GNSS AUGMENTATION NEEDS FOR RAIL

D3.4

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VERSION 1.4

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D3.4 - GNSS AUGMENTATION NEEDS FOR RAIL

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VERSIONS OF THE DOCUMENTS

Revision	Date	Description
1.0	14/12/2020	Stable Iteration version prepared by ADS: submitted to CLUG internal review
1.1	20/01/2021	Implementation of reviewers' remarks (ADS and Naventik)
1.2	30/06/2021	Final iteration version prepared by ADS submitted to consortium review, paving the EGNOS Next roadmap: - D3.1.4 (WP3.3) outcomes the need of the SBAS EGNOS authentication against feared event (§4.4), in particular for the Airbus track determination algorithm mentioned in §4.3; - potential integrity service associated to the Galileo HAS in §4.5; - deeper analysis on the SBAS dissemination evolutions in §6; - ERTMS CR1368 introducing a solution for SBAS dissemination for rail with integrity and complement in combined ground and space dissemination approach (§6.2.5 et §6.2.7).
1.3	29/07/2021	Final iteration version prepared by ADS: implementation of reviewers' remarks (ADS) and CLUG Quality Manager comments (DBN) Final version submitted for EUSPA review and approval
1.4	09/09/2021	Final version after EUSPA review and comments; The document becomes "Public" instead if "CLUG Confidential" after CLUG partners authorization to Airbus proposition.

EXECUTIVE SUMMARY

This document is the deliverable "D*3.4 – GNSS Augmentation Needs for Rail* " of the European project “Certifiable Localisation Unit with GNSS in the railway environment” (hereinafter also referred to as “CLUG”) as part of the delivery of the CLUG Work package WP3.4 "GNSS Augmentation and Dissemination" from the CLUG Work package WP3 "*Localisation System Design*".
This document benefits from CLUG analysis to present how additional EGNOS data for rail (or for terrestrial users), could improve the safe train localization, in particular the localisation performances for along-track position, speed, and rail track determination functions. It also provides first clues for EGNOS data safe dissemination with integrity to be ensured up to train localization units.

This document is based on the terms and conditions established in the Grant Agreement (GA) and its Annexes, as well as in the Consortium Agreement (CA).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPLICABLE DOCUMENTS

The following documents define the contractual requirements that all project partners are required to comply with:

- Grant Agreement N°870276 (which includes DOW, Grant Preparation Forms and annexes): This is the contract with the European Commission which defines what has to be done, how and the relevant efforts.
- Consortium Agreement: This defines our obligations towards each other.

Each of the above documents was established at the start of the project, and copies were supplied to each partner. Each document could potentially be updated independently of the others during the course of the project following a prescribed process. In the event of any such update, the latest formal issued version shall apply.

In the event of a conflict between this document and any of the contractual documents referenced above, the contractual document(s) shall take precedence.

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ACRONYMS

C

CA
Consortium Agreement
CAPEX and OPEX *CAPital and OPerational EXpenditure*
CDF
Cumulative Distribution Function
CPF *Central Processing Facilities*

D

DAL *aviaition Development Assurance Level*
DF
Dual Frequency
DFMC
Dual Frequency Multi-Constellation
DFRE *Dual Frequency Range Error*
DPBE
Doppler Bias Error
DPRE
Doppler Range Error

E

EDAS *EGNOS Data Access Server*
EGNOS
European Geostationary Navigation Overlay Service ,
ENT
EGNOS Network Time ,
ERTMS *European Rail Traffic Management System*
EUSPA *European Union Agency for the Space Programme*

F

FRMCS Future Railway Mobile Communication System

G

GA
Grant Agreement
GIVD
Grid Ionospheric Vertical Delay ,
GIVE
Grid Ionospheric Vertical Error
GNSS
Global Navigation Satellite System
GPS
Global Positioning System ,

H

H or V
Horizontal or Vertical
HAL
Horizontal Alert Limit
HPL
Horizonal Protection Level

I

IGP
Ionospheric Grid Point

L

LPV200 *Localizer Performance with Vertical guidance - 200 feets*

M

MCI
Maximum Confidence Interval
MOPS
Minimum Operation Performance Standard

N

NLES *EGNOS Navigation Land Earth Station*

O

ODTS
Orbit Determination and Clock Synchronisation ,
Orbit Determination and Time Synchronisation

P

PL
Protection level
PPP
Precise Point Positioning
PRN *PseudoRandom Noise code*

R

RDFBE
Railway Dual Frequency Bias Error
RDFRE
Railway Dual Frequency Range Error
RECT
Residual Error Correlation Time

S

SARP
Standards And Recommended Practices
SBAS
Space-Based Augmentation System
SF
Single Frequency
SFSC *Single Frequency Single Constellation*
SL0
Service Level 0
SL2
Service Level 2
SoL
Safety of Life

T

TLOBU
Train Localisation On-Board Unit
TTA
Time to Alert ,

U

UDRE
User Differential Range Error
UTC
Universal Time Coordinator ,

V

VAL
Vertical Alert Limit
VPL
Vertical Protection Level

W

WUL
Worst User Location

1 INTRODUCTION

The European Geostationary Navigation Overlay Service (EGNOS) coming version 3.2 providing Dual Frequency Multi-Constellation (DFMC) is the considered version in the CLUG proof of concept study. Indeed, the EGNOS V3.2 DFMC benefits from better performances compared to EGNOS versions V2 and V3.1 augmenting only the GPS satellites, when the coming version V3.2 augments both GPS and GALILEO satellites. So, it strongly improves the train access to safe Signal in Space (GPS+GAL) against masking effect for railway users.
Then, in terms of performances, the (CLUG, D3.1.1 - GNSS Augmentation Usage 2021) have highlighted the main limitations of EGNOS V3.2 (so implicitly also V2 and V3.1) to completely achieve the performance requirements, expressed from the CLUG WP2 "*Mission Definition and System Requirements*", of the Train Localization On-Board Unit for architectures taking benefits from the safety levels offered by the SBAS (EGNOS).
Indeed:

1) Using the current version of EGNOS with a MOPS compliant receiver would not completely fulfil the railway requirements due to some limitations, such as performance integrity on speed when not using current odometer system combining several and independent speed sensors with redundancy and voting to reach SIL 4 level.
2) Using Bayesian filtering capabilities in the TLOBU with the upcoming EGNOS DFMC will not be sufficient to fulfil railway protection level requirements expressed from the CLUG Work Package "*WP2 Mission definition and System requirements*", cf. in particular (CLUG, D2.3 - High Level System Requirements 2020) and (CLUG, D2.4 - Preliminary Hazard Analysis 2020), led by the rails actors. The safe bounds provided by DFMC will result in larger confidence intervals than required.

Thus, an augmentation service for rail, associated with a Bayesian-based receiver is the most promising and preferred solution answering positively to train safe localization requirements. This SBAS service for rail could be built upon EGNOS v3.2 DFMC service but with additional features to comply with railway user needs, the data fusion and Integrity concepts defined in CLUG project. This could be incorporated or merged in an EGNOS service for terrestrial users also named EGNOS Range Multi-Missions as thought in coming EGNOS-Next studies.

Therefore, this version of the document provides first clues of such an EGNOS service answering rail sector needs. The approach is based on the following documents to answer (CLUG, D2.3 - High Level System Requirements 2020):

- Integrity concept solution described in (CLUG, D3.1.4 - Integrity Concepts & Algorithms 2021)
- Data fusion concept defined in (CLUG, D3.1.3 - Sensor Fusion Algorithms 2021)
- TLOBU architecture definition from (CLUG, D2.5 - Preliminary Architecture Document 2020) and (CLUG, D3.1.5 - Train Localisation On-Board Unit Design Document (Solution A) 2021)

It is mentioned that the following topics are not addressed in this document but should be considered in the future for completing the global picture:

- Design of the SBAS infrastructure to provide such augmentation service: under current study EGNSS-R (European GNSS Navigation Safety Service for Rail) and EGNOS-Next;
- Design of the Telecom Euroradio safe infrastructure to disseminate the augmentation data with ensured data integrity up to TLOBUs: from the current norm GSM-R (based on the GSM technology - 2G equivalent) to the next generation under work FRMCS (based on 5G norm);
- Definition of Minimum Operations Performance Standard (MOPS) for satellite-based augmentation TLOBU;
- Definition of Standard And Recommendation Practices (SARP) for the railway service like it is done in aviation sector;
- Roadmap information (economical, programmatic) to implement the service and its provision;
- Global chain of stakeholder to deliver and provision safely this service;
- Certification process of the service;
- Liability and perimeter of responsibility of stakeholders in case of accident.

The document is structured as follows:

- Chapter §2 defines the perimeter of the SBAS augmentation service

- Chapter §3 describes the equivalence of localisation performance related concepts between aviation and railway domains.
- Chapters §4 presents how future EGNOS data for rail could contribute to the localisation performance requirements for along-track positioning, along-track speed and rail track determination functions. The chapter for each of these 3 topics describes the following:
  - The need based on (CLUG, D2.3 - High Level System Requirements 2020). Only mostly stringent requirements are presented.
  - How the requirements may be fulfilled by augmentation techniques or other approaches
  - What the EGNOS data for rail shall fulfil the requirements when augmentation techniques are useful (SBAS products to be disseminated)
- Chapter §5 defines a future service area of railway SBAS
- Chapter §6 provides a first estimate of the bandwidth required for disseminating the railway SBAS service parameters and presents multiple dissemination approaches supporting railway SBAS products.
- Chapter §7 provides a conclusion.

2 GNSS AUGMENTATION SERVICE PERIMETER AND ROADMAP

2.1 GNSS AUGMENTATION SERVICE PERIMETER

In the context of the study, a service is a mean for delivering value (location information under multiple forms) to users (Train Localisation Function). This value can be combined with other information to provide additional value for end-users (safety critical applications).

The perimeter of the GNSS augmentation service is illustrated in the following figures from (CLUG, D2.5 - Preliminary Architecture Document 2020). It shall be noted that the service provided by the TLOBU to the critical mission applications is not the subject of this document even if the mission requirements, including performance, are defined at this level and not at GNSS/SBAS level.

Figure 1: Scope of the GNSS Augmentation service among the 3 main contributing segments

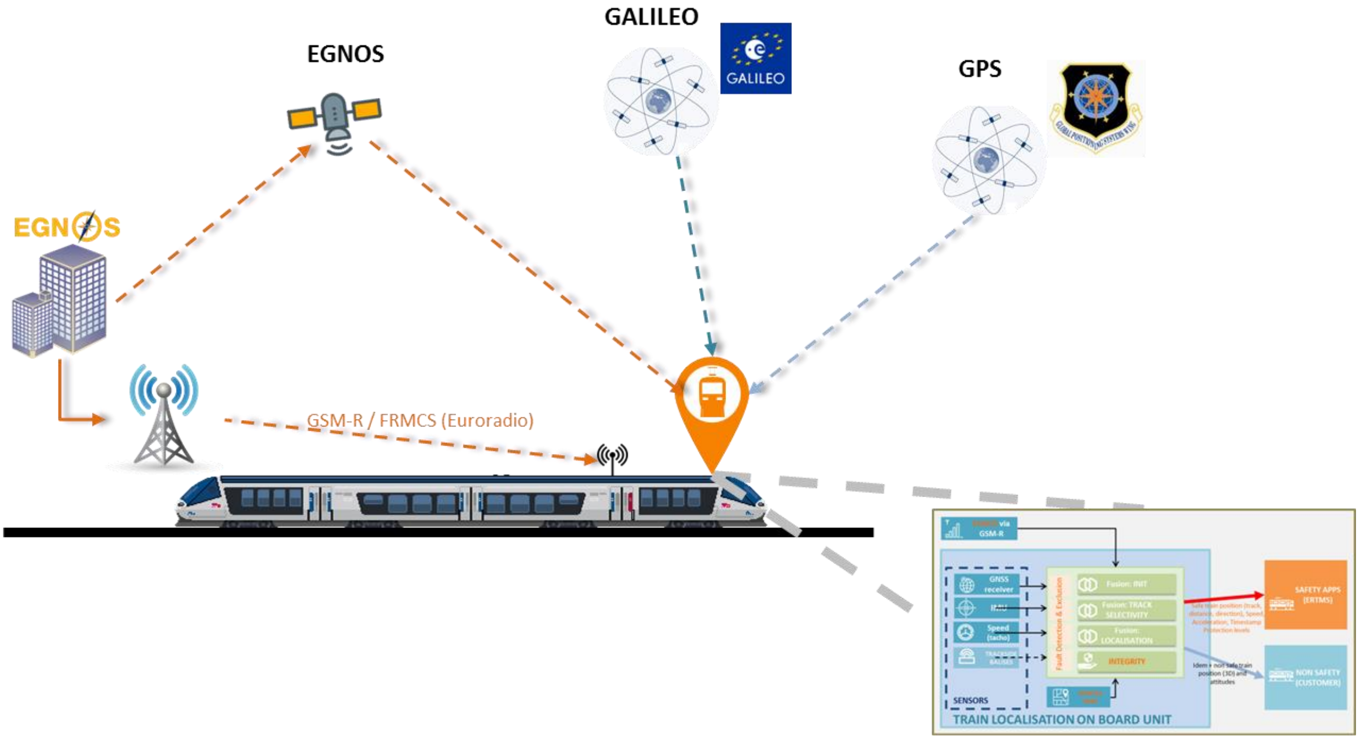

Figure 2: EGNOS Augmentation Services in liaison with the GNSS : within the perimeter in TLOBU architecture

2.2 GNSS Augmentation roadmap in Europe

As explained in (CLUG, D3.1.1 - GNSS Augmentation Usage 2020), the GNSS Augmentation service being provided in Europe is the EGNOS (European SBAS) in operation since 2011 delivering Safety of Life services for Aviation.

