GNSS AUGMENTATION USAGE FOR CLUG

D3.1.1

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VERSIONS OF THE DOCUMENTS

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1.0	30/07/2020	Stable Iteration version: CLUG internal
1.1	18/09/2020	Update following internal CLUG consortium review
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1.3	28/09/2020	Update following internal CLUG consortium review
1.4	11/03/2021	Final version – submitted to consortium review
1.5	12/04/2021	Final version following internal CLUG consortium review (Airbus, SNCF, CLUG quality manager), Final version submitted for GSA review and approval
1.6	07/06/2021	Final version after GSA review and comments; The document becomes "Public" instead if "CLUG Confidential" after CLUG partners authorization to Airbus proposition.

EXECUTIVE SUMMARY

This document is a part of the deliverable "D*3.1 - Train Localisation On-Board Unit Design Document*" of the European project "Certifiable Localisation Unit with GNSS in the railway environment" (hereinafter also referred to as "CLUG") as the main production delivery of the CLUG Work package WP3 "Localisation System Design". This document is the section "*D3.1.1 GNSS augmentation usage for CLUG*" of the WP3.4.

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).

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APPLICABLE DOCUMENTS

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

- Grant Agreement N°870276: This is the contract with the European Commission which defines what has to be done, how and the relevant efforts.
- Consortium Agreement CLUG_CA96_20001_V2.7_CO: 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

B

BER
Bit Error Rate
BPSK
Bipolar Shift Keying

C

C/N0 *Carrier to Noise ratio*
CA : *Consortium Agreement*
CCI
Code Carrier Incoherence
CLUG *Certifiable Localisation Unit with GNSS in the railway environment*
CoS
Class of Service

D

DFMC
Dual Frequency Multi Constellation

E

EDAS
EGNOS Data Access Server
EGNOS
European Geostationary Navigation Overlay Service
ERTMS *the European Railway Traffic Management System*
EW
Evil Waveform

F

FE
Feared Event
FEC
Forward Error Correction

G

GA : *Grant Agreement*
Galileo *Europeen GNSS system*
GEO *GEOstationnary satellite*
GLONASS *Global Orbiting Navigation Satellite System*
GNSS : *Global Navigation Satellite System*, : Global Navigation Satellite System
GPS
Global Positioning System

L

LPV200 *Localizer Performance with Vertical guidance - 200 feets*

M

MI
Misleading Information
MOPS *Minimum Operational Performance Standards*
Minimum Operational Performance Standard

N

NLES
Navigation Land Earth Station

R

RF
Radio Frequency
RIMS
Ranging Integrity Monitoring Station

S

SBAS
Satellite-Based Augmentation Systems
SoL
Safety of Life
sps
symbols per second

T

TLOBU
Train Localization On Board Unit

1 INTRODUCTION

The Train Localization On-Board Unit (TLOBU) of CLUG is based on the Dual Frequency Multi Constellation (DFMC) Satellite Based Augmentation Service (SBAS) provided by European Geostationary Navigation Overlay Service (EGNOS) version 3.2 (GSA, EGNOS goes from strength to strength 2020). This Safety of Life Service is developed as per the specifications of the Civil Aviation Domain. WP3.4 activities explore the usage of GNSS augmentation (SBAS) in the context of CLUG project and provide potential clues that will shape an EGNOS service answering to railway sector needs. This document describes the current EGNOS services (Safety of Life, DFMC) in chapters 2 and 3, and its application and limitations to the railway environment in the context of CLUG in the chapter 4.

Then, "*D3.4 - GNSS Augmentation Needs for Rail*" describes high-level approaches for a dedicated augmentation service for railway sector.

2 EGNOS SERVICE OVERVIEW

The Satellite-Based Augmentation Systems (SBAS) are regional differential systems that provide augmentation and integrity information for Global Navigation Satellite Systems (GNSS), i.e. worldwide position and time determination systems that use satellites ranging signals to determine user location. These systems are currently designed to provide a Safety of Life service answering to the civil aviation Safety of Life Operational needs, by transmitting the augmentation signals via geostationary satellites.

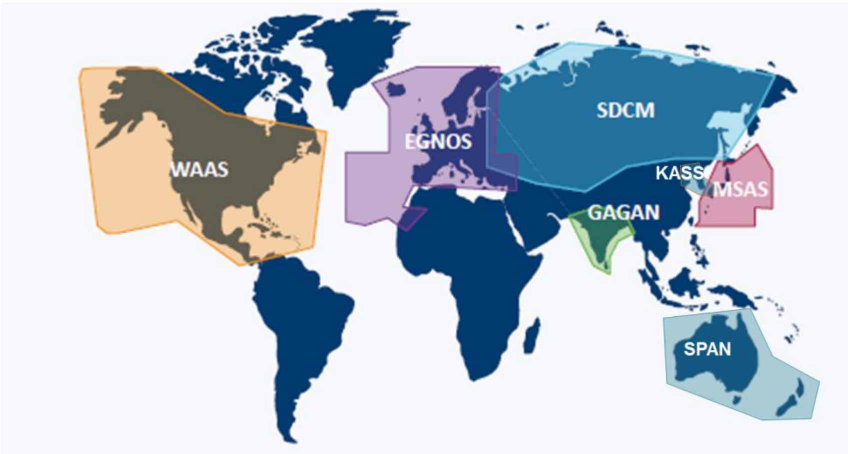


Figure 1: Existing and planned SBAS EGNOS (cf "EGNOS Safety of Life (SoL) Service Definition Document")

