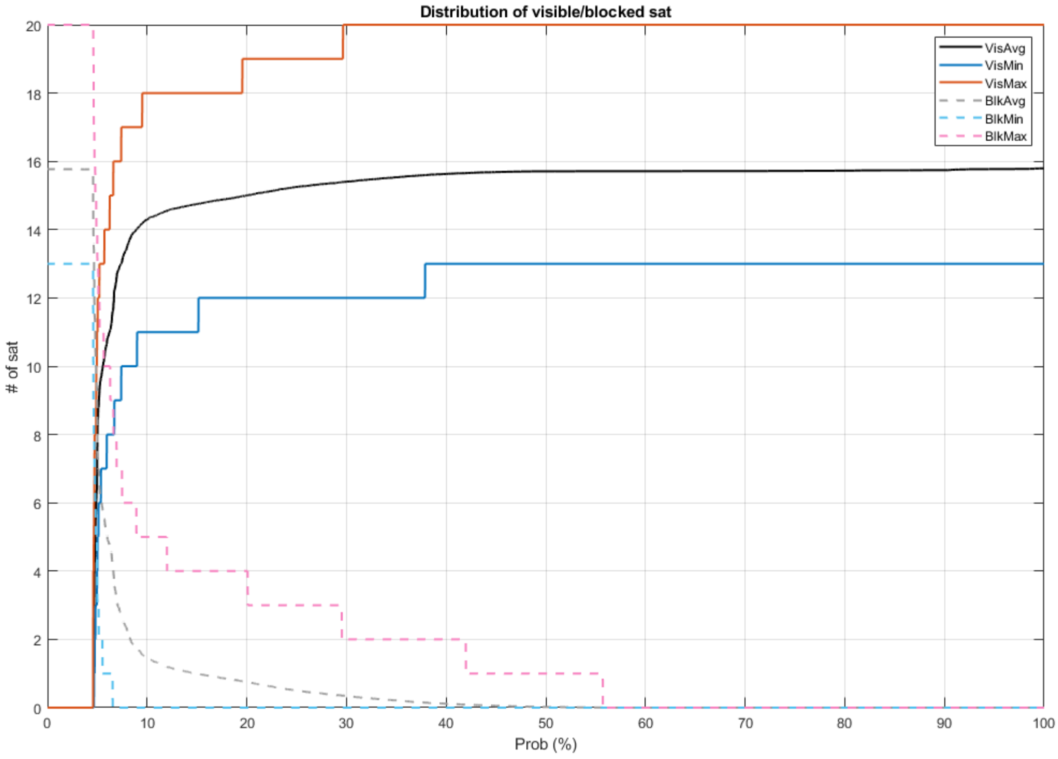


Figure 20 - Visible and Block Satellites Distribution

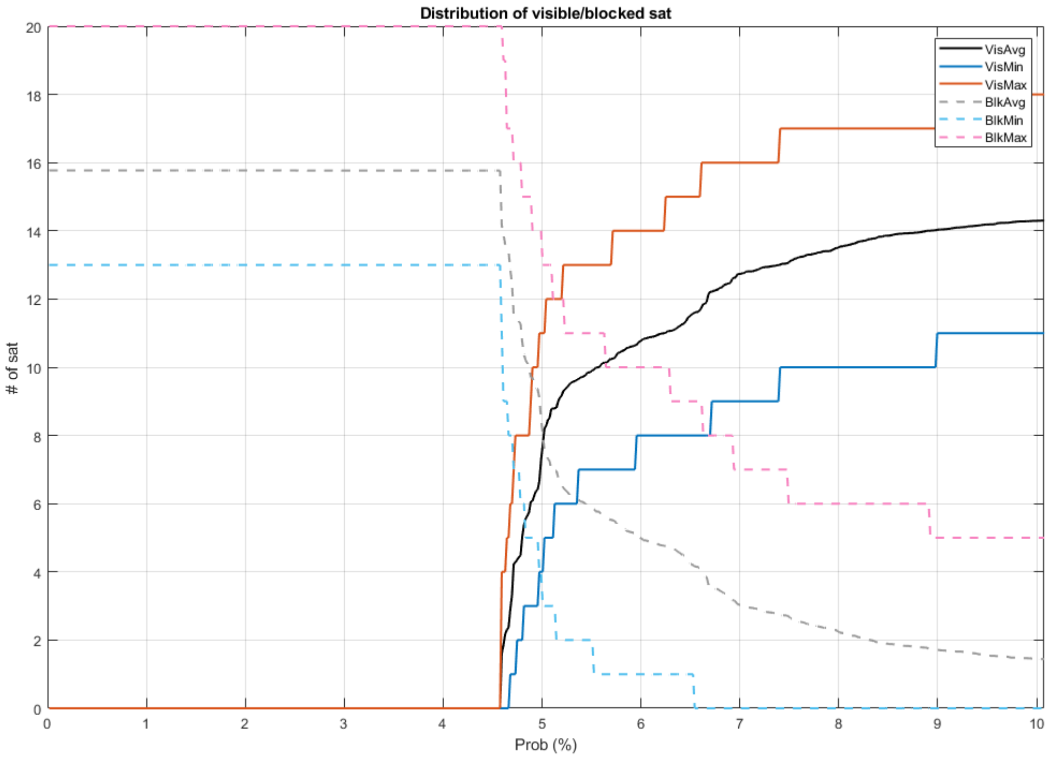


Figure 21 - Visible and Block Satellites Distribution Zoom

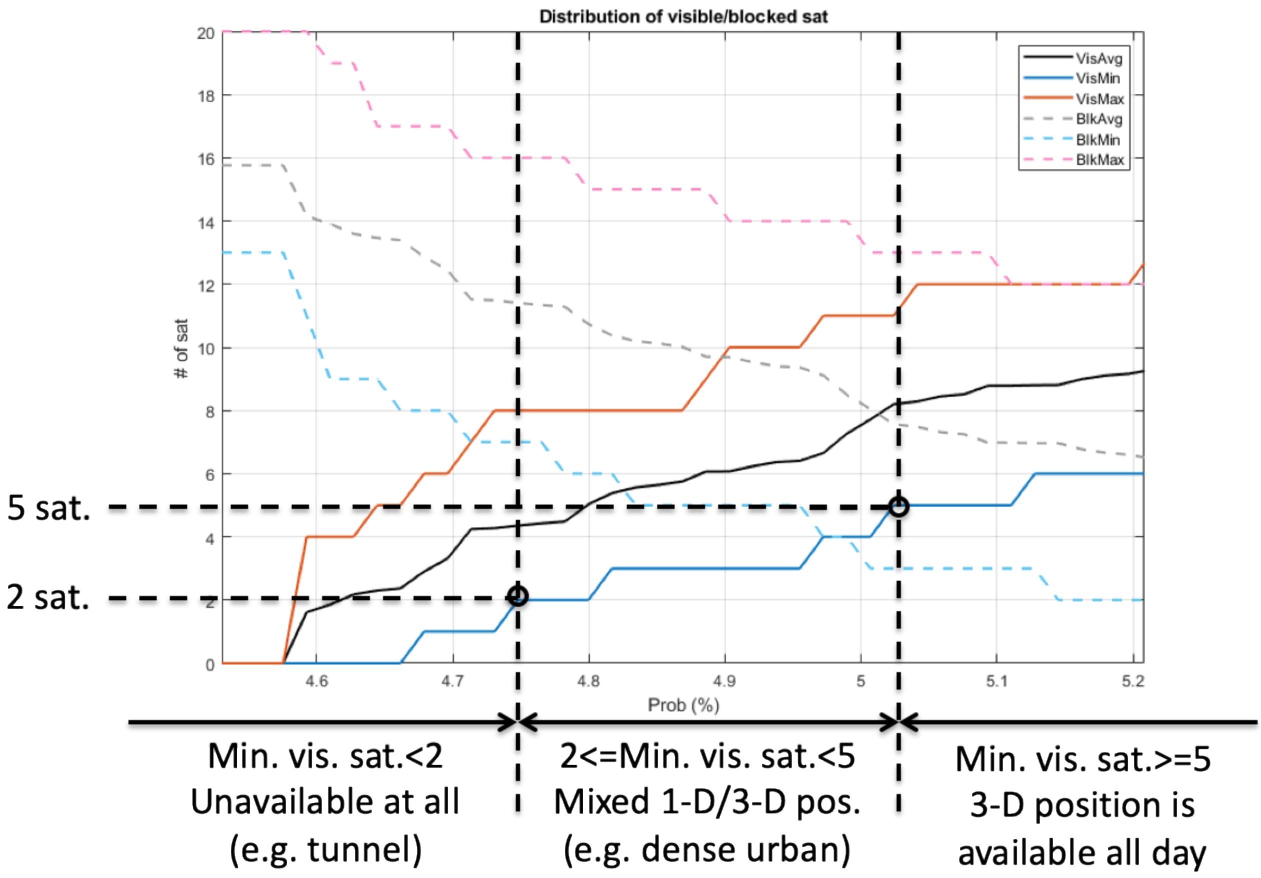


Figure 22 - Environment Boundary Setting

The partitioning of classes begins by defining the *tunnel* class as that for which all satellites are blocked some of the time. The exact relation is set at the minimum number of visible satellites being at least 2 for such a location, as shown in Figure 22. The justification for this is that for the tunnel environment legacy mode of localisation must be active without the access (either all the time, or some of the time) to GNSS signals. The environment immediately to the right on this scale is designated *dense urban* and should be addressed by the *enhanced odometry* mode of the GBLS. The *enhanced odometry* mode must have a reasonable means to estimate the along track arc distance deviations as well as the receiver clock drift. It would be possible to coast to some extent relying on other odometry sensors in the absence of such measurements but in order to ensure conservatism, a minimum of 2 is set.