Regarding Railway concern, the starting point of the CLUG study is the EGNOS V3.2 DFMC (Dual Frequency Multi-Constellation) release under development, led by Airbus. It is planned to broadcast a test Signal in Space (SIS) of this service over Europe around 2025 – 2027, then expected to be in operation in 2027, as per last evolutions roadmap shared by EUSPA to international GNSS consortium. The DFMC service for aviation being now well defined, i.e. SBAS L5 MOPS & SARPS are under final phase for publications, an augmentation service for rail, built upon and completing the EGNOS v3.2 DFMC, could now be engaged with the European Institutions via phase A & B definition studies. At the time of writing this issue, already two H2020 studies, driven by ESA together with European Commission & EU Space (EUSPA), are in competition, where the project is expected to start in 2021, aiming to look at the future of EGNOS V3, for the horizon of 2030. This includes services that not only targeted to meet the needs of Railway but also for Maritime and other Terrestrial users.

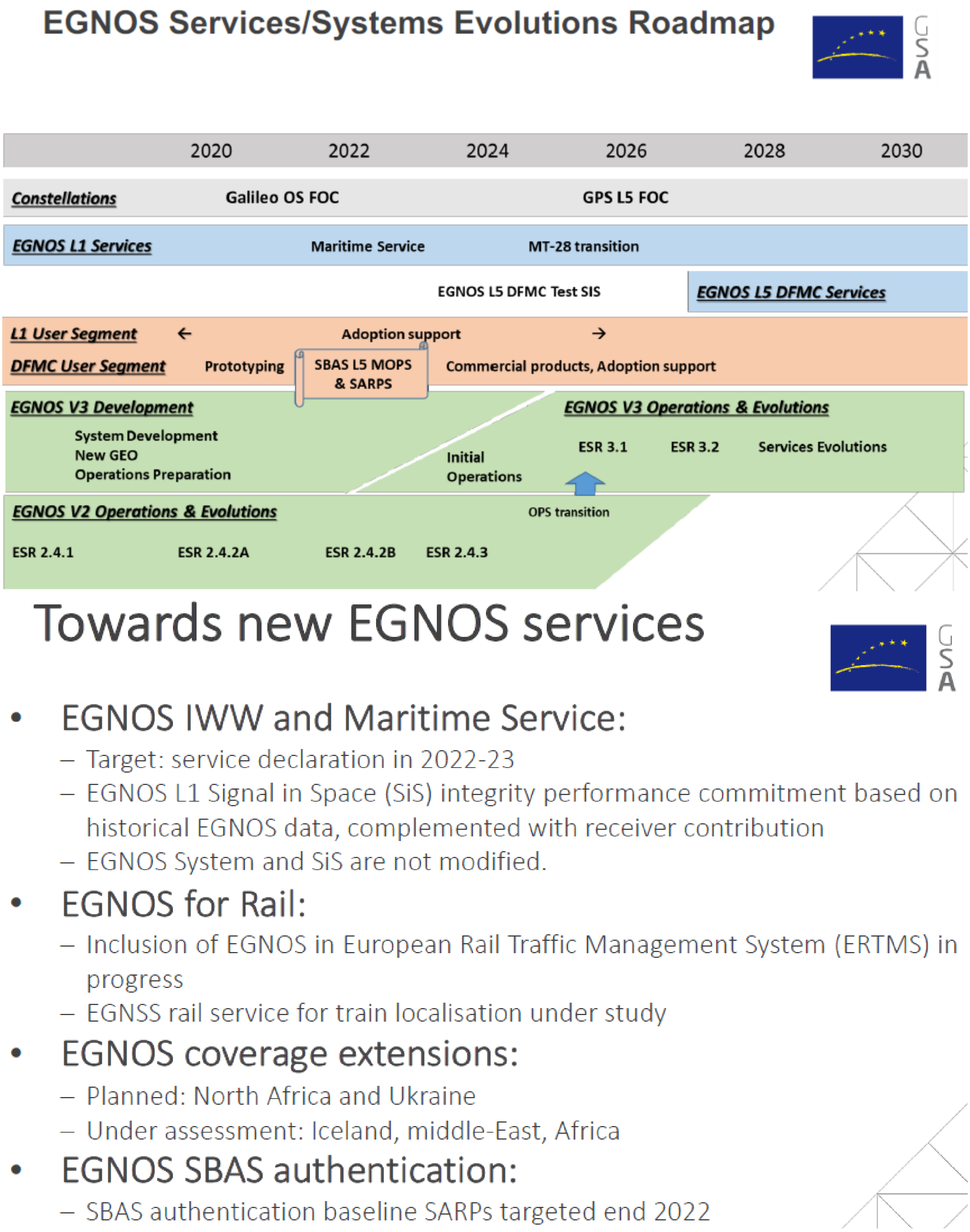

Figure 3: EGNOS Services Evolutions Roadmap (source: Munich Satellite Navigation Summit 2021, presentation" EGNOS Programme Update" by Vincent Brison – EGNOS Exploitation Programme (EUSPA)

2.3 GNSS Augmentation key advantages for railway in Europe

As highlighted in the ERTMS change request (CR1368) and several railway studies, SBAS, so EGNOS, offers the following improved capacities to the railway operators:

- EGNOS **safe corrections to GPS and Galileo** are the pre-requisite for safe use of GPS and Galileo based localization in ERTMS;
- EGNOS **improves localisation accuracy**

- EGNOS provides **safe barriers against external feared events** (fault and failures) **of GPS and Galileo**;
- EGNOS **delivers information with integrity of GPS and Galileo**;
- EGNOS ensured the **integrity of these transmitted information up to the SBAS users**;
- EGNOS safe data with integrity are provided by the EU **for free**, so no "vendor lock-in" scenario;
- EGNOS does not compromise **interoperability of future decisions in ERTMS**.

3 LOCALISATION PERFORMANCE-RELATED CONCEPTS BETWEEN AVIATION AND RAILWAY

The corresponding concepts between aviation and railway sector can be defined from (CLUG, D2.3 - High Level System Requirements 2020).

3.1 Accuracy

Accuracy has the same meaning in both domains. The following figure recalls EGNOS augmentation performance comparison with other GNSS-based localisation techniques.

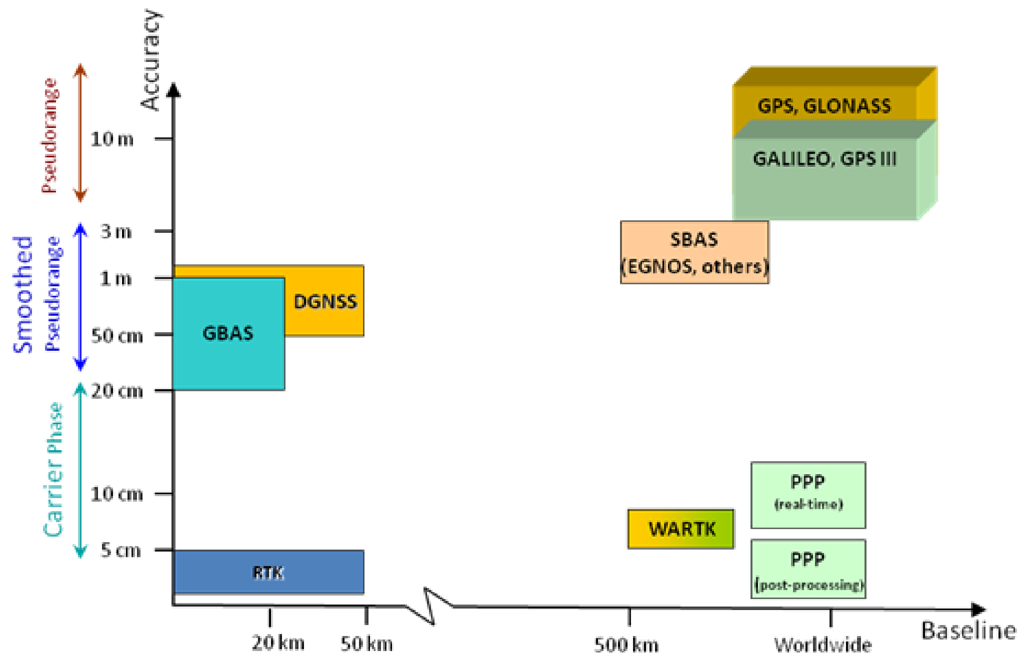

Figure 4: Usual comparison of GNSS-based localisation accuracy at 2 sigma (source ESA Navipedia[1])

3.2 Performance Integrity

The SBAS integrity concept as described in EGNOS SoL Service Definition Document for aviation is based on the following concepts:

- Integrity risk is the probability that the position error is larger than the Alert Limit defined for an intended operation and the user is not warned within the Time to Alert (TTA).
- Navigation System Error is the difference between the real position and the estimated one.
- Integrity Event occurs when the Navigation System Error is greater or equal to the corresponding Protection Level for the intended operation and the receiver does not trigger an alert within the Time to Alert.
- Alert limit describes the region not to be exceeded without issuing an alert. There is Horizontal Alert Limit (HAL) and Vertical Alert Limit (VAL).

[1] Source: https://gssc.esa.int/navipedia/index.php/GNSS_Augmentation

- Protection Level (PL) bounds the position error horizontally (Horizontal Protection Level) or vertically (Vertical Protection Level) with a confidence level derived from integrity risk. They are conservative estimate of the user position error with a probability of 1-2x10-7 per approach.
- Time to Alert (TTA) is the maximum allowable time elapsed from the start where H or V position error is greater than H or V Alert Limit and the on-board equipment raises an alert. The most demanding aviation operation TTA is 6 seconds.

From (CLUG, D2.3 - High Level System Requirements 2020), the following railway-aviation equivalences are proposed:

- The Maximum Confidence Interval (MCI) for Operation is equivalent to the Alert Limit defined for aviation.
- The Confidence Interval (CI) between the Maximum and Minimum Safe Front End for Train Unit is equivalent to the Protection Level.

These concepts of MCI for Operations (Alert Level) and of CI for Train Unit (Protection Level) apply to along-track position, along-track speed and along-track acceleration domains. Therefore, an integrity event or hazard occurs when the real position/speed/acceleration is outside the corresponding confidence internal: behind the Maximum Safe Front End or in front of the Minimum Safe Front End. In this case, the position/speed/acceleration error estimate is higher than the confidence interval (Protection Level).

- At this CLUG project phase, there is no defined or required Time to Alert (TTA) value as in the aviation domain. Specifying a fixed value, like in aviation, is not adequate because it depends on the railway strategy to densify the trains on tracks versus lengths of each monitored track edge.