The next generation of European Geostationary Navigation Overlay Service (EGNOS - European SBAS) version 3.2 DFMC provides a monitoring and augmentation service to the satellites of the Global Positioning System (GPS) & the European Galileo constellations, for their dual frequency signals; GPS L1 & L5 and Galileo E1 & E5a, over Europe and its neighbouring regions.

This Augmentation Safety of Life Service is designed to the specifications of the Civil Aviation needs but available openly and free of cost for the other potential safety critical transport users looking for an augmented positioning with a safety of life service compatible with aviation needs. The other advantage of this regional augmentation service is that the corrections are provided for most of the satellites that are visible in the entire region and the service remains valid and continuous for most users within this region, very similar to the guiding principles of the regional approach of ERTMS.

The major advantage of this kind of service is the need of minimal or no ground specific infrastructure required to exploit the EGNOS V3.2 DFMC service users, but only an on board receiver capable of handling the SBAS dual frequency correction signal transmitted in the L5 frequency band. This feature makes such a safety of life positioning approach a more cost effective & beneficial for regional aviation transportation systems.

The railway environment and needs are very different from aircraft/aviation ones. As explained in section §5 "*Conclusion*", the current EGNOS augmentation service is not completely suitable for railway sector.

The EGNOS services have been used by several civil aviation operations around Europe. The figure below gives the airports where the EGNOS based operational procedure is approved around Europe. This shows the wide acceptance of EGNOS by the civil aviation community in the operational environment. In the next generation EGNOS V3.2 the support of EGNOS to the aviation operations will be enhanced from the LPV200 procedures (Localizer Performance with Vertical guidance for approach up to 200 feets) to more stringent Autoland. EGNOS V3.2 is also targeted to support Maritime Operations.

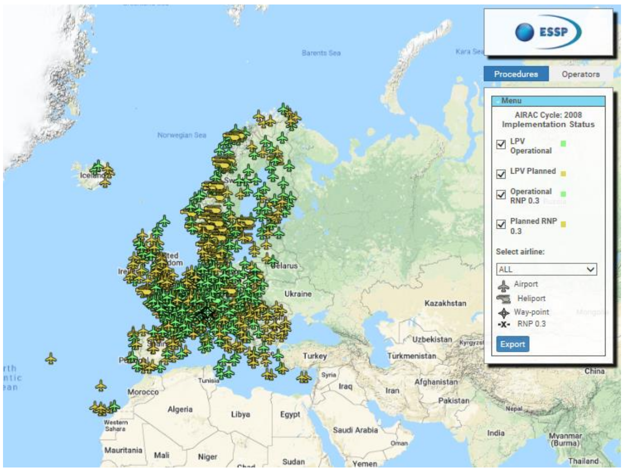


Figure 2: Airports where EGNOS based Procedure either operational or planned (courtesy: EGNOS User Portal: ESSP)

EGNOS V3.2 will also add security features to ensure the service is less prone to security threats and therefore more reliable. Such features encompass

- RF monitoring on Ranging and Integrity Monitoring Stations (RIMS) and Navigation Land Earth Station (NLES) sites to perform advanced characterisation of RF environment such as interferences jamming and spoofing,
- cyber-security monitoring (classified topic),
- security functions such as central authentication, anti-malware management, Public Key Infrastructure management.

From the perspective of the transmitted signals EGNOS V3.2 services can be categorised as:

- Legacy Service: Providing monitoring, augmentation and integrity of GPS L1 signals. The transmitted augmentation includes GPS satellite orbit and clock corrections, ionospheric corrections and integrity data are broadcast in a L1 C/A-code signal by SBAS geostationary satellites. The characteristics of the SBAS L1 service are fully described in the ICAO SARPS, and the standards for SBAS L1 equipment are defined in MOPS DO-229E.
  As per the above generic service definition, EGNOS V3.2 monitors and augments the GPS L1 signals.

- DFMC Service: Providing monitoring, augmentation and integrity of GPS L1&L5, Galileo E1&E5a signals. As per the definition, DFMC SBAS service augments dual-frequency signals from one to four core constellations (GPS, GLONASS, Galileo, Beidou). The resulting differential correction and integrity data are broadcast in a L5 like signal, also by SBAS geostationary satellites that may have non-geostationary orbits. The characteristics of the SBAS L5 service are fully described in the ICAO DFMC SARPS, and the standards for SBAS L5 equipment are defined in MOPS DO-259A.
  As per the above generic service definition, EGNOS V3.2 monitors and augments the GPS L1&L5, Galileo E1&E5a signals.