The following environment class, is denoted as *medium urban.* It is likely that *enhanced* odometry mode would also be in operation here as some satellites may be lost from multipath mitigation strategies (C/N0 screening is proposed here). However, two possible reasonable metrics could be used here which more or less coincide at the same percentile. Firstly, since under snapshot positioning, which using two constellations, requires a minimum of 5 satellites in view, this may be the second environment defining boundary. Or alternatively, the locations for which the average number of visible satellites exceeds the average number of blocked satellites may also be used.

Moving on then to Figure 23 a reasonable mid-point condition is set on the average number of satellites being above or below 10. The value 10 here might be considered arbitrary but it also represents the point at which the number of measurements is twice the number of estimated states, thus a two-to-one ratio of redundancy is achieved. This class is denoted as *light urban*.

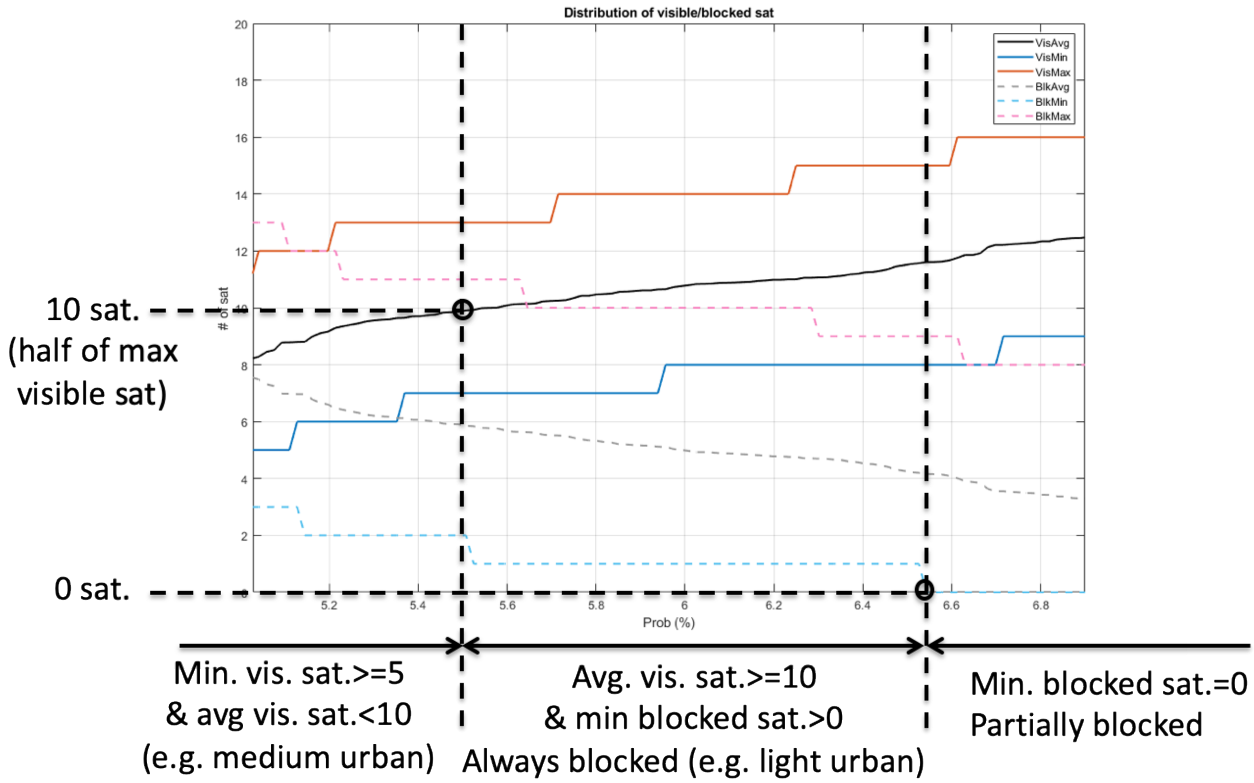


Figure 23 - Environment Boundary Setting

The final set of classes is obtained considering the number of blocked satellites. Those locations which have on average less more one blocked satellite are classified as *suburban 1,* those which have less than one *suburban-2,* except for those which have zero blocked satellites and are designated as *open sky* environment class. These relations are shown in Figure 24. A summary of the different classes is then given in Figure 25. On the basis of the Ile-de-France track examples, the percentiles of the various classes are given in Figure 26.