From (CLUG, D2.4 - Preliminary Hazard Analysis 2020), it can be stated that:

- The Integrity risk is independent from train operation phase.
- This integrity risk associated to the Protection Level on along-track position and along-track speed domains is 5*10-10/h for each. These targets to be reached at TLOBU level are very challenging. This figure shall be compared with the most stringent SBAS requirements for aviation operation, 2*10-7/150s. The apportionment of this integrity risk to GNSS/SBAS sensor is out of scope of CLUG project.

It shall be noted that the GNSS + SBAS sensor contribute only to the estimation of position and speed, and that acceleration is estimated by other sensors (typically an IMU).

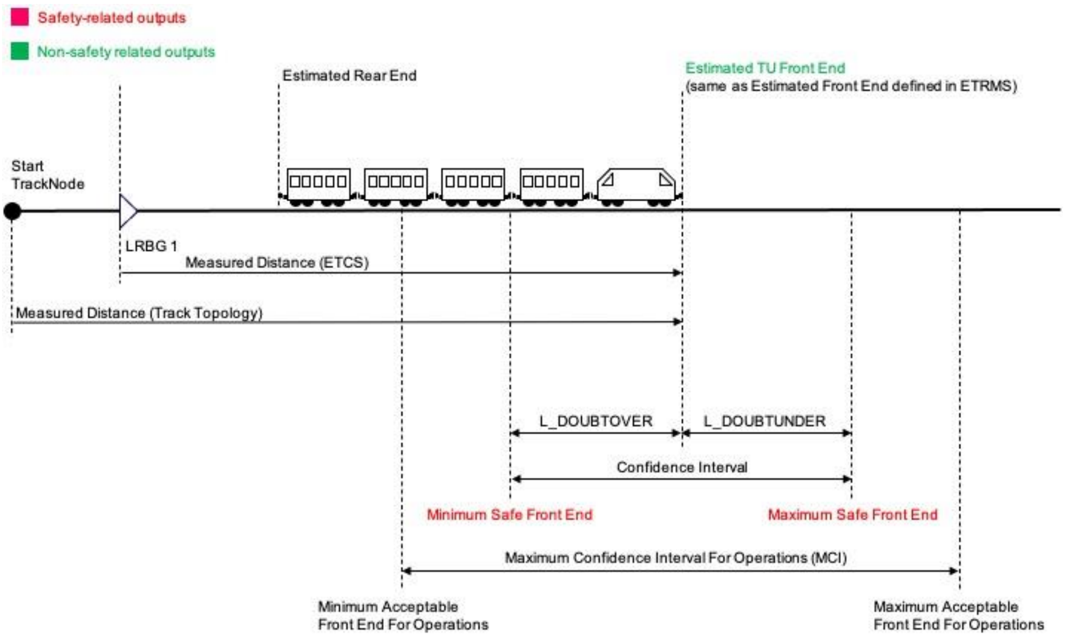

Figure 5: Confidence Interval definition for Train Localisation

The THR (Tolerable Hazard Rate) concept is similar to the integrity risk defined in the aviation sector. The time window exposure for THR is 1 hour as per railway safety requirement whereas integrity risk for aviation operation such as LPV200, the time exposure window is 150s. The THR expresses a risk acceptance level due to occurrence of hazard associated to the train level impact in terms of severity, for which the railway level function (TLOBU) shall be designed.

3.3 Availability

As defined (CLUG, D3.3 - Performances Analysis report 2021), it is proposed to define that the TLOBU system is considered available when:

- Position/Speed Accuracy requirements are met
- Position/Speed CI (Protection Level) < Position/Speed MCI (Alert limit)

3.4 Continuity

Continuity of a system is defined as the capability of this system to perform its functions with the required performance without unscheduled interruptions during the intended operation.

No continuity risk concept is defined in railway domain as performances of the positioning solution are not defined according to the operation or mission of the train.

It shall be noted that a large CI beyond the required performance of MCI (PL>AL) results in loss of capacity (delays of train) but not in cancellation of operations as it is the case in aviation.

3.5 Alert

The TLOBU shall alert the safety critical application in case of integrity event (error position outside the Protection Level).

4 TLOBU FUNCTIONAL NEEDS

4.1 Along-Track Position Requirements Fulfilment

This section defines the railway needs in terms of along-track position performance requirements, how to fulfil them, the SBAS apportionment and the outputs that the SBAS for rail service should provide.

4.1.1 Railway Requirements for Along-Track Position

The most stringent performance requirement from (CLUG, D2.3 - High Level System Requirements 2020) for along-track positioning function at TLOBU level used by applications at safety critical level is the following:

- The half-width of the Maximum Confidence Interval for Operations (MCI) in nominal/reverse direction is 10 m for speed lower or equal to 36 km/h with integrity risk of $1\ to\ 5 \times 10^{-10}/hr$. Then the MCI linearly increases as defined in the figure below.

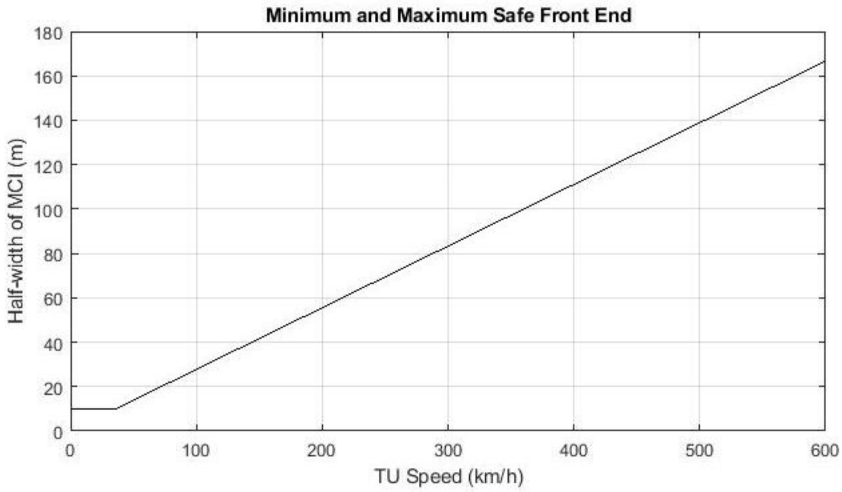

Figure 6: Min and max safe front end position versus train speed

It shall be noted that at this maturity, no position accuracy requirement with 2 sigma precision has been defined for safety critical applications but only protection level requirements (linked to integrity risk).

4.1.2 Requirements fulfilment for Along-Track Position

Reaching the MCI performance requirement is likely to require an improvement of the corrections provided by SBAS service when comparing them to the current results[2]. As MCI expresses an alert level, it means the accuracy to reach shall be lower than 10 m. This section presents different approaches for improving SBAS corrections.

4.1.2.1 Railway SBAS position Augmentation Improvement

Generally, there are different ways to improve SBAS position corrections by providing more accurate orbits, clocks and biases estimates for GPS and Galileo satellites through:

1. Improving the quality of the measurements (through evolutions of the ground systems);
2. Improving the orbit and clock ODTS (Orbit Determination and Clock Synchronisation) algorithms by extracting bias from error bounds

[2] Source: EGNOS Open Service real time performance (https://egnos-user-support.essp-sas.eu/new_egnos_ops/os_deviation) on position accuracy w/o considering integrity bounds compared to GPS. EGNOS correction improves the positioning accuracy in Horizontal plane roughly by a factor of 2 at 2 sigma at lower latitude.

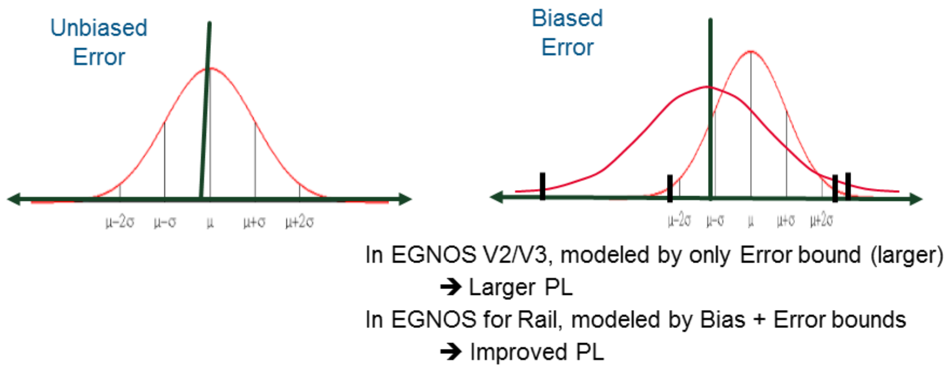

Figure 7: EGNOS V2/V3 assumed unbiased errors vs separation of bias and error bounds (optimal)

3. Adding new measurements via new sensor stations into the Orbit Determination and Time Synchronisation (ODTS) processing sub-system.
4. Increasing the SBAS correction production refresh rate.

Table 1 Improving the positioning estimate though SBAS.

Solutions	Pro's	Con's
1. SBAS driven: Improving the quality of the measurements	Generally done during the life time of the SBAS in case of issue of measurement quality (through site survey) Technique well known	Does not improve the accuracy if quality is already provided. To be reassessed according to EGNOS V3 performance
2. SBAS driven: Improving the Orbit and Clock algorithm	Algorithms being improved (TBC when EGNOS V3 performance will be available): 1) providing more digits will reduce the range error bounds so will reduce the train real time Protection Levels; 2) potential Orbit and Clock bias could conduct to separate bias from error bounds so will reduce the width of error bounds	Increase the SBAS data rate.
3. SBAS driven: Adding new sensor stations	Depending on the location of new sensor station (in Europe and/or worldwide), can really improve the orbit determination accuracy (thanks to worldwide stations). This solution is used in PPP techniques for orbit/clock/bias estimates. Adding worldwide station improve ODTS accuracy and enables to monitor satellites 100% of the time avoiding to protect against feared event occurred during the period	Complex and expensive solution to add worldwide and maintain new sensor station on sites belonging to European countries. In addition, the selection of the sites shall ensure each satellite to be pursued typically by 4[3] stations in order to feed the ODTS sub-system but also to be monitored for integrity purpose.

[3] For snapshot Reverse PVT (UDRE, orbit and clock product integrity monitoring) it is theoretically necessary to have 4 RIMS seeing a satellite. However, in EGNOS v3 design it can be achieved with fewer satellites. For integrity monitoring, having 2 RIMS seeing each satellite brings robustness in case where one RIMS fails.

Solutions	Pro's	Con's
	where the SV is not visible.	
4. SBAS driven: Increasing the SBAS correction production refresh rate	Easier to implement	The validity of orbit EGNOS correction is typically 2 hours based on typically 48 hours of measurements. Reducing this production validity would not improve drastically the accuracy due to time-correlated measurements contained in the measurements batch. Satellite Clock estimates is performed every 30 seconds.

These improvements of augmentation correction could be provided as specific parameters for rail service or could be provided as part of improvement of current EGNOS V3 DFMC corrections. At this stage of the study, it has been considered not to provide dedicated correction parameters for rail but to consider as an improvement of current service.

4.1.2.2 Railway SBAS position Integrity Monitoring

The SBAS integrity concept for railway is described in (CLUG, D3.1.4 - Integrity Concepts & Algorithms 2021). Integrity monitoring function is composed of:

- Fault detection and exclusion function
- Protection level computation function in fault-free and faulty situations

SBAS and TLOBU integrity monitoring functions shall protect against feared events as per the allocation between the SBAS and the TLOBU.

This section sums up the main drivers of this integrity concept to be supported by the Rail SBAS service. It shall be noted that the safety case analysis shall be confirmed from SBAS system design. This system design is not addressed in this study. It is recalled that the SBAS as per EGNOS V3 guarantees integrity in the pseudorange domain and in the position domain. The integrity impact probability between the pseudorange and the position domain is conservatively set to 1.