EGNOS V3.2 transmits also its data via Internet through EDAS without being an integrate dissemination mean and also no guarantee of service, meaning it can be used for test or non Safety of Life application, so for CLUG TLOBU experimentations only.

3 EGNOS DFMC SERVICE DESCRIPTION

3.1 INTRODUCTION AND CONTEXT OF EGNOS V3.2

Over the last decade GNSS landscape has evolved from the US based Global Positioning System (GPS) and the Russian Global Orbiting Navigation Satellite System (GLONASS), with the emergence of new satellite constellations such as European Galileo and Chinese Beidou, along with the additional signals from these constellations dedicated to navigation.

EGNOS V3.2 conceptualised to provide the benefit of these GNSS evolutions to the European SBAS user community, with the support of monitoring & augmentation to the GPS and Galileo constellations and their respective navigation signals compatible with the new International Civil Aviation Standards & transmitted via L1 (GPS)/E1 (Galileo) and L5(GPS)/E5a(Galileo). EGNOS V3.2 is the first program to be launched around the world, for the development of this DFMC operational service.

EGNOS V3.2 will not only continue to provide the augmentation for the legacy service for the GPS L1 only signals via its SBAS L1 frequency signal (1575.42MHz), but also transmit the DFMC service via its SBAS L5 frequency (1176.45MHz). Since EGNOS uses and shares the same frequency band as the GNSS satellite signals, single GNSS antenna is sufficient to receive both GNSS dual frequency signals and the corresponding EGNOS V3.2 corrections. The EGNOS V3.2 augmentation service will be broadcast via a couple of dedicated Geo Stationary Satellites (GEO), which has the footprint on and beyond the targeted service area around Europe (latitude <72°).

In addition to the GEO based broadcast of the correction signals, EGNOS also provides EGNOS Data Access Service (EDAS), which is a terrestrial offered service offering ground-based access to EGNOS data through the Internet on controlled access basis in near real time without guarantee of service but for non Safety of Life application. EDAS therefore provides the opportunity for service providers to deliver EGNOS data to users who cannot always view EGNOS satellites (such as in urban canyons and mountains) or to support a variety of other value added services, applications and research programmes. EDAS provides the raw data collected by the EGNOS subsystems (RIMS) and also the generated augmentation messages as transmitted by the Geo satellites.

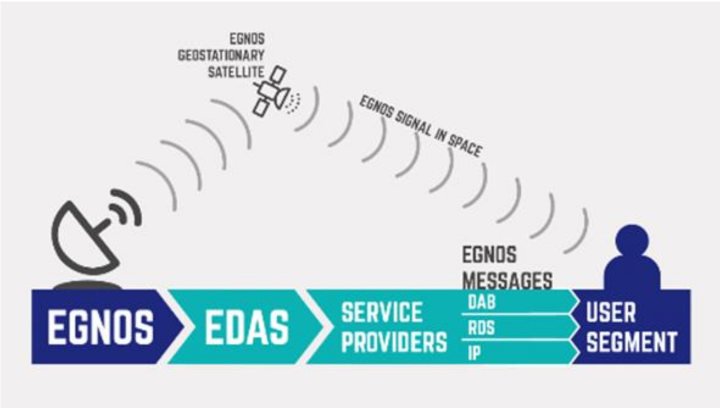


Figure 3: EGNOS Services Dissemination Means (courtesy: EGNOS User Portal: ESSP)

From the perspective of use, EGNOS V3.2 services can be categorised as:

- Open Service: free and open to the public, the Open Service is used by mass-market receivers and common user applications;
- EGNOS Data Access Service (EDAS): free but offered on a controlled access basis (i.e. via the internet and mobile phones) for customers requiring enhanced performance for professional use;
- Safety of Life Service (SoL): for safety-critical transport applications, including civil aviation, which require enhanced and guaranteed performance and an integrity warning system.

The major advantage of the DFMC service is the capability to augment multi constellation, therefore, allowing the user to use more visible & augmented satellite signals, thanks to adding Galileo constellation to the current EGNOS V2 GPS constellation only, thus improves robustness against poor satellite geometry to the user receiver and the ionospheric scintillation. The possibility to use more satellites shall help transportation applications that shall operate under limited visibility to the sky, such as in urban canyons or dense foliage. Nevertheless, the dissemination of the augmentation data by GEO is still too limited in railway environment with urban canyon, mountains, canopy as demonstrated in section §4.2 and probably from coming WP4 real data collection.

The use of dual frequency is targeted to better estimate the ionospheric delays on the satellite signals, which is one of the major source of error in the calculated pseudo range between the GNSS satellite and the user Rx antenna, so an improved accuracy of the user position.
The user of the DFMC service shall be equipped with a GNSS receiver capable of using the two GNSS frequencies (typically L1/E1 & L5/E5a), which allows them to eliminate the effect of ionosphere on the received GNSS signals. Since the calculation of ionosphere-free pseudo-range is transferred to the DFMC user, EGNOS V3.2 need not and does not transmit the ionosphere monitoring information and the corrections for the ionosphere delays. This also saves the bandwidth for the DFMC service compared to the legacy service. The DFMC SBAS service provides the satellite clock and orbit corrections only.