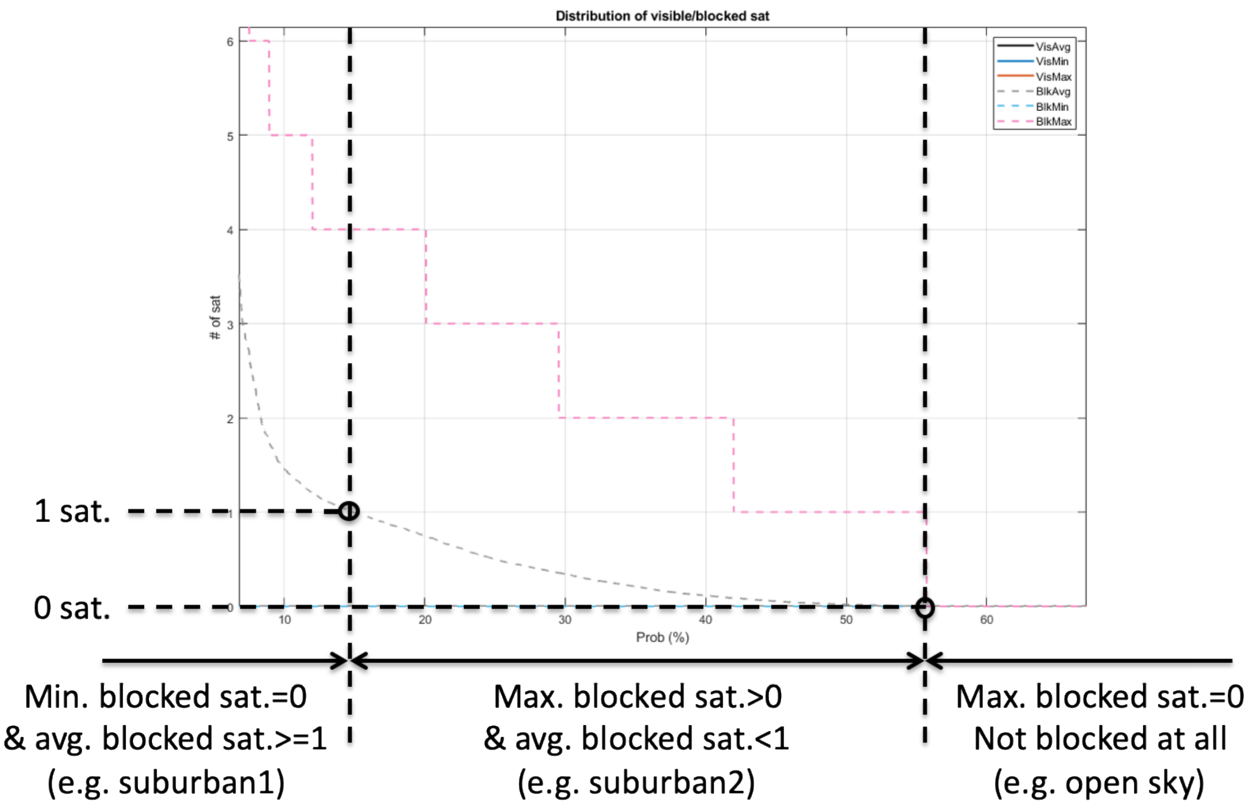


Figure 24 - Environment Boundary Setting

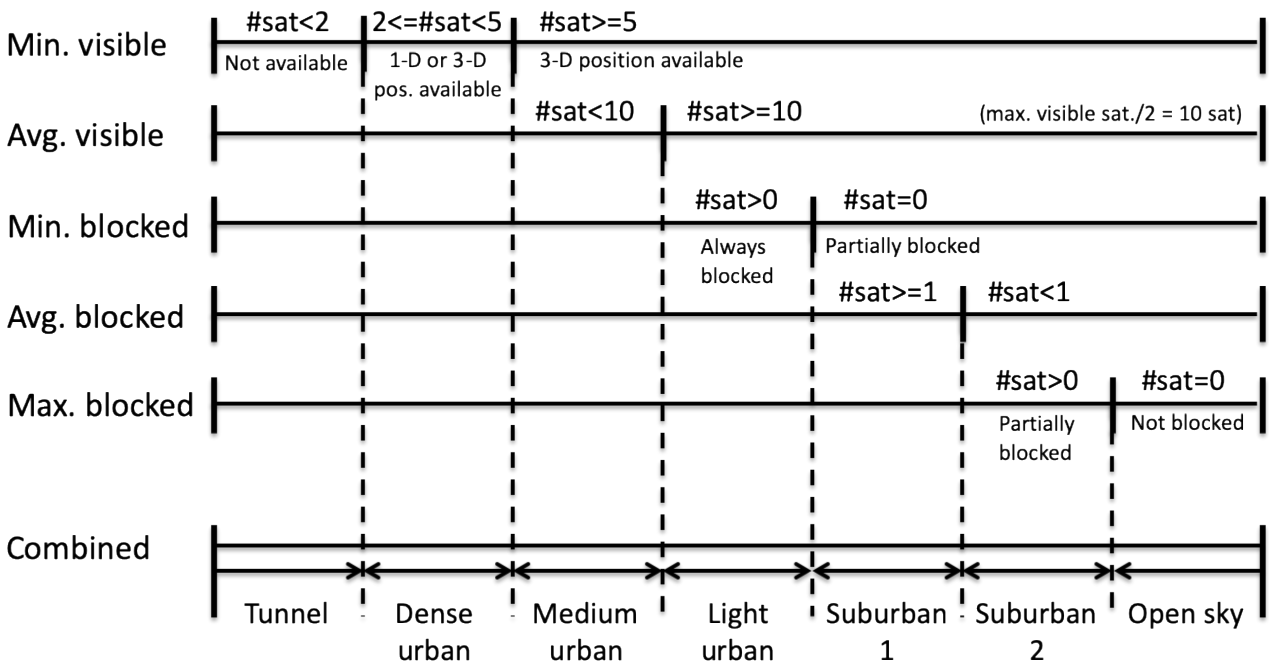
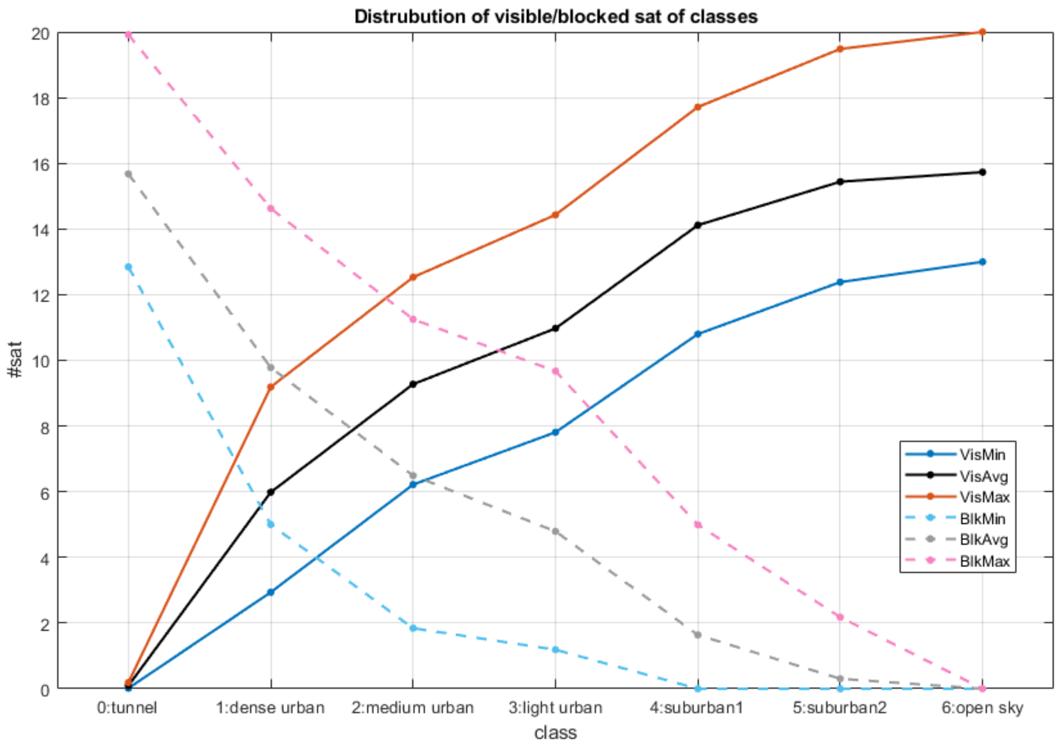


Figure 25 - Environment Classes



Percentage	4.6%	0.4%	0.6%	1.0%	8.3%	40.8%	44.3%

Figure 26 - Distribution of Classes Ile de France Route

Whilst the analysis which leads to the exact percentiles seen in Figure 26 is based on a particular data set and the rail route considered, the methodology may be applied to and route and similar proportions would be likely observed depending upon the proportions of urban regions. Figure 27 shows the distributions of the different classes along the route. It is clear that *open sky* and the lighter *suburban 2* classes dominate. Figure 28 shows a zoom of these classes for the central Parisian area.