Therefore the main outcomes of the integrity concept associated to the along-track function are the following:

1. Data fusion algorithms are Bayesian algorithms which make assumptions on the state dynamics and on the distribution of the measurement errors. The dynamic model is used for state prediction whereas the measurements are used to correct the prediction. Kalman Filter (KF) assumes that the measurement error is white Gaussian noise. The consequence is that, if the measurement error is correlated in time, the Kalman Filter is suboptimal in terms of accuracy and the estimated state covariance is no longer conservative. Different approaches are explained in (CLUG, D3.1.4 - Integrity Concepts & Algorithms 2021). The best approach consists in having the SBAS providing satellite residual error correlation time. Indeed, sequential user algorithms are to be informed with the correlation time of the measurement errors for implementing techniques so that the state covariance is conservative (which is used for protection levels computation). This parameter is satellite dependant.
2. Generally, as Kalman filter is used in the CLUG integrity concept, the SBAS shall provide paired overbounding parameters (biases and sigmas) and not only sigma of overbounding Gaussian CDF (Cumulative Distribution Function) as it is done for current integrity parameters for aviation sector. The introduction of bias of paired overbounding will enable to reduce the range of sigmas of integrity parameters and therefore to get less conservative protection levels.
3. Integrity DFRE parameter (see section §4.1.3.1) is computed by SBAS for aviation sector according to MOPS. The SBAS for railway shall provide dedicated DFRE for rail (sigma and bias) assuming that the integrity risk for rail is lower than the aviation one and taking into account this initialisation period trade-off.

Note : smoothing filters. It shall be noted that the aviation receiver applies an ionosphere-free code-carrier smoothing filter specified in DFMC MOPS to reduce the noisy code pseudorange measurements with precise carrier phase measurements. This filter is initialised during a period of 100s to reach a steady-state. A main issue for rail is that this filter reinitialisation shall occur after each masking event due to the environment. Therefore, this will reduce the availability of the service to users. In case this period of initialisation is reduced to improve availability, some feared events such as pseudorange step, Code/Carrier Incoherency, Satellite Evil Waveform errors can be propagated during this initialisation period and not correctly bounded at the required integrity risk level. Therefore, it would be necessary to inflate the Protection Level in order to protect the user. This topic is described in (CLUG, D3.1.4 - Integrity Concepts & Algorithms 2021) without more results that could be summarized here. Thus, the assumptions of aviation receiver specified in MOPS shall be updated for railway sector in order to compute appropriate integrity bounding parameters.

4.1.3 Railway SBAS Outputs for Along-Track Position

This section presents the current SBAS Single/Dual Frequency products and the new ones for railway SBAS service that could be defined to fulfil railway Along-Track Position requirements.

4.1.3.1 EGNOS Single/Dual Frequency Correction & Integrity Products

The EGNOS SBAS ground system for Single Frequency Service (currently V2 release and coming V3.1 release) delivers satellite corrections and prediction parameters for each monitored GPS satellite as well as ionospheric corrections and prediction parameters for each IGP (Ionospheric Grid Point).
These parameters for Single Frequency (SF) Service (Safety of Life for Aviation) that are included in the L1 message type, broadcasted from geostationary satellites, are composed of:

- Long term ephemeris and clock error corrections including degradation factors
- Fast corrections including degradation factors
- Satellite position error and Clock offset error estimates covariance matrix associated to the corrections
- Parameters for EGNOS Network Time (ENT) to Universal Time Coordinator (UTC) offset
- ENT parameters
- Ionospheric vertical delays GIVD (Grid Ionospheric Vertical Delay) representing the residual range error due to ionospheric delay after applying the EGNOS ionospheric correction.
- Iono degradation factor
- Safe parameters used to compute the bounding limit respectively for the pseudorange error at the Worst User Location (WUL) and the ionospheric delay, for Single Frequency Service included in the L1 message type:
  - User Differential Range Error (UDRE) parameters and UDRE indicator
  - Grid Ionospheric Vertical Error (GIVE) parameters and GIVE indicator. Ionospheric vertical delays GIVD (Grid Ionospheric Vertical Delay) are defined as correction parameters – See section §4.1.1.

The EGNOS SBAS ground system for Dual Frequency Service (coming V3.2 release) will deliver satellite corrections and prediction parameters for each monitored GPS and Galileo satellite.
These parameters for Dual Frequency (DF) Service (Safety of Life for Aviation) that are included in the L5 message type, broadcasted from geostationary satellites, are composed of:

- SBAS Satellite Ephemeris and covariance matrix
- Satellite Clock-Ephemeris error corrections and covariance matrix
- Degradation parameters
- Parameters for EGNOS Network Time (ENT) to Universal Time Coordinator (UTC) offset

EGNOS SBAS ground system computes these SF or DF correction/integrity parameters regularly based on ground station sensors (RIMS) providing measurements of GPS and Galileo satellites.

4.1.3.2 EGNOS Integrity Products for Rail Safety Service

From these outcomes, it can be concluded that SBAS service for rail should deliver the following parameters to the TLOBU:

- SBAS upper bound of residual error correlation time for each GNSS satellite in order to handle measurement errors correlated in time: Residual Error Correlation Time (RECT)
- DFRE dedicated for railway users and associated bias at WUL. It is proposed to produce only dual frequency range error for rail to take benefit of the second frequency: Railway Dual Frequency Range Error (RDFRE) and Railway Dual Frequency Bias Error (RDFBE).

4.2 ALONG-TRACK SPEED REQUIREMENTS FULFILMENT

This section defines the railway needs in terms of along-track speed performance requirements, how to fulfil them, the SBAS apportionment and the outputs that the SBAS for rail service should provide.

4.2.1 Railway Requirements for Along-Track Speed

The most stringent performance requirement from (CLUG, D2.3 - High Level System Requirements 2020) for along-track speed function used by applications at safety critical level is the following:

- The half-width of the Maximum Confidence Interval Train Unit Speed for Operations is ± 2 km/h for speed lower than 30 km/h with integrity risk of $1\ to\ 5\ \times 10^{-10}/hr$., then increasing linearly up to ± 14 km/h at 600 km/h.

It shall be noted that at this stage no position accuracy requirement for 2 sigma precision has been defined for safety critical applications but only protection level requirements (linked to integrity).

4.2.2 Requirements fulfilment for Along-Track Speed

The GNSS/SBAS/IMU will provide an estimate of train speed thanks to Doppler measurements that will be used in the fusion sensor algorithm. As mentioned in (CLUG, D3.1.3 - Sensor Fusion Algorithms 2021), the use of Doppler measurements within the data fusion algorithm based on EKF is valuable in order to significantly improve the accuracy of the train velocity estimation.

In addition, another speed sensor, e.g. tachometer, will be used to have a global solution providing the speed estimate under integrity risk of $5\ \times 10^{-10}/hr$.

4.2.2.1 Railway SBAS speed Augmentation Improvement

DFMC EGNOS SBAS does not provide any range-rate error for velocity-related integrity. As mentioned in (CLUG, D3.1.4 - Integrity Concepts & Algorithms 2021), the SBAS should provide velocity-related integrity data (first-order of time derivative of range error) in order to bound residual error on the Doppler measurements.

As for position augmentation parameters, the SBAS should provide paired overbounding parameters - biases and sigmas - for velocity-related integrity. See §4.1.2.1 and in particular the item 2 "*Improving the orbit and clock ODTS (Orbit Determination and Clock Synchronisation) algorithms by extracting bias from error bounds*" applied to the GPS and Galileo orbit rates.

4.2.2.2 Railway SBAS speed Integrity Monitoring

Same recommendation as in §4.1.2.2

4.2.3 Railway SBAS Outputs for Along-Track Speed

The SBAS service for rail should deliver the following parameters to the TLOBU to fulfil railway along-track speed requirements:

- Doppler Range Error and Doppler Bias Error for each GNSS satellite at WUL: Doppler Range Error (DPRE) and Doppler Bias Error (DPBE).

4.3 Rail Track Determination Requirements Fulfilment

This section defines the railway needs in terms of rail track determination performance requirements, how to fulfil them, the SBAS apportionment and the outputs that the SBAS for rail service should provide.

4.3.1 Railway Requirements for Track Determination

The most stringent performance requirement from (CLUG, D2.3 - High Level System Requirements 2020) for track selectivity/determination function at TLOBU level used by applications at safety critical level is the following:

- Track selectivity inside TLOBU shall determine the "trackedge identifier" of the track where the train is running with an integrity risk of $\underline{1\ to\ 5\ \times 10^{-10}/hr}$.

4.3.2 Requirements Fulfilment for Track Determination

Rail track determination is a major function in order to identify with a given probability the track edge where the train is.

Because the above integrity requirements are very stringent, SBAS augmentation improvement described in section §4.1.2.1 will not be sufficient. The following section presents other solutions and trade-offs answering the rail track selectivity challenge:

- One solution is based on across-track accuracy solution which shall be typically less than 0,7 meter to determine the track, or to be run only when the digital map informs a sufficient separation distance between tracks. Due to integrity reason, the across-track protection level should be around 1,7 m. These figures can be extracted from EUSPA study (EGNOSHA 2018). This first solution consists in introducing an augmentation solution like Precise Point Positioning (PPP) or Real Time Kinetic relative positioning (RTK) with associated integrity monitoring.
- Another innovative solution uses the on-board sensors fusion to identify the track change. A new approach is reported in paper (ION2020 - Philippe Brocard, Raphael Pons, Gabriele Ligorio, Jan Wendel, Airbus 2020) proposing Along-Track positioning & Track Determination specific algorithms. This paper describes an infrastructure-free multi-sensor based positioning solution for rail signalling. In the proposed approach, the Train Localization On-Board Unit (TLOBU) provides track identification thanks to a separate specific function different from the along-track positioning function. The paper focuses on the performances of these algorithms in function of the quality of their nominal inputs. The problem of integrity monitoring and the sensitivity of the proposed solution with respect to feared events are also qualitatively discussed.

The trade-off between these solutions is described in (CLUG, D3.1.5 - Train Localisation On-Board Unit Design Document (Solution A) 2021). The on-board data fusion determination solution is a good candidate to provide the track information to critical applications. This relative approach exploits the differences in the dynamics that can be observed at intersections, the decision capacity decreases after intersection (e.g. if the tracks are parallel).

4.3.3 Railway SBAS Outputs for Track Determination

The on-board solution for track determination does not require any specific augmentation parameters.

4.4 Authentication Services

Authentication services ensure that signals, GNSS and/or SBAS, are authentic and come from real source. These are parts of FDE functions to be implemented in the TLOBU when available. Indeed, authentication allows detecting and excluding falsified signals. Authentication starts being deployed on GNSS: Galileo OS-NMA is operational in 2021-2022 and some receivers, as for example Septentrio, already implement it.

As mention in (CLUG, D3.1.4 - Integrity Concepts & Algorithms 2021) section § "*Spoofing feared event*", SBAS message needs to be protected against spoofing and authentication is a consistent answer.
So a priori not directly linked to the roadmap for a SBAS service for rail, the TLOBU GNSS and SBAS FDEs need to be augmented by data authentication checks for both GNSS and SBAS data.

4.5 POTENTIAL INTEGRITY SERVICE ASSOCIATED TO THE GALILEO HAS

Non safe Galileo High Accuracy Service (HAS) is being in service in 2021 and confirmed to not provide Safety of Life data, nor currently at the start of the service neither in the future, confer extract here from EUSPA Galileo HAS - Info note[4]:

> "*road autonomous driving is a safety-critical application that requires additional critical measures, such as integrity, to ensure safe navigation.*
> *These will be provided by integrators and service providers integrating various sensors and navigation technologies (including GNSS) in a hybrid solution.* "
> And confer the specific mention for railways "*In the future, it is also planned to introduce GNSS as one of the ERTMS game changers for train signalling. High-accuracy services can further improve the performance of non-safety relevant applications and can reduce the need for additional sensors, helping to further decrease maintenance costs for both railway infrastructure managers and train operators*"
> => **Galileo HAS can't be used for Safety of Life railway applications**.

This service is targeting 20cm accuracy (95%) via E6b space dissemination, providing an interesting feature for train only if it can be ensured safe by an external service or capacity.
In particular, on going studies are evaluating the capacity to augment the Galileo High Accuracy Service (HAS), in terms of safety and integrity levels. Pending these outcomes, having better accuracy should improve TLOBU safe application performance, only if sufficient integrity level is ensured, as the main purpose of EGNOS system.