Initial performance assessments reveal that the EGNOS V3.2 DFMC service improves the EGNOS performance significantly over the entire service area with respect to its previous version.

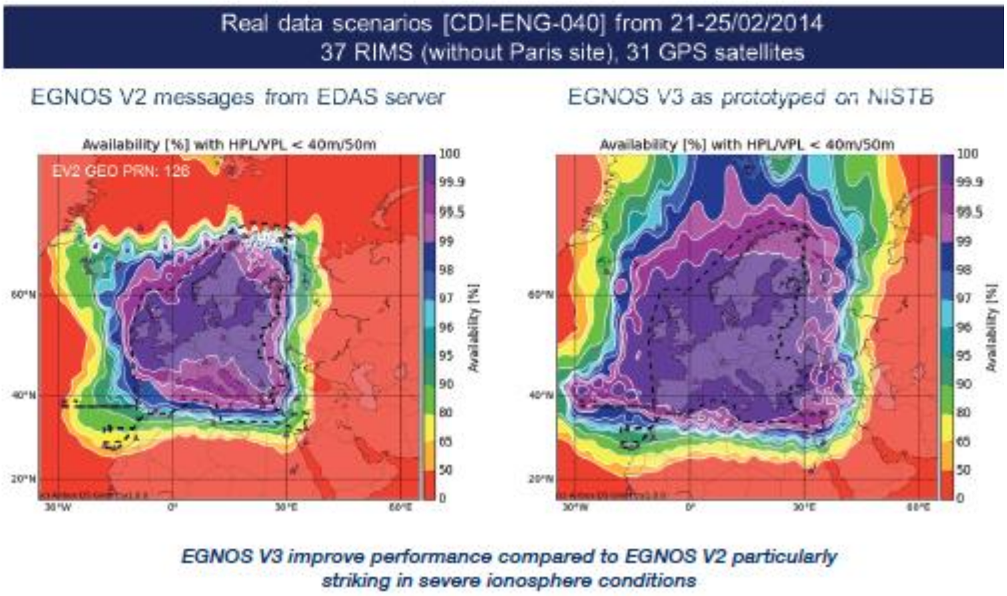


Figure 4: EGNOS V3 service availability improvement over the entire service area demonstrated by initial assessments (Airbus source)

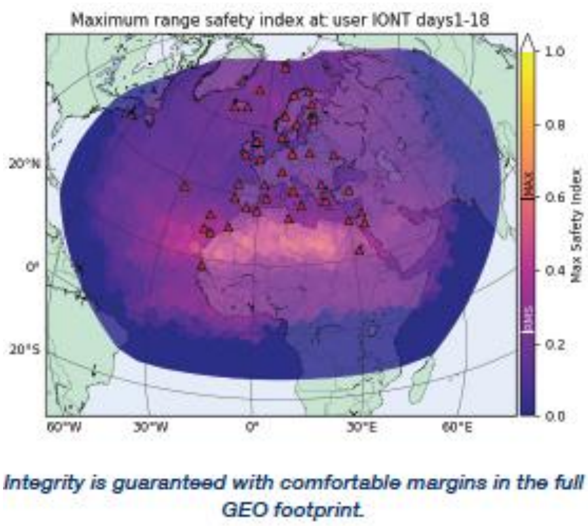


Figure 5: EGNOS V3 Integrity Assessment on the entire Geo footprint area (Airbus source)

Moreover, DFMC service will enable meter level accuracy positioning as illustrated by Figure 6.

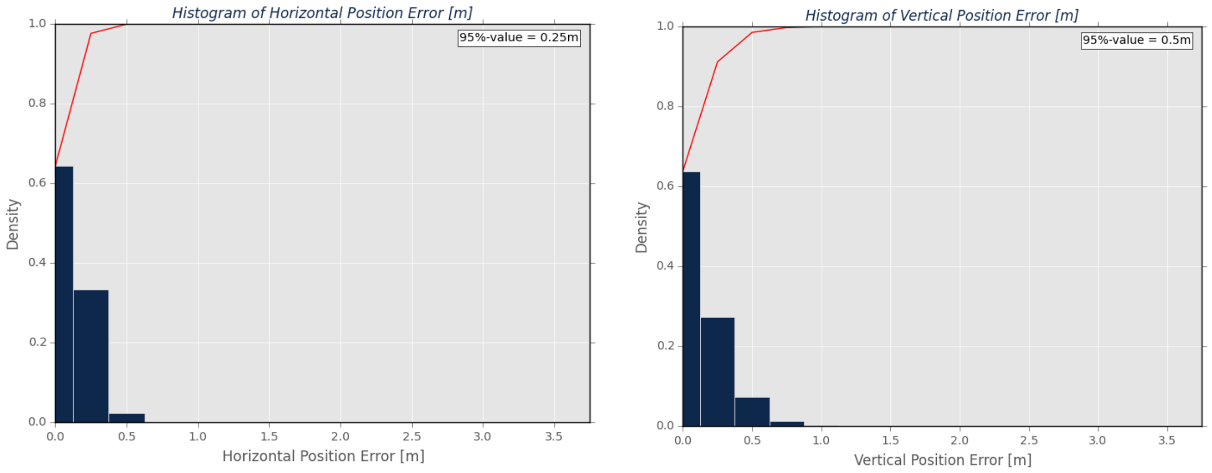


Figure 6 Histograms of the horizontal and vertical position error (GPS24+GAL24, L1/L5) (Airbus source)

3.2 DFMC Message Structure

EGNOS V3.2 adheres to the message structures and information defined in the documents "Minimum Operational Performance Standard for Galileo / Global Positioning System / Satellite-Based Augmentation System Airborne Equipment", MOPS ED-259A.