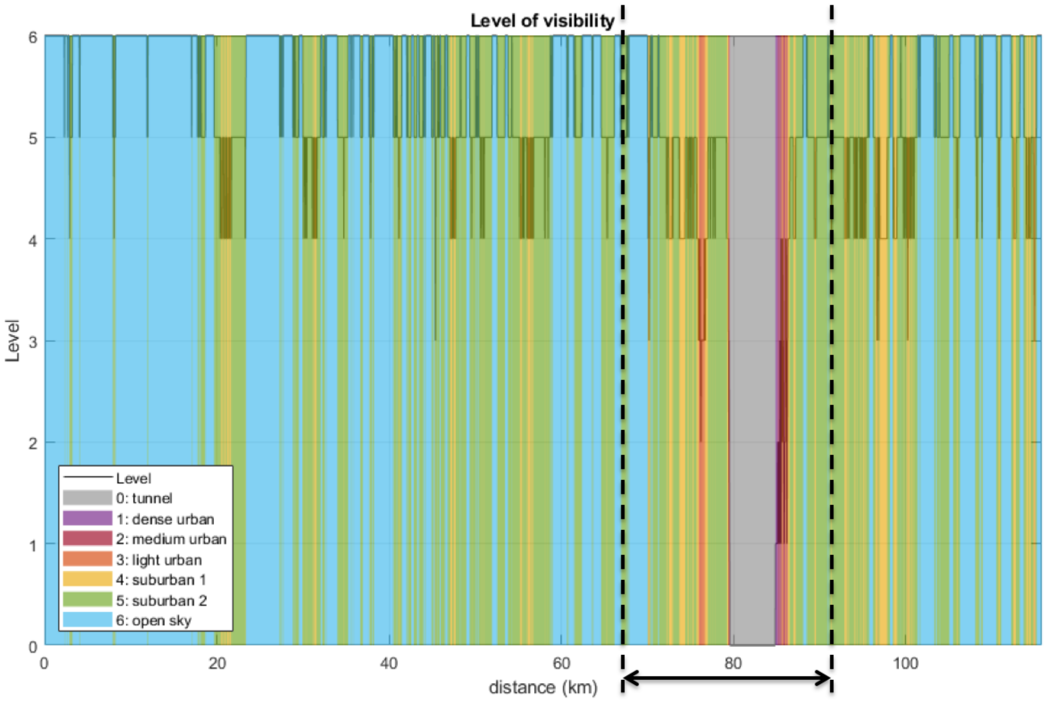


Figure 27 - Environment Classes Along Route

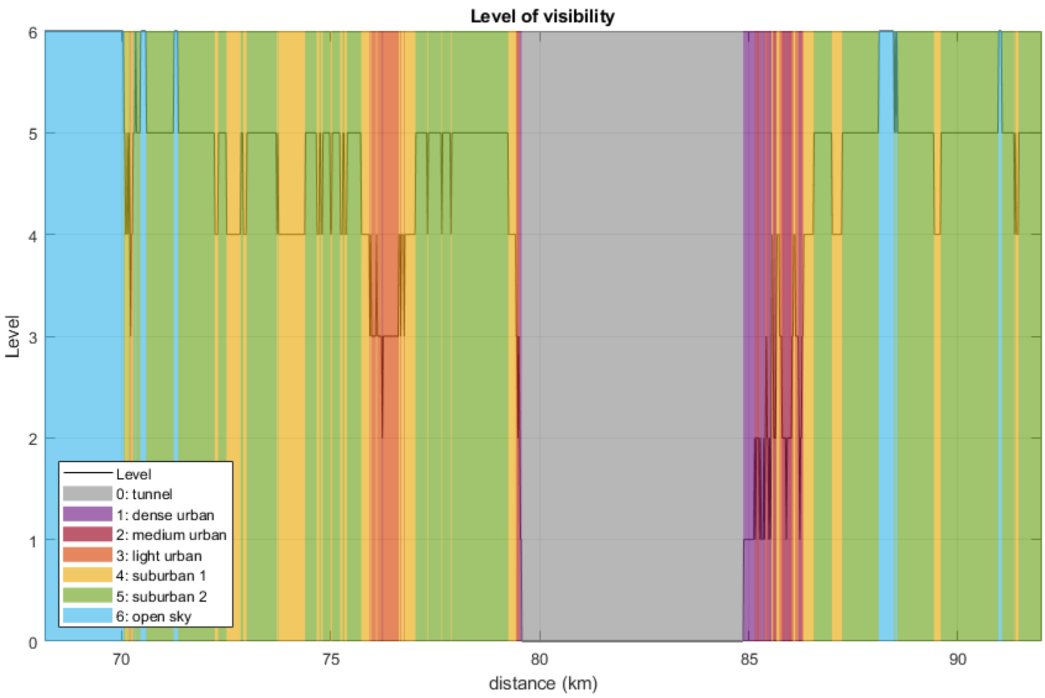


Figure 28 - Environment Classes Along Route Zoom

4 Localization system in railways

Considering a GNSS-based Moving Block system in ERTMS lev.3. and the Virtual Balise (VB) concept, the operational requirements associated to GNSS show the need of integrating the localization system with some functions to fulfill rail protocols.
The performance parameters reported are partially compliant with ERTMS specifications on location and velocity reported in §3.4 and therefore their implementation could impact on ERTMS specifications.