[4] Source: EUSPA «Galileo High Accuracy Service (HAS) - Info note» 2021

5 GEOGRAPHICAL/SERVICE AREA OF RAILWAY GNSS AUGMENTATION SERVICE

The current EGNOS geographical service area definition, driven by aviation needs, combines service compliance and availability:

- A service area as per ICOA Annex 10 Service Area Definition is defined as follows: “The Service Area shall be defined within an SBAS coverage area where SBAS meets the signal-in-space requirements and supports the corresponding approved operations”.
- The EGNOS geographical coverage area is (latitude, longitude) within respectively [72° N, 20° N], [40° E, 40° W].
- According to Draft SBAS Guidance Material in DFMC SBAS SARPs Attachment D, a coverage area typically corresponds to the union of SBAS satellite footprint areas, comprising one or more service areas. Therefore the coverage area is linked to the dissemination capability of SBAS; in particular, geostationary satellites, being the only satellites broadcasting the SBAS signal, cannot cover higher latitudes than 72° to ensure at least a line of sight above 5° elevation.
- The SBAS service area is defined in aviation in a sky environment and is a sub part of the geographical coverage area where performance requirements are verified pending on the locations of the ground sensor stations (RIMS).

For transposition to the railway sector, we propose a definition of the Rail SBAS Service area in two layers:

1) Functional Service Area, geographical area where the signal allows to meet performance requirements when used by the user application, that does not depend on the signal accessibility by the TLOBU in trains
2) Dissemination Service Area, geographical area where the signal must be accessible by the TLOBU in trains. This area depends on the communication media used for dissemination and on the train environment.

Typically the Rail SBAS Functional Service Area could be defined to include continental European countries (land part only) [72° N, 20° N], [40° E, 40° W]

The extension of this functional service area is an important topic as it drives the size and distribution of the ground sensor station network required for SBAS integrity monitoring function.

The dissemination area is less easy to define as a need. It could be defined with respect to GPS and Galileo signals availability extended to areas where SBAS could be needed when GNSS is not available (e.g. inside tunnels or stations). It may also be defined as a continuity requirement over time, e.g. maximum outage duration.

It is well recognized that reception of SBAS signals/data at TLOBU level from GEO satellite dissemination will be very limited due to masking environment, so a safe ground network dissemination such as Euroradio is mandatory to complement space dissemination. The capacity of different dissemination media is addressed in Chapter §6.

6 DISSEMINATION OF SBAS RAILWAY SERVICE

Beyond the service availability corresponding to delivering a service within its performance requirements, another important topic is related to the availability of the augmentation data at user level (TLOBU).
Shared with SBAS dissemination outcomes from STEMS study[5], CLUG proof of concept study highlights that the current safe (i.e. with integrity ensured up to the aviation users) dissemination of EGNOS V2 and EGNOS V3 via GEO satellites only, is not sufficient for railway. Robustness, i.e. continuity more than availability, of SBAS dissemination is paramount to enable its use in railway, so a solid ground network to be safe and integrate, such as the railway Euroradio (now GSM-R, later FRMCS), is the first pillar for GNSS+SBAS use in railway.
This section presents different solutions and trade-offs of several ways of SBAS data dissemination to make them available continuously as much as possible to the railway users. The following criteria shall be taken into account:

- Geographical coverage where the serviceto be disseminated
- The availability of the dissemination solutions linked to its intrinsic availability due to technology taking care of the environmental conditions at reception level (open sky, urban, tunnel, canopy)
- The robustness of the dissemination solution to make sure that no corruption can be inserted due to the safety of life nature of the service
- The bandwidth available to the SBAS data
- The latency to make sure that the data is available before their end of validity and within the TTA budget (not yet defined in the railway sector cf. §3.2)
- The readiness of the solution in terms of technology
- The CAPEX and OPEX of the dissemination solution. This point will not be assessed as part of this study.

SBAS GEO satellites alone, even when delivering augmentation of a multi GNSS constellation, suffer a tougher environment due to urban canyon or canopy. As explained in (CLUG, D3.1.1 - GNSS Augmentation Usage 2021), the probability of masking GEO SBAS in European (latitude 45° N – 55° N) urban environment is between 0 and 0,5 because of EGNOS GEO are approximately 30° above the horizon in central Europe. It means that a train circulating in urban environment is likely to not receive the augmentation data during urban crossing. As stated in MOPS, the receiver shall use SBAS message until it has timed out. The timeout values are depending on the aviation approach from 12 to 18 seconds. In addition, when using integrity monitoring and no valid message has been received for 4 seconds, all received integrity data shall timeout and then shall be discarded. After acquisition or reacquisition of any SBAS signal, the receiver shall forbid the use of any correction or integrity data collected from this signal until reception of some specific message types (SBAS almanac or ephemeris) which are sent every 120 seconds. Reacquisition is performed after loss of signal or when minimum SBAS satellite signal power is not fulfilled. Therefore to conclude, in European urban environment where probability of masking is high, the TLOBU shall wait up to 120 seconds for the reception of ephemeris, almanac in case of loss of signal to be able to use integrity parameters again. Therefore the dynamic of SBAS message processing at TLOBU in this environment, will induce long periods where the position computed by the receiver will not be safe. The SBAS service availability will be low in urban environment due to masking of GEO signals and therefore must be complemented by other dissemination mean(s).

Following sub-sections presents current and some new SBAS data dissemination solutions in order to improve drastically the SBAS access to the railway users (TLOBU):

- EGNOS GEO L1 (SFSC): current SoL service for aviation, using space dissemination (GEOs)
- EGNOS GEO L5 (DFMC): an upcoming service also SoL service for aviation, using space dissemination (GEOs), alternative or complementing L1
- EGNOS E5b: potential future SoL signal for potentially rail and/or terrestrial users space dissemination
- Internet EDAS: currently disseminated for test or monitoring, but not Safety of Life
- Terrestrial railway SoL network Euroradio currently GSM-R and in future FRMCS that could be connected to a safe dissemination source of EGNOS (currently only GEO L1 and GEO L5 space dissemination ensures data integrity up to end users at aviation DAL B safety level)

[5] Source: STEMS (NSL, TPZ, GMV, TUV consortium). « ESA NAVISP Element 1 - System Suitability for Train Positioning using GNSS in the European Rail Traffic Management System (STEMS) - Executive Summary Report. » 2021.

- Other non GEO satellites that could disseminate L1 and/or L5 and/or E5b still in SoL so under a certain level of Safety and data Integrity
- Combined approach for availability but also mainly for integrity issue: SoL or non-SoL terrestrial network and SoL space dissemination

Before analysing all these means, the following section presents a preliminary estimate of the bandwidth needs based on the railway SBAS products proposed in the previous chapter.

6.1 Railway SBAS Integrity Products Dissemination

6.1.1 Railway SBAS Message Type

In order to optimise the bandwidth to disseminate the parameters defined in section §4.1.3.2 and §4.2.3, it is proposed to adopt the same approach as DFRE dissemination. The bandwidth optimisation is needed as the dissemination means proposed in section §6.2 will include the space segment in addition to terrestrial means:

- Two message types containing 5 tables for the scale of Error correlation time, Doppler range error, associated Doppler range bias, Dual Frequency Range Error for rail and associated range bias. The message types could be organised as defined in Table 2. It shall be noted that at this stage, the range of these parameters is undefined. Further studies should define these ranges and also the required scale factor. The following table provides an example assuming that the Residual Error Correlation Time (RECT)| Doppler Range Error (DPRE)| Doppler Bias Error (DPBE) tables can be formatted in the same message. Depending on the scale factor, additional message types could be introduced.

  These messages would be updated every 120 seconds depending on the operational use case for railway sector.

Table 2 Message type for SBAS Railway Service Parameters Table – Part 1

Information to be disseminated	Name	Length (bits)	Scale factor	Range		Comments
				Min	Max	
Common Header	Common Header	10	N/A	N/A	N/A	
Residual Error Correlation Time (RECT) Table	$RECT_{RECTi=x}$	4	$Scale_{RECT}$	Min_{RECT}	Max_{RECT}	Value of the range error when RECTi=x with x=[0;$Max\_Indicator_{RECT}$]
Doppler Range Error (DPRE) Table	$DPRE_{DPREi=x}$	4	$Scale_{DPRE}$	Min_{DPRE}	Max_{DPRE}	Value of the range error when DPREi=x with x=[0; $Max\_Indicator_{DPRE}$]
Doppler Bias Error (DPBE) Table	$DPBE_{DPBEi=x}$	4	$Scale_{DPBE}$	Min_{DPBE}	Max_{DPBE}	Value of the range error when DPBEi=x with x=[0; $Max\_Indicator_{DPBE}$]
Spare	Spare	4(n+1)				n = max (0, 216-4*($Max\_Indicator_{RECT}$ + $Max\_Indicator_{DPRE}$ + $Max\_Indicator_{DPBE}$)
Common Trailer	Common Trailer	24				

Table 3 Message type for SBAS Railway Service Parameters Table – Part 2

Information to be disseminated	Name	Length (bits)	Scale factor	Range	Comments

				Min	Max	
Common Header	Common Header	10	N/A	N/A	N/A	
Rail Dual Frequency Range Error (RDFRE) Table	$RDFRE_{RDFREi=x}$	4	$Scale_{RDFRE}$	Min_{RDFRE}	Max_{RDFRE}	Value of the range error when RDFREi=x with x=[0; $Max\_Indicator_{RDFRE}$]
Rail Dual Frequency Bias Error (RDFBE) Table	$RDFBE_{RDFBEi=x}$	4	$Scale_{RDFBE}$	Min_{RDFBE}	Max_{RDFBE}	Value of the range error when RDFBEi=x with x=[0; $Max\_Indicator_{RDFBE}$]
Spare	Spare	4(n+1)				n = max (0, 216-4*($Max\_Indicator_{RDFRE}$ + $Max\_Indicator_{RDFBE}$)
Common Trailer	Common Trailer	24				

- 5 message types containing SBAS parameter change indicator. For example, the following table defines the change indicator for DPRE parameter. The change indicator as per Aviation MOPS could have the following meaning:
  - 0 means that the indicator value of the parameter for GNSS augmented satellite has not changed
  - 1 means that the indicator value of the parameter has changed and that the index is transmitted in the associated message type
  - 2 means that the indicator value of the parameter has changed by 1 index
  - 3 means that satellite corresponding to augmented slot is set to “Not for use in SBAS mode”

Table 4 Message type for SBAS Railway Service DPRE Parameter Change Indicator

Information to be disseminated	Name	Length (bits)	Scale factor	Range		Comments
				Min	Max	
Common Header	Common Header	10	N/A	N/A	N/A	
DPRECi	DPRECi 1	2	1	0	3	DPRE indicator for augmented Slot Index 1
	to DPRECi 92	2	1	0	3	DPRE indicator for augmented Slot Index 92[6]
Spare	Spare	32				
Common Trailer	Common Trailer	24				

This message would be updated every 6s depending on the operational use case for railway sector. Nevertheless, it is likely that the frequency of RECTCi message types should be 120 seconds due to the dynamic of correlation time.

[6] To cover GPS, Galileo, Glonas and Beidou constellation as per aviation MOPS

- 9 message types containing the three indexes of each of these parameters (RECT, DPRE, DPBE, RDFRE, RDFBE) for each GNSS satellite (GPS, Galileo, Glonass and Beidou as per MOPS). It can be mentioned that indicators of all parameters which are distributed with the same refresh rate (DPREi, DPBEi, RDFREi, RDFBEi) for the Four GNSS constellation can be transmitted in 9 messages[7]. It is likely that RECTi can be transmitted every 120 seconds.