The table below summarises the different message types transmitted by the DFMC service, with a message size of 250 bits per second and within which the 216 bits of information.

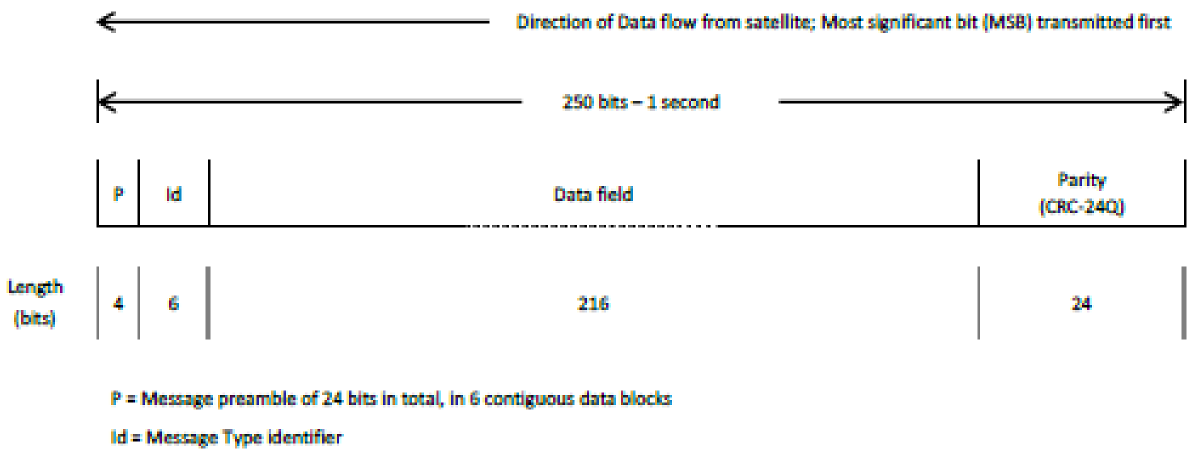


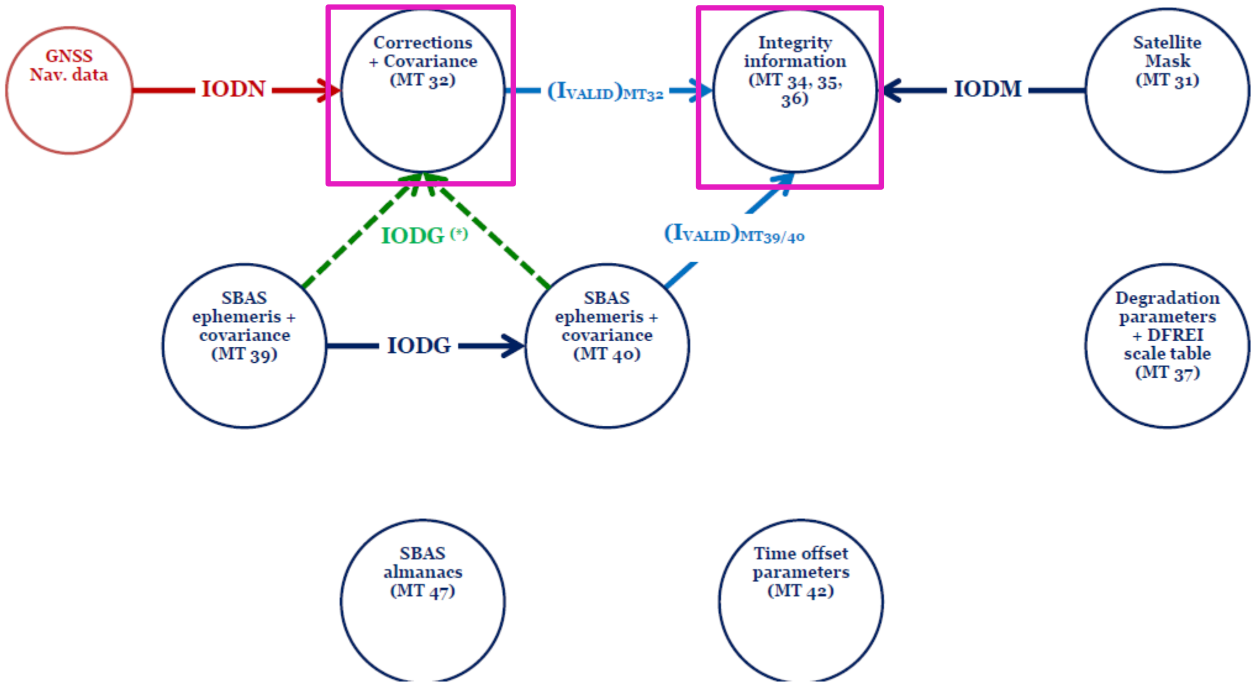
Figure 7: DFMC SBAS Message Structure (SARPS and MOPS source)