The start of mission in station needs physical balises to ensure the discrimination of track even in a GNSS-based Moving Block system with Virtual Balise (VB).
In other situations when at the start of mission the position cannot be acquired from location unit, complementary operational procedures should be defined.
In particular the train operations related to location functions in station have to be considered with the introduction of complementary technologies assisting GNSS system.
The particular closed environments with GNSS system's unavailability also has to be compensated with other positioning sources.

In the environment classes defined in the previous chapter (§3.5), the GNSS-based location system has different integrations with physical balises to ensure on board the position complying with rail protocols.
Further to aid the GNSS receiver, two complementary positioning systems based on dead reckoning technology have been considered: Doppler Radar and Wheel odometer.

In particular analysing the different environment classes, the GNSS-based location system have to be combined with these complementary positioning systems and physical balises.

Considering the following environment classes:

- Tunnel
- Dense Urban
- Medium Urban
- Light Urban
- Suburban
- Open sky

we have different accuracy of the GNSS-based location system in absence of complementary positioning systems, that could imply higher train footprints impacting on lines operations to assure acceptable safety level.

If we consider the performances listed in Table 5, the train operations have not to change in the different environment classes: the GNSS-based location system integrated with complementary positioning systems and physical balises has to satisfy the needs for train operations and traffic management.

5 Conclusions

This document summarizes the characteristics of GNSS-based location system and defines the performance requirements in railway scenarios. In the chapter 2 the situations that are challenging for the GNSS-based location system are identified, highlighting the main positioning issues. In the chapter 3 the main operational performances of GNSS-based location system are described identifying the environment classes that influence the performances of the system. In the chapter 4 the main solutions that allows the use of GNSS for train operations in a Moving Block signalling system without trackside train detection are outlined

It suffices to say that the specification of requirements and recommended practices or operating procedures for GNSS based equipment to be employed for safe train localisation is at this stage greatly limited by the lack of knowledge and an agreed solution to the impact of local errors. Before an appropriate methodology is defined for these effects its becomes very difficult to confidently restrict the architecture to be employed. The approach of this report has been to attempt to innovate in other areas.

It is the view of ASTRAIL that, in order for any MOPS to be appropriate to the application to rail, the different environments must be classified in some manner within the standard. It is too early to categorically proclaim one approach as optimal, in this report one method has been proposed based on some analyses of the constellation geometry obtained taking into consideration the local terrain and topography, including building elevation data.

Furthermore, one of the challenges identified within ASTRAIL has been the difficulty of requirements setting and the wide range of results from previous studies [1]. In this work, an alternative to setting alert limits is proposed, instead relying upon the computation of a variable protection level that is used by the onboard system to determine what speed (with respect to the appropriate braking curve) may the train move at safety. One aspect which will have to be investigated in future, if this idea is to be employed, is the prediction of protection levels. This might be necessary to avoid some sharp emergency braking protocols if the protection level were to jump abruptly.

This work is based on the use of topographic height data, which it is intended to use (potentially a similar source such as LIDAR or camera) as a basis for characterising the local environment along the rail route network. This might feasibly be done in real time in future solutions, here though it is based on offline processing which allows both an error model to be defined for that location and also a means to determine the receiver mode. Three receiver modes have been defined which account for the variable environments, taking care to appease the needs for legacy compliance and backward compatibility. We've concluded that, to satisfy the needs for train operations and traffic management, the GNSS-based location system shall be integrated with complementary positioning systems when in enhanced odometry mode and physical balises to support the legacy mode and between virtual balise sections.