Table 5 Message type for SBAS Railway Service Parameter Indicator for Augmented slot 1 to 53

Information to be disseminated	Name	Length (bits)	Scale factor	Range		Comments
				Min	Max	
Common Header	Common Header	10	N/A	N/A	N/A	
DPREi	DPREi 1	4	1	0	15	DPRE indicator for augmented Slot Index 1
	to DPREi 53	4	1	0	15	DPRE indicator for augmented Slot Index 53
Spare	Spare	4				
Common Trailer	Common Trailer	24				

Table 6 Message type for SBAS Railway Service Parameter Indicator for Augmented slot 54 to 92

Information to be disseminated	Name	Length (bits)	Scale factor	Range		Comments
				Min	Max	
Common Header	Common Header	10	N/A	N/A	N/A	
DPREi	DPREi 54	4	1	0	15	DPRE indicator for augmented Slot Index 54
	to DPREi 92	4	1	0	15	DPRE indicator for augmented Slot Index 92
Spare	Spare	56				This spare can be used to disseminate indicator from other parameters for optimisation purpose.
Common Trailer	Common Trailer	24				

The messages for DPREi, DPBEi, RDFREi, RDFBEi would be updated every 6 seconds depending on the operational use case for railway sector.

[7] 7 messages x 212 bits > 92 satellites x 4 bits x 4 parameters > 6 messages x 212 bits

6.1.2 Data Rate needs for Railway Augmentation

A rough assessment of additional information to be disseminated using message type payload bit is provided in the following table.

Table 7 Assessment of data rate required for SBAS service for rail

SBAS Railway Service Integrity Message Type	Number of bits	Typical Refresh rate in seconds
RECT Parameter Table Message Type	250	120
DPRE Parameter Table Message Type	250	120
DPBE Parameter Table Message Type	250	120
RDFRE Parameter Table Message Type	250	120
RDFBE Parameter Table Message Type	250	120
RECT Change Indicator Parameter Message Type	250	120
DPRE Change Indicator Parameter Message Type	250	6
DPBE Change Indicator Parameter Message Type	250	6
RDFRE Change Indicator Parameter Message Type	250	6
RDFBE Change Indicator Parameter Message Type	250	6
RECT Indicator Parameter Message Type	500	120
DPRE Indicator Parameter Message Type	500	6
DPBE Indicator Parameter Message Type	500	6
RDFRE Indicator Parameter Message Type	500	6
RDFBE Indicator Parameter Message Type	250[8]	6

The data rate required as a first estimate depending on scale factor of SBAS Railway integrity parameters will be as a minimum 550 bits/s.

6.2 Service Dissemination

6.2.1 EGNOS GEO L1

L1 signal is operationally used to disseminate the EGNOS SoL service for aviation. As described in the MOPS, all SBAS satellites and ionosphere correction data to be sent to the users cannot be sent at each epoch (every second) due to its specification as being a "GPS like signal" (250 bits/s for complete message and corresponding to 212 bits/s for the augmentation corrections and integrity data). In order to allow the users to receive all SBAS products, the SBAS standard splits the data into Message Type (MT) with an associated refresh rate (typically between 120 seconds to 300 seconds depending on the type of data) involving a need of reception continuity. The current data rate is mainly occupied by MT2 (Fast corrections), MT6 (UDREI), MT24 (mixed fast and long

[8] The indicators RDFBEi for Augmented slot 54 to 93 will be included in the message types of DPREi, DPBEi, RDFREi for Augmented slot 54 to 93

term corrections) and MT26 (Ionospheric delay correction)[9]. Therefore, each MT message transporting 212 bits is roughly disseminated every 10 seconds.
This signal being already deployed and operational for SoL aviation, its adaptation for railway cannot be envisaged. Adding new L1 signals, whatever "GPS-like" with additional PRN number or new modulation type, i.e. at the same frequencies allocated to aviation users, is hardly conceivable because of the "GPS-like" signal performance requirements applied to L1. Orthogonal component with new modulation as done for Galileo could be explored.

6.2.2 EGNOS GEO L5

This signal, almost defined at the time of writing (DFMC MOPS and SARPS should be published soon) will be used to disseminate the DFMC augmented data service as part of EGNOS V3 for aviation SoL service too. The data rate is identical to EGNOS GEO L1 channel. From DFMC MOPS ED-259 v0.4, SBABS DF Integrity Information (DFREI) shall be broadcast at least every 6 seconds for each monitored satellite Message Type 31 (Satellite Mask) specifies up to 92 slots to address corrections for GPS satellites, Galileo satellites, Beidou satellites, Glonass satellites and other for future GNSS satellites and reserved/spare. Assuming a complete GPS and Galileo constellation and 2/3 of satellites being simultaneously monitored (as visible), the GEO L5 estimated data rate occupation by message type for EGNOS V3 without considering Message type 63 (Null message) is, in nominal case (no alarm raised) about 72% leaving 70 bits/s for new messages (~ 60 useful bits/s) .
Because this signal is almost deployed to be operational for SoL aviation at short/middle term, its adaptation for railway is also unlikely.
There are 2 orientations to explore:

- potential capacity of the signal modulation type to add new data stream at equivalent rate, but several types of content are envisaged, including an EGNOS DFMC complement for rail.
- addition of new L5 signals by additional PRN numbers and separated to the aviation PRN range. Currently PRN ranges are shared between Galileo (so under EU authorization), aviation and spare range are identified. Considering the signal performance requirements applied to L5 are less stringent than the L1 ones, it increases the probability of feasibility even if L5 frequency is also defined as an aviation reserved frequency.

6.2.3 EGNOS E5b

E5b signal is another GNSS frequency operationally used by Galileo (so under EU influence) and not yet defined as a safety of life frequency for any service user.
It is a very good candidate for SBAS for rail (or for terrestrial users or for Range Multi-Missions service). Several service candidates are identified to be allocated to E5b frequency within its data rate capacity…
This E5b signal, if confirmed to host SBAS for rail data, is very promising to complement the ground terrestrial railway network as synthesised in §6.2.6.

6.2.4 Internet EDAS

Internet EDAS[10] provides ground-based access to EGNOS data through a collection of services which are accessible to registered users through internet : Service Level 0 (SL0), Service Level 2 (SL2), Data Filtering, SISNeT, NTRIP and FTP services. The EDAS service availability is between 98% to 98,5%. The latency[11] is between 1.3 to 1.75 seconds for UDP/TCP-based protocols. Internet EDAS is not a safety dissemination vector and cannot be used today to disseminate a Safety of life service. EDAS is independent of the internet access at end-user.

6.2.5 Terrestrial Railway SoL channel

The EU directives officially adopted the GSM-R as the basis for mobile communication between train and track for voice (train radio), control-command and in particular the localization signalling data (ETCS) targeting ERTMS level 3 for which the train localisation on the track won't be done anymore from the rail infrastructure but from the train itself (TLOBU). So the European Rail Traffic Management System aims to form as much as possible a worldwide standard. GSM-R has been a great success not only in Europe where more than 100,000 km of railway tracks are daily operated through GSM-R but also worldwide. GSM-R is intended to be replaced by FRMCS (see below).

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[9] Source : https://egnos-user-support.essp-sas.eu/new_egnos_ops/message_bandwidth
[10] Source : EGNOS Data Access Service (EDAS) Service Definition Issue 2.2
[11] It should be highlighted that EDAS services latency performance is nominally lower than these figures.

European Network size	In km of line	Percentage of (%)	
		Total network	GSM-R network
Total Railway Network	218 726		
GSM-R planned	162 978	74,5%	
GSM-R constructed	114 782	52,5%	70,4%

Figure 8: Number of km of GSM-R planned& constructed lines in 2016[12]

Future Railway Mobile Communication System (FRMCS) is the future worldwide telecommunication system designed by International Union of Railway (UIC), in close cooperation with the different stakeholders from the rail sector, as the successor of GSM-R.
This standard defines use cases where the FRMCS will be used including the following ones:

- Automatic Train Protection data communication
- Train Integrity monitoring data communication
- Inter-working and service continuation with GSM-R to manage the interoperability between those 2 systems

Until the end of 2022, FRMCS is still in preliminary exploratory phase. From 2023, calls for tender will be prepared and opened for the different network elements (5G core, base station networks, onboard system, etc). This phase will end-up in 2027 with the selection of industrials that will deploy the service:

- 2027-2029: deployment on a pilot line
- From 2029: deployment on full national network

The Telecom system will manage QoS such as critical data or very critical data and multiple latencies.
Disseminating satellite augmentation data thanks to the GSM-R network or FRMCS network will involve to develop an end to end transmission with integrity functions ensuring the delivery without corruption up to all railway users (TLOBU) at the same time and without Euroradio network single point of failure at the integrity level of SIL 4.
Then the SBAS data coming from the EGNOS system shall safely reach the Euroradio network. Possible solutions:

1) EGNOS system is upgraded to enable a safe direct connection from the EGNOS DFMC Central Processing Facilities (CPF) and complement needed augmentation data from the EGNOS4rail CPF, both connected to the Euroradio network with redundant schemes. EGNOS CPF are already redounded, so redounded connection to Euroradio is easily feasible. This is not possible with the existing EGNOS Data Access Service (EDAS), dissemination by Internet, only used for test or monitoring so not Safety of Life for any sector;

[12] Source: https://www.era.europa.eu/sites/default/files/library/docs/studies/systra_study_on_migration_of_railway_radio_communication_from_gsm-r_to_other_solutions_en.pdf

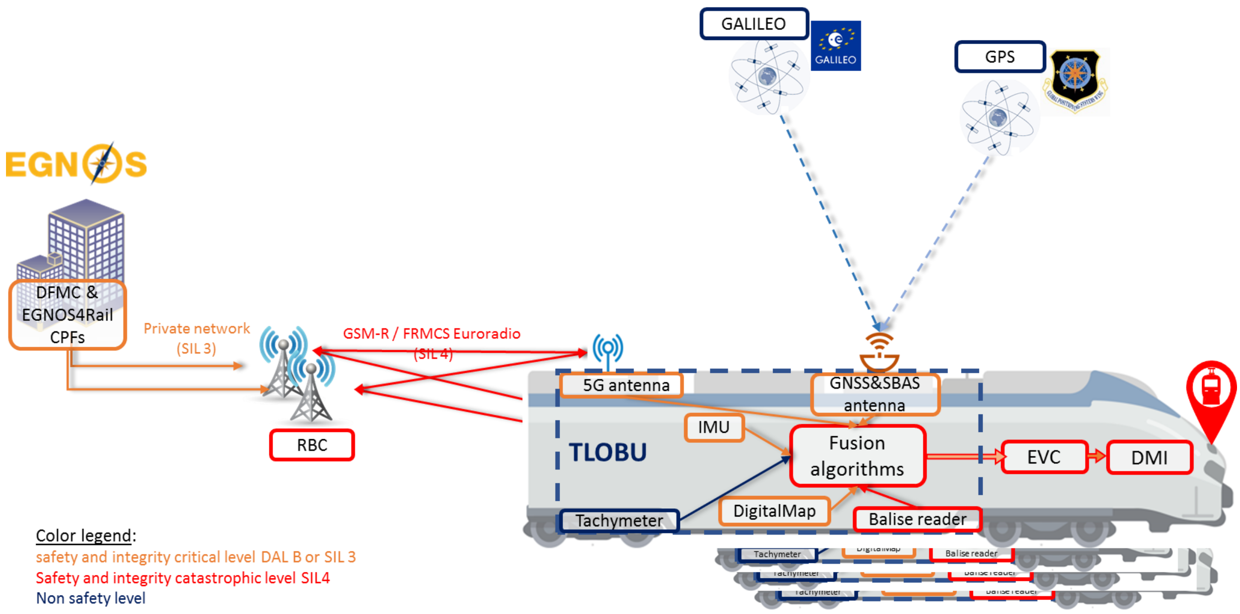

Figure 9: terrestrial dissemination only via private link between EGNOS to Euroradio

2) The ERTMS change request (CR1368) will only be part of the next ERTMS TSI update in 2027, and it is fostering a connection from the SBAS safe space dissemination (L1 and L5) to the railway safe terrestrial network via track side receivers (SIL 4); so involving the connection of the aviation DAL B safety level to the railway SIL 4 safety level that is not obvious because certification translation between aviation and railway does not exist and because DAL B THR is insufficient to comply to SIL 4 THR. This is also the assumption of SBAS dissemination in the STEMS study[13].

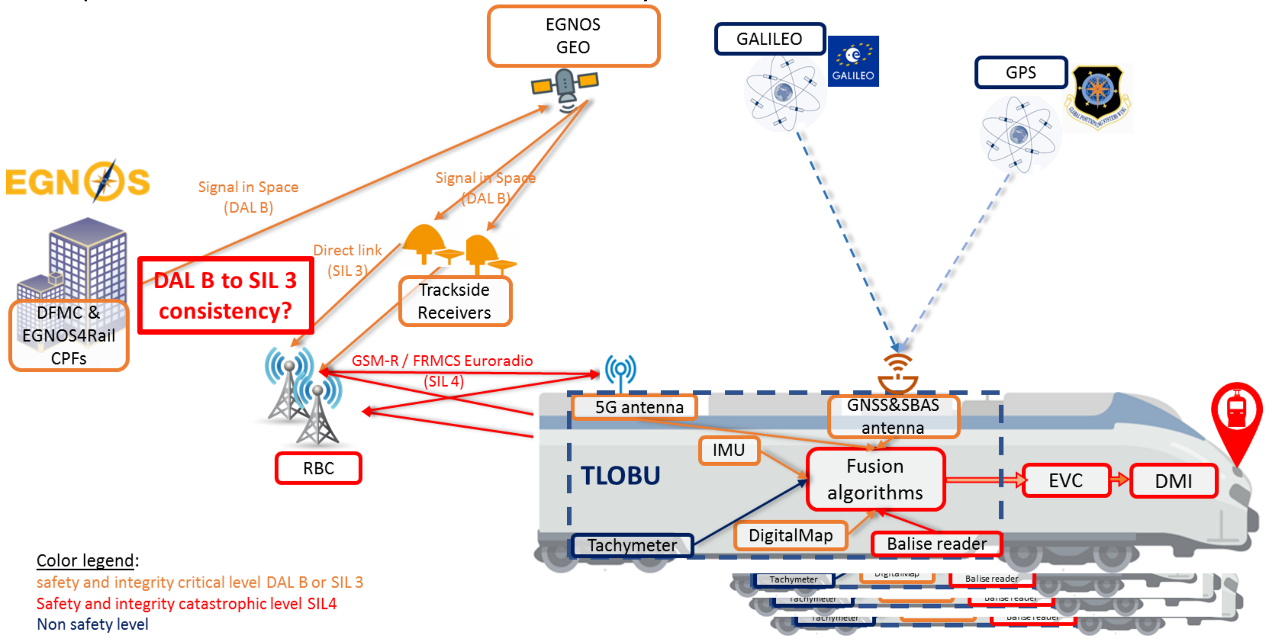

Figure 10: terrestrial dissemination only via SBAS trackside receiver (ERTMS CR1368)

3) Dual approach both terrestrial and space dissemination, see next § 6.2.7

Main drawbacks of solutions 1) and 2) are:

- to ensure the safe and integrity level (SIL 4) up to each train TLOBU;
- to ensure low latency constraint(s), in relation to TTA, not sufficiently defined yet in this CLUG phase;
- to ensure availability and continuity for each TLOBU involving strong Euroradio network equipment redundancy against trackside equipment potential failures or vandalism.

[13] Source: STEMS (NSL, TPZ, GMV, TUV consortium). « ESA NAVISP Element 1 - System Suitability for Train Positioning using GNSS in the European Rail Traffic Management System (STEMS) - Executive Summary Report. » 2021.

6.2.6 Other non GEO satellite that could disseminate L1 and/or L5 and/or E5b

Today the MOPS on L1 requires a stringent time-synchronisation schema at the output of the SBAS satellite antenna with regard to the GPS time, putting a high technical complexity into the SBAS NLES (Dissemination station to the SBAS GEO). This time synchronisation is relaxed for L5/E5b which makes the usage of non-GEO satellites for dissemination easier than L1. [14]

Therefore, satellite constellations in non-GEO orbits (LEO, MEO and HEO/IGSO) may be good candidates to disseminate over L5/E5b. Applied to Europe, they provide better visibility in urban canyon environment or mountains thanks to their higher latitudes than GEO, cf. (CLUG, D3.1.1 - GNSS Augmentation Usage 2021) section §4.2. For example, Japan develops QZSS system based on GSO satellites. QZSS system allows improving precision of GPS and is less sensitive to environment.

Due to this relaxation, the dissemination station complexity in SBAS ground segment can be efficiently reduced in terms of technical complexity, CAPEX and OPEX.

Some satellite orbits key elements:

<u>LEO satellites</u>

Satellites in LEO orbits, hosting a SBAS payload, could be used to disseminate in real-time the SBAS message. Nevertheless, due to small footprint of LEO L-band antenna (500 – 2000km footprint diameters because of low altitude orbits), it would require a large number of LEO satellites and of emitting stations towards the LEO satellites to disseminate SBAS augmentation messages.

<u>MEO satellite</u>

As for LEO, MEO satellite constellation could be used and particularly Galileo G2G satellites (beyond the first batch of G2G satellites to consider the capacity to host a reduced SBAS payload. The number of satellites over 20° of elevation that will be available at TLOBU interface would be around 6 to 7 satellites in average with a better diversification in azimuth and at least one of them at high elevation angle which improves strongly the availability of SBAS message at TLOBU interface cf. (CLUG, D3.1.1 - GNSS Augmentation Usage 2021) section §4.2.

These satellites could host a dedicated SBAS payload, reduced from the one usually hosted in the SBAS GEO satellites in the world. The SBAS dissemination stations will remain separate and independent from the Galileo system, like for SBAS stations toward GEO. In addition, the dissemination station infrastructure cost of the SBAS ground segment would be strongly reduced compared to LEO and should be cheaper, or comparable pending unexpected requirements, to the existing ones for GEO.

<u>HEO/IGSO satellite</u>

As LEO and MEO, HEO/IGSO satellites are a good target to host a SBAS payload for dissemination purpose. The interest of this orbit is its capacity to offer permanently a high elevation angle for land user visibility, centred to European land area (>~70° with 3 equi-party IGSO satellites). So 2 or 3 IGSO satellites, + 1 backup in orbit, would be enough to cover Europe. The main drawbacks of the IGSO solution are double:

- the lack of existing or forecasted telecom/science/observation/civil missions to become reality and so to host a SBAS payload;
- and its complete infrastructure to create.

Indeed, more or less to be deeply analysis for Europe land area, MEO and IGSO satellites provide a very high level of visibility so better availability of dissemination message up to TLOBU in urban canyons situations, mountain area and also in higher Europe latitude region. The dissemination station infrastructure cost of the SBAS ground segment would be reduced compared to LEO, and finally in a lower or equivalent number of current GEO NLES uplink stations towards GEOs: 3 GEOs (2 operational and 1 backup), 2 NLES per GEO.

From this high-level analysis, it can be anticipated that MEO and IGSO are better candidates to disseminate SBAS data for rail.

[14] Range steering: code phase deviation (~absolute ranging bias at satellite antenna output): L1 (<1µs) is 1000 times more stringent than L5 and assumed E5b (<1ms), cf ICAO DFMC SBAS SARPs (mainly Part B v2-1) defining the L1 & L5 steering requirements

6.2.7 Combined approach: terrestrial and space

First approach is the one recommended via the current ERTMS change request (CR1368) mentioned in §6.2.5. It is not in the scope of the combined approach here proposed.

Indeed, this approach, strongly recommended by Airbus, consists in **disseminating the SBAS railway data via the terrestrial network Euroradio** being SoL qualified but potentially "not reasonably feasible up to SIL 4 level" (catastrophic safety level), **combined with a space SoL dissemination with an easy data integrity check mechanism and a very low latency capacity safely ensured up to each TLOBU** under the coverage (same data integrity mechanism as for Aviation). Thus, it prevents easily from the risk of single point of failure into the terrestrial network Euroradio. Several reasons justifying this:

- to improve the availability and continuity of service coverage due to tough environment (not accessible by satellite) or Terrestrial Channel blank zone (Infrastructure not deployed) or local trackside equipment potential failures or vandalism;
- even not continuously, it will offer an **obvious double independent links to ensure the required railway integrity level (currently in CLUG: SIL 4) of SBAS data dissemination from the EGNOS service data for rail up to the railway users (TLOBU) within a low latency for Time to Alert purpose**. This can simply be done by simple integrity check function at TLOBU level, like it is done by EGNOS/NLES at safety level DAL B ensuring integrity up to the aviation user Receivers.

Indeed, the current Integrity/Safety level of EGNOS L1 and L5 (coming DFMC) is at the DAL B level for aviation having no correspondence to the here CLUG required level at SIL 4 for mainly of the localization parameters.

A solution to satisfy the railway safety and integrity level could consist in a combined dissemination of 2 demonstrated independent safe networks:

- EGNOS ground dissemination connected to the railway FRMCS Euroradio of the DFMC data and potentially the needed DFMC complement data for railway, thanks to the EGNOS DFMC CPF and a EGNOS for rail CPF (or EGNOS Range Multi-Missions CPF);
- EGNOS space dissemination of (L1,) L5, E5b (with hopefully the needed DFMC complement data for railway) thanks to GEO in short term prototyping target, then more importantly and efficiently to MEO or IGSO satellites in middle / long term;

Space dissemination will involve some data interruptions due to local environment. Pending both a TTA value not sufficiently defined yet in this CLUG phase, and these interruption durations, the integrity level could be upgraded from DAL B ("kind of SIL 3 THR") to the required railway SIL 4 level thanks to these independent means.

Indeed, similarity of non-continuous safe data mechanism is observed and accepted in the current rail system:

- Absolute position is provided in a discrete manner because of balises every few meters up to around 2km,
- Balise reader hazard rate is lower than SIL 4 rate for detection but upgraded thanks to independent periodic monitoring of good behaviour enabling to reach and comply the SIL 4 level (cf. (ERTMS/ETCS 2016, issue 3.6.0).

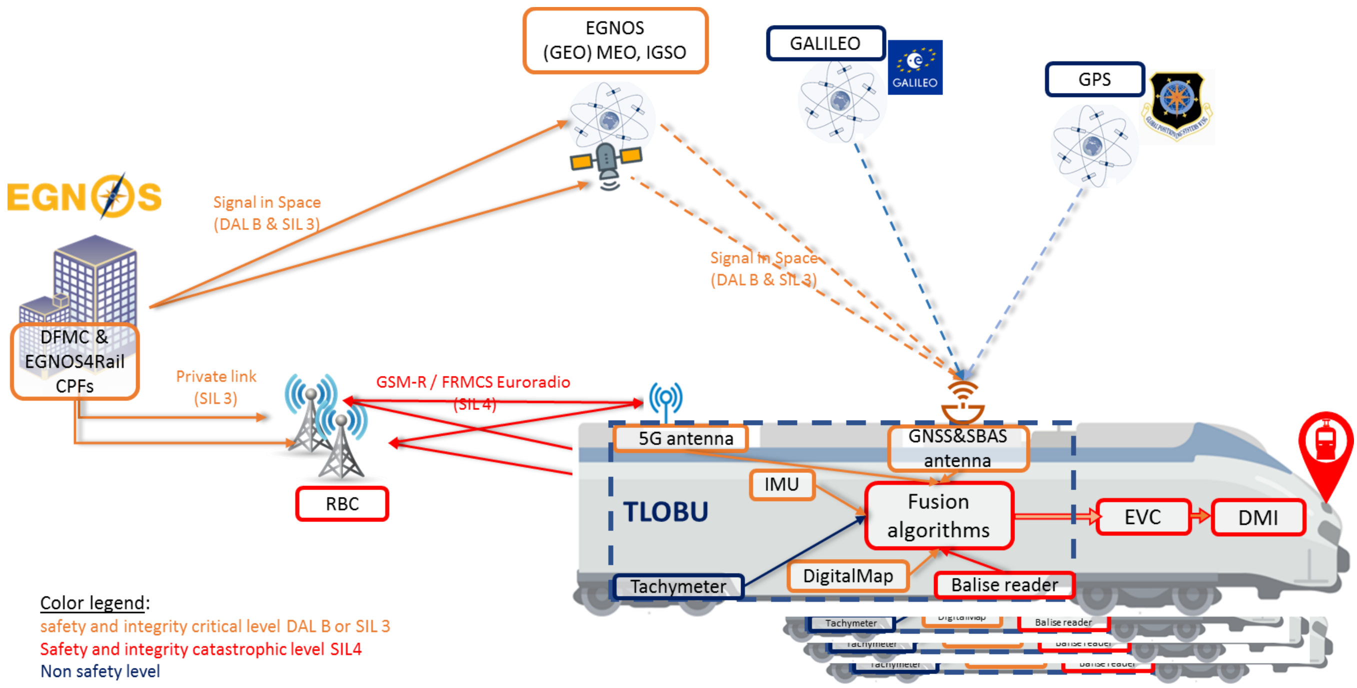

Figure 11: Combined terrestrial and space dissemination for integrity check up to TLOBU and improved availability and continuity

This approach upgrade the safety level of SBAS data received at each TLOBU:

- EGNOS CPF {DFMC and EGNOS for rail or RMM} are qualified at railway SIL 3 safety level, received with the same SIL3 level at the TLOBU Euroradio 5G/FRMCS receiver; These data are redounded by space dissemination for integrity check up to TLOBU and improved availability and continuity;
- EGNOS CPF DFMC is qualified at aviation DAL B safety level, received with the same DAL B level at the TLOBU GNSS+SBAS receiver via the Signal in Space;
- Completed by independent EGNOS CPF for rail or RMM is qualified at railway SIL 3 safety level, received with the same SIL3 level at the TLOBU GNSS+SBAS receiver via the Signal in Space;

Thus, both independent ground and space disseminations should upgrade the railway safety level to SIL 4 (TBC by certification authorities).

6.2.8 Service Dissemination Trade-off

The following table presents the trade-off of the dissemination of SBAS augmentation data for railway. Qualitative trade-off and adequacy for railways or for terrestrial users in general:

- In red: not adapted;
- In orange: not adapted but could be an intermediate solution for prototyping and adoption before an operational train localisation system;
- In green: well adapted.

Table 8 Trade-off of Service dissemination

Solutions	Pro's	Con's
1. **EGNOS GEO L1 (SFSC)**	Existing signal used for Aviation SoL.	GEO L1 is a sanctuary for aviation SoL. As explained in section §6, availability of the land user reception is poor because of EGNOS GEO are approximately 30° above the horizon in central Europe.
2. **EGNOS GEO L5 (DFMC)**	Opportunity to "insert" SBAS for rail data complementing DFMC SBAS data for Aviation. These rail data could be used for Aviation as a new dual frequency	L5 frequency is also defined as aviation reserved frequency. As explained in section §6, availability of the land user reception is poor because of EGNOS GEO are approximately 30° above

Solutions	Pro's	Con's
	Safety of Life service. Existing SoL dissemination infrastructure enabling GNSS+SBAS introduction in train localisation for prototyping and adoption before an operational train localisation system.	the horizon in central Europe. EGNOS data rate inducing message sequencing and refresh against masking rate in railway.
3. EGNOS E5B potential future SoL signal	Usage of a complete new channel under SBAS angle to disseminate railway SBAS augmentation parameters (or Range Multi Missions) More "under EU control" as E5B is a frequency allocated to Galileo.	If disseminated by GEO: same issue of availability of the land user reception. Several different services are candidating on E5B such as no SoL PPP so assessed out of SBAS scope procuring SoL services first. As explained in section §6, availability of the land user reception is poor because of EGNOS GEO are approximately 30° above the horizon in central Europe.
4. Internet EDAS	Existing non SoL dissemination infrastructure enabling GNSS+SBAS introduction in train localisation for prototyping and adoption before an operational train localisation system. No issue of bandwidth nor latency.	Currently used for test or monitoring only. EDAS infrastructure not developed according to aviation safety standard. No forecast to become SoL.
5. Terrestrial Railway SoL network Euroradio	Existing Euroradio infrastructure (GSM-R to become FRMCS). This channel support safety information used for railway signalling system at SIL 4 TBC. TBC: this dissemination channel will reduce the TTA by 450 ms compared to GEO assuming 50 ms Euroradio performance.	GSM-R Adoption is not complete in Europe. Not all the lines are deployed with GSM-R To developed the connection between SBAS system to Euroradio and to ensure integrity of the data up to each railway users (TLOBU)
6. Other non GEO satellite that could disseminate L1 and/or L5 and/or E5b	MEO: Future G2G constellation could be a good candidate with an existing infrastructure. Good availability of the land user reception in urban canyons and mountain areas. Could be in service ~2028-2030 via G2G batch 2. TBC: Less complex NLES to develop than GEO one. HEO/IGSO: good availability of the land user reception in urban canyons and mountain areas. TBC: Less complex NLES to develop than GEO one.	MEO: ≈6 NLES MEO stations to create. HEO/IGSO: Space missions to create with new space control infrastructure requiring a high investment; Ground segment, so 4 to 6 number of NLES IGSO stations to create. Won't be in operation before 2030-2035.
7. Combined approach (Terrestrial and space)	Existing Euroradio infrastructure (GSM-R to become FRMCS) to be the baseline dissemination mean, complemented by space dissemination based on non-GEO and/or potentially GEO (ready for use) for: Quick TLOBU introduction in train;	Won't be in operation if IGSO 2030-2035.

Solutions	Pro's	Con's
	Strong availability for reception whatever environment; Solution ensuring integrity dissemination of the data up to each railway users (TLOBU). Could be in operation if MEO via G2G batch 2 ~2028-2030.	

Following the required bandwidth estimated in previous section, the best solution consists in disseminated via terrestrial network and non-GEO satellite channels (MEO or HEO/IGSO) to maximise the availability of railway SBAS message at TLOBU interface and to ensure integrity and time to alert at required high safety level. Further analysis shall be conducted on non-GEO satellite dissemination and are out of scope of CLUG study.

7 CONCLUSION

This document wraps up multiple recommendations from CLUG project documentation in order to propose a future SBAS augmentation service for railway, that can also be an opportunity for other terrestrial users because at pseudo range and range-rate level. This service would include the additional integrity parameters that shall be disseminated safely to the train localization functions embedded in the TLOBU.

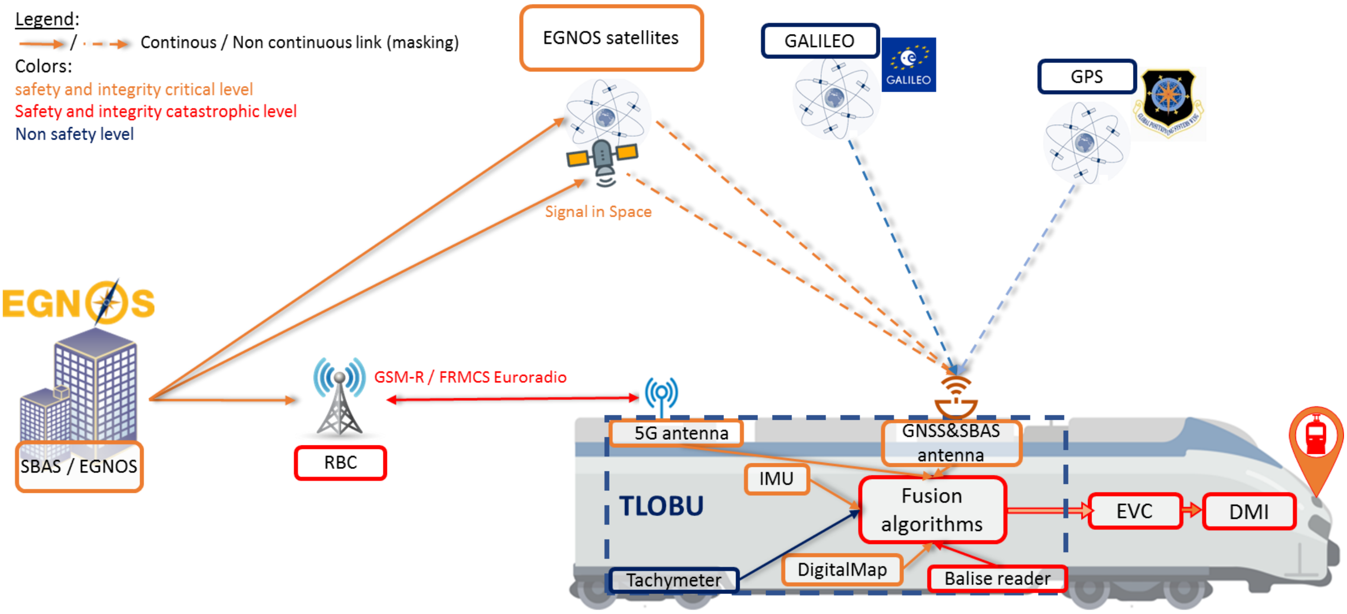

Figure 12: recommended combined terrestrial and space dissemination for real time integrity verification up to TLOBU, and for improved availability and continuity

This will reduce the train Protection Levels to comply more on the railway requirement, under the same safety level.

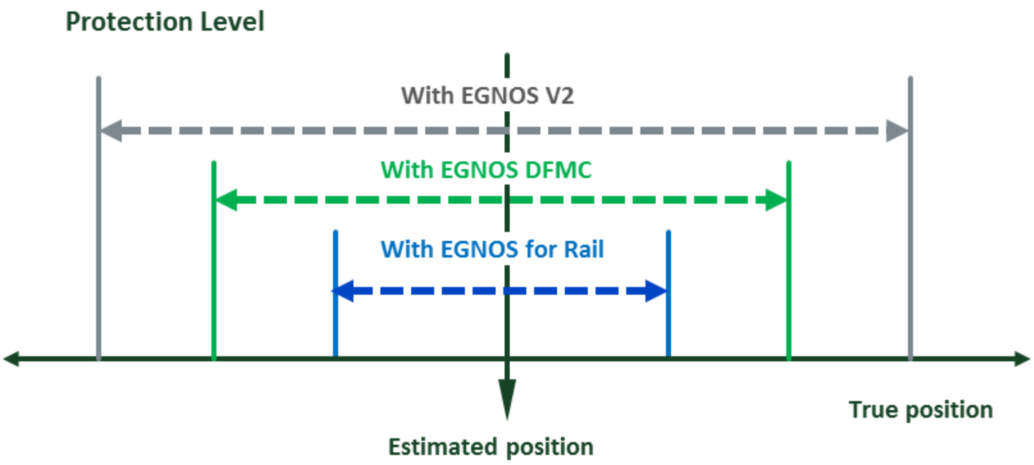

Figure 13: Qualitative train protection levels versus EGNOS versions

In addition to this new service, the TLOBU shall embark new type of algorithm for track determination.

The current CLUG TLOBU proof of concept addresses 2 main objectives:

- Firstly, the technical performance to fulfil the localization mission for train, and
- Secondly, to provide this at the required safety level defined and requested from WP2.

Among the two, the objective to reach the required safety level meeting integrity constraints is more challenging. It is essential to have a prototyping phase in post processing mode then in shadowing mode to verify the attainable realistic levels for both objectives. This prototyping phase can confirm the different envisaged approaches

1. applicability of the DFMC service and achievable performance levels
2. Improvements by a dedicated Augmentation Service for Rail, associated with a Bayesian-based receiver

It is recalled that current assessment of CLUG, cf. (CLUG, D3.3 - Performances Analysis report 2021) demonstrates that DFMC service alone is not sufficient to meet all the integrity performance targets set in CLUG WP2 "*Mission Definition and System Requirements*".
Indeed, the implemented method enables to get predicted performance results versus targeted safety integrity risk by Tolerable Hazard Rate without the need of real data; the performance results is the availability of the estimated safe position ensured inside the Maximum Confidence Interval.

In addition, further H2020 studies, driven by ESA together with EUSPA, are starting in 2021 aiming to look at the future of EGNOS V3 (after EGNOS V3.2 DFMC release) for the horizon of 2030, in particular:

- EGNSSR (European GNSS Navigation Safety Service for Rail) to define an EGNSS-based Rail safety service ensuring "*to bring continuous position integrity on board all European trains*";
- EGNOS-Next: to target new Safety of Life services particularly for terrestrial users, including railway sector via the definition of a Range Multi-Missions;
- Partly in NLES-Next: to target alternatives dissemination to GEO for SBAS dissemination with higher elevations and azimuth diversities for continental Europe latitudes.