Type	Contents
0	Do not use this SBAS L5 signal for safety applications (for SBAS L5 testing)
31	Satellite Mask assignments
34, 35, 36	Integrity information (DFREI and DFRECI)
32	Satellite Clock-Ephemeris error corrections and covariance matrix
39, 40	SBAS satellites ephemeris and covariance matrix
37	OBAD parameters and DFREI scale table
47	Almanacs of SBAS satellites
42	SBAS Network Time/UTC
62	Internal SBAS L5 test message
63	SBAS L5 null message

Figure 8: DFMC Messages (SARPS and MOPS source)

The messages on SBAS L1 and L5 shall be treated independently and only message types 0, 62 & 63 share the same identifiers on both the frequency channels. The main correction message is the message type 32 with Integrity information in message types 34, 35 & 36.

The figure below presents also the relationship between the different DFMC message types and their relationship to the GNSS navigation data transmitted by the GPS & Galileo constellations.



Legend:
MT: Message Type;
IODM: Issue of Data Mask
IODG: Issue of Data GNSS
IODM: Issue of Data Mask

Figure 9: Relationship between SBAS DFMC message types (DFMC MOPS source §A.3.5)

For details of the messages it is recommended to refer to the EUROCAE DFMC standard version ED-259A 0.4A, Appendix A.

3.3 DFMC Message Dissemination

3.3.1 By GEO

DFMC SBAS signal is transmitted primarily by two or more Geo stationary satellites in a carrier frequency of L5 (1176.45 MHz, bandwidth >20MHz).
The SBAS L5 signal is using a BPSK modulation with a 10.23 M-chips spreading code and a rate-1/2 Forward Error Correction (FEC) encoding always applied to the data. The symbols are Manchester encoded. Manchester encoded symbols (at a rate of 500 symbols per second (sps)) are added modulo-2 to a 10230-bit PRN code. The resulting chip stream which has a rate of 10.23 M-chips per second is then BPSK-modulated onto the RF carrier.
This dissemination means has an advantage that the same source (GEO) is visible through the entire service area (Europe and neighbouring regions, latitude <72° for more than 5° elevation visibility) and supports the real time constraints of the SBAS, therefore the trusted source for the Safety of Life (SoL) applications.
On the other hand, since the GEO satellite is aligned to the equator, at high latitudes the satellite signals are not available and also there are strong limitations to the reception of the satellite signal in the urban canyons, mountain areas in addition to the foliage and the tunnels.

3.3.2 By EDAS (via Internet)

For non-Safety of Life applications such as research, agriculture etc. a replica of the EGNOS SBAS messages is transmitted via Internet. This dissemination is near real-time without guarantee of service and therefore not suitable for the use of safety of life applications due to non-compliance against availability, continuity and integrity requirements.
However, due to the nature of delivery via Internet the signal is available where possibly the GEO outages occur such as higher latitudes, urban canyons etc.

Despite the fact that the DFMC SBAS is designed for civil aviation, it is possible to imagine its adaptation and adoption to the other safety critical transport systems including the Railway sector. The following chapter will describe this aspect to see how an SBAS could be introduced in the CLUG project.

4 EGNOS DFMC SERVICE EXPLOITATION FOR TRAIN

4.1 SBAS USAGE EXTENSION TO RAILWAY

There are different approaches possible in order to use SBAS in rail. These approaches are described hereafter and ranked in function of their impact on SBAS ground segment (from the least impacting to the most impacting).
These can be summarized in the following way with 3 approaches:

- Approach 1: EGNOS DFMC with a MOPS compliant receiver
- Approach 2: EGNOS DFMC with a Bayesian-based receiver
- Approach 3: EGNOS augmentation service designed for rail with a Bayesian-based receiver

4.1.1 Approach 1: EGNOS DFMC with a MOPS compliant receiver

The first approach consists in using already existing SBAS service. There is no impact at all on the augmentation system. This approach is very restrictive due to the following reasons:

- Firstly, the functional/performance requirements shall be less stringent than the requirements for which the system has been designed (being civil aviation): A system design to provide 10-7/h integrity performance cannot be used alone for critical railway application requiring 10-9/h integrity risk.
- Secondly, the receiver shall then be MOPS (Minimum Operational Performance Standard) compliant as the EGNOS ground system algorithms have been designed and tuned accordingly. MOPS compliant receiver is very restrictive in terms of signal processing algorithms, loops configurations, and positioning algorithm (weighted least square algorithm being a "snapshot algorithm").
  This approach is then not adapted to Bayesian filtering, being continuous in time, such as Kalman filter which is widely used in terrestrial localization application. Indeed, integrity in snapshot algorithms at position domain is guaranteed by verifying that position error does not exceed the associated bound, whereas Bayesian algorithms estimated bounds (which are narrower in general) validity relies on additional assumptions not checked by the SBAS ground segment.
- Therefore, such approach is expected to perform poorly in urban environments due to degraded geometry and increased local error budget due to multipath. Receiver applicable standard shall be modified (and the impact of the modifications has to be addressed): for instance, local error budget model designed for aviation is no longer valid in rail context. Moreover, in CLUG context, the TLOBU is subject to velocity related requirements with high Safety level requirement. Current SBAS systems do not provide any bounds in the velocity domain (and MOPS does not allow it).

4.1.2 Approach 2: EGNOS DFMC with a Bayesian based receiver

The second approach consists in using the already existing SBAS service with a Bayesian-based receiver, and making additional assumptions on:

- the TLOBU system inputs, e.g. stability of nominal Doppler error in time. Such assumption shall be proven to be valid, either offline meaning a model has been defined and validated in non-real time manner, or online with some additional dedicated real-time detectors. An integrity budget shall be allocated to cover the risk of loss of integrity in case such assumption is not valid.
- the performances of the SBAS system and the characteristics of its residual errors. When using a Kalman filter (Bayesian method) for positioning solution, the position domain error bounding is in general based on the predicted covariance. The validity of this covariance relies on the validity of assumptions on the measurement error (error correlation in time, error probability density function), which in turn relies on the absence of Feared Events (FE).
  SBAS can be used as a Feared Events monitor because it provides flags in case of integrity condition violation and Feared Events are likely to lead to integrity condition violations depending on their magnitude. It is possible to make assumptions on the performance of such black box. Then, such performance assumptions have to be fulfilled by the SBAS system. As such systems are already designed, it is not possible make this requirement applicable to SBAS. Therefore, the proposed alternative would be to use a <u>bottom up approach</u> with an existing SBAS system, validated with commitment from the system

(tests to prove that the SBAS meet these posterior “requirements”). Such method is developed in D3.1.4 "*Integrity Concept*" §4.1.2.1 with examples reported:

- SBAS shall guarantee integrity in the range domain (it is the case of EV3) and protect against Misleading Information (MI) (not designed to protect from Hazardous Misleading Information);
- Requirements on the probability of miss detection of Feared Events shall be assumed.

This approach does not impact SBAS system except through commitment on performance axis that shall be verified. It is not too much restrictive on the user side and even compatible with the third approach described hereafter. Nevertheless, Approach 2 raises some restrictions on the user segment, such as:

- MOPS defines all possible receiver configurations (bandwidth front end, chip spacing) aligned with EGNOS ground segment algorithms to ensure the user protection, particularly on Evil Waveform (EW). This set of possible configurations is named the "MOPS user space". Extending this MOPS user space to other configurations to fulfill railway user needs might change its protection against some Evil Waveforms.
- Code Carrier smoothing based on hatch filter is commonly used to reduce (“to smooth”) the noise and multipath errors in pseudo-range measurements by using the high precise relative distance of carrier phase measurements. To be partly “protected” against Code Carrier Incoherence (CCI), the user shall be less “reactive” than the output of a hatch filter with 100s smoothing constant (because the SBAS system take advantage of this delay for its design). User MOPS compliant hatch filter is based on a smoothing constant of 100s. Keeping this 100s in a railway environment due to discontinuities (cycle slips …) is likely to induce poor performance (e.g. availability of each GNSS data continuously during a 100s slipping window) as the hatch filter shall be reset each time there is carrier phase discontinuity because of SBAS signal masking (can be faced thanks to a safe ground network, e.g. Euroradio see D3.4 "*GNSS Augmentation needs for rail*"). Reducing the smoothing constant below 100s will induce better performance as the filter convergence will be faster but error bounds to protect the user shall be inflated. Error bounds of measurements are inflated but having more measurements available improve performances of the global solution. In other words, a good compromise by real rail testing should be found between the hatch filter duration (100S in MOPS for aviation users) and the acceptable error bounds depending on the GNSS to rail environment.

Regarding the performance, approach 2 is expected to perform poorly due to the following reasons:

- The assumptions that are made on the SBAS are very loose in order to minimize the risk that the SBAS is not compliant. Then, the benefit of satellite augmentation is much lower than what it could be with a classical top down design approach. It will result in a distributed integrity concept between SBAS and user that is very demanding on user side (which has poor monitoring capacity), and not enough on SBAS side (which has much monitoring capacity due to the number of observables/ground stations/coverage). This will finally result in non-optimal (i.e. large) protection levels, resulting in reduced availability. An increased protection level involves a decreased availability as protection level will exceed the upper limit.
  - Current SBAS are not designed to detect Feared events but to detect Misleading Information. SBAS is designed not to flag Feared Events with low magnitude to guarantee continuity (because low magnitude is unlikely to generate Misleading Information). On the contrary, an SBAS designed for rail (approach 3) should be more sensitive to such low magnitude Feared Events, because data fusion with IMU would reduce the continuity impact of satellite exclusions.
- More details are given in D3.1.4.

There is always the risk that the SBAS is not compliant to the requirements taken in assumption for train positioning system design (impossible commitment from SBAS). This risk cannot be ignored, but it could be mitigated by involving SBAS design authorities in hypothesis definitions.

4.1.3 Approach 3: EGNOS augmentation service designed for rail with Bayesian-based receiver

The third possible approach consists in defining a new SBAS system and standard dedicated to railway needs or complementing the EGNOS V3.2 DFMC for aviation. Then analysis would result in the definition of some requirements applicable to the SBAS system. It shall be noted that the TLOBU architecture is identical to Approach 2 TLOBU architecture as defined in D3.1.5 "*Train Localisation On-Board Unit TLOBU solution A Architecture and Design*".

Typically, approach 3 would lead to the definition of missing requirements on:

- Corrections: The production of pseudorange rate corrections. Corrections of the orbit/clock error components and their time derivative may be needed. It is the purpose of the Long Terms Corrections (LTC) of existing SBAS. If a single frequency service is proposed, ionospheric absolute corrections and time gradient have to be contained in the augmentation message. The product accuracy requirement depends of the position and velocity accuracy requirement.
- Bounds: Residual error correlation time bounds (details can be found in D.3.1.4.) for position and residual bounds to be used for integrity in the velocity domain. This information can only be relative to orbit/clock and ionospheric residual errors (absolute and its time derivative). In current SBAS, sigma (UDRE/GIVE) are broadcast and are sufficient for the user to compute a conservative bound of the range error. Here it will be necessary to compute and transmit bounds of these residual range rate errors.

  In case of receivers based on snapshot algorithm even not recommended, moreover the bound in the range domain remains valid in the position domain (applying MOPS protection levels computation formula) as the user estimates its position using a weighted least square estimator.

  Data fusion algorithms, used in terrestrial receivers, are general Bayesian algorithms (Kalman filters, EKF, UKF, Particle filters) 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. There are several method to adapt the Bayesian algorithm to correlated inputs, which are described in D.3.1.4., but they all have in common that the user need to be informed of the time correlation of the residual error (or at least an upper bound of it). Two solutions are then possible:
  - Either the error correlation time is a parameter that is static for the user. In this case it shall be valid for all the GNSS measurements and any epoch. It will be large for conservativeness which is not optimal. Moreover as it is an assumption of the user, it would be specified as a requirement for the GNSS augmentation system.
  - Either the error correlation time is contained in the GNSS augmentation message. This approach shall be preferred because it enables to reduce conservativeness, and does not constraint the augmentation system with a requirement.

Other parameters may be included in the GNSS augmentation message, answering to stringent potential Time-To-Alert (TTA) requirement: Probabilities of satellite faults, similar to what is contained inside ARAIM ISM could be distributed in case the integrity is distributed between SBAS and user.

Approach 3 is expected to be optimal and outperform the two previous ones. It will be necessary to develop a new SBAS system, or preferred, to upgrade existing one with additional modules inside the EGNOS Central Processing Facility, dedicated to the production of SBAS message dedicated to rail, then to define the corresponding new standard.
ESA together with European Commission & EU Space is already looking at the future of EGNOS V3, i.e. the EGNOS roadmap after EGNOS V3.2 DFMC, for the horizon of 2030+, named "EGNOS Next" (Phase A/B0) study aiming to define added Safety of Life services and in particular for rail and terrestrial users, and being launched in 2021.
The CLUG D3.4 "GNSS Augmentation Needs for Rail" describes what should be this complementing service needed for railways, the readiness between CLUG TLOBU and SBAS service for rail. It is a good starting point for EGNOS Next study.

4.2 SBAS Augmentation Data Dissemination

Regarding the dissemination of SBAS products to the end-user, the case of train is much more challenging than aircrafts, which are always in clear sky conditions. Indeed, SBAS service relies on the ability of the user to receive the corresponding message every second, in particular in order to receive alerts in case integrity conditions are violated.

Unfortunately, trains are likely to operate in mountains, forest, suburban to urban environments and even in tunnels, i.e. environments where the reception of messages transmitted via GEO satellites is not guaranteed.

The latitude of most of the countries in continental Europe is between 35° and 55°, which corresponds to a maximum GEOs elevation of about 30°. The elevation of the GEOs in function of user latitude is plotted in Figure 11. In urban environment, the probability for a satellite to be masked depends on some parameters such as the building height distribution and distance to the building. It has been modelled in INP DE TOULOUSE - P. Brocard study "*Integrity monitoring for mobile users in urban environment*", which is the reference used in CLUG.

Let us make the analysis for a given area and pick Paris. Paris being at 49°Latitude, EGNOS DFMC GEO 1/2/3 are seen at 33.9°/27.3°/33.5° elevation. So to get a direct visibility (or also named Line of Sight) at 30° elevation, the probability of GEO masking occurrence in the street (so loss of EGNOS