Acronyms

Acronym	Explanation
Active Antenna	Term for a passive antenna integrated with a preamplifier.
BPSK	Binary Phase Shift Keying, a type of modulation employed in GNSS signal design
BW	Bandwidth
C/A	Coarse Acquisition, the name of the initial civil signal on the GPS L1 frequency
Coverage	The network coverage provided by the system that permits the user to determine the position to the specified level of accuracy.
CRC	Cyclic Redundancy Check, a parameter used to check data integrity
CW	Continuous Wave, a type of radiowave interference
DD	Double Delta, a method for discriminating the code delay
DLL	Delay Lock Loop, a component of the GNSS receiver employed in tracking the code signal
DOP	Dilution of Precision. Various DOP have been defined (GDOP, PDOP, HDOP, VDOP) as measures of the "goodness" of the geometry; a DOPs are desirable, high DOPs are undesirable
DR	Dead Reckoning, a method for updating the estimated position
ECEF	Earth Centred, Earth Fixed
EGNOS	European Geostationary Navigation Overlay Service
E-L	Early minus Late , a method for discriminating the code delay
FD	Fault Detection, a function to detect the presence of measurement faults
FDE	Fault Detection and Exclusion, a function to detect and exclude the presence of measurement faults
FEC	Forward Error Correction, a method for data error integrity
Geometric Range	The true distance between satellite transmitting antenna and user receiver antenna
GEO	Geostationary
GIVE	Grid Ionospheric Vertical Error, an SBAS term for ionospheric error corrections
GNSS	Global Navigation Satellite System (GNSS) is the world-wide position, velocity, and time determination system, that includes one or more satellite constellations, receivers, and system integrity monitoring
GPS	Global Positioning System
HOW	Hand Over Word
HPL	Horizontal Protection Level
INS	Inertial Navigation System, a system of accelerometers and gyroscopes which provides measurements of used to update the position, velocity and orientation of the vehicle
IOD	Issue of Data
IODC	Issue of Data Clock
IODE	Issue of Data Ephemeris
IPP	Ionospheric Pierce Point, employed in SBAS to designate the intersection of the signal path and the assumed ionospheric surface
LSB	Least Significant Bit
LSR	Least Squares Residual, the statistical measure of the consistency of measurements using the Least Squares Estimation technique
MA	Movement Authority: Permission for a train to run from a point to a specific

	location within the constraints of the infrastructure with supervision of speed
Mask Angle	The elevation angle below which satellite measurements are not employed by the receiver
Misleading Information	Misleading information is defined to be any localisation solution that is output containing an error larger than the relevant alert limit or protection level, without any indication of the fault within the time-to-alert
MOPS	Minimum Operational Performance Standards, designed to set the minimum requirements on the on-board vehicle localisation system
MSL	Mean Sea Level
MT	Message Type
MTBF	Mean Time Between Failure
PR	Pseudo Range
PRC	Pseudo Range Correction
PRN	Pseudo Random Noise
Pseudorange	The geometric range plus an unknown user clock offset
RAIM	Receiver Autonomous Integrity Monitoring is a technique performed onboard the receiver to check the integrity of the GNSS navigation signals through consistency checking and thus relying on a redundancy of measurements.
Reliability	The probability of performing a specified function without failure under given conditions for a specified period of time.
RF	Radio Frequency
RSS	Root-Sum-Square
SBAS	Satellite Based Augmentation System (SBAS)
S/A	Selective Availability is a function for denying the full accuracy and selecting the level of positioning, velocity, and time accuracy of GPS available to users of the Standard Positioning Service
SPS	Standard Positioning Service is the standard level of positioning, velocity and timing accuracy that is freely available to any user on a continuous basis
SV	Satellite Vehicle
TC	Tropospheric Correction
TOW	Time of Week
TTA	Time to Alert
UDRE	User Differential Range Error
UERE	User Equivalent Range Error
URA	User Range Accuracy is the one-sigma bound of user range errors in the navigation data for each individual satellite including space or control segment errors
UTC	Universal Time Coordinated
WAAS	Wide Area Augmentation System
WGS-84	World Geodetic Survey 1984

Definitions

Accuracy	The difference between true and computed position (absolute positioning), expressed as a value with its confidence level.
Active Antenna	Term for a passive antenna integrated with a preamplifier.
Availability	The percentage of time the position, navigation or timing solution can be computed by the user.

Blocked (satellite)	A satellite which would be visible under open sky conditions is blocked since buildings, other infrastructure of terrain are present along the line-of-sight vector
Continuity	Ability to provide the required performance during an operation without interruption, once the operation has started.
Coverage	The network coverage provided by the system that permits the user to determine the position to the specified level of accuracy.
Geometric Range	The true distance between satellite transmitting antenna and user receiver antenna
Integrity	The measure of trust that can be placed in the correctness of the position or time estimate provided by the receiver. This is usually expressed as the probability of a user being exposed to an error larger than alert limits without warning
Mask Angle	The elevation angle below which satellite measurements are not employed by the receiver
Misleading Information	Misleading information is defined to be any localisation solution that is output containing an error larger than the relevant alert limit or protection level, without any indication of the fault within the time-to-alert
Pseudorange	The geometric range plus an unknown user clock offset
Reliability	The probability of performing a specified function without failure under given conditions for a specified period of time.
Visible (satellite)	A satellite which is in light-of-sight view from the train-based receiver

List of figures

List of tables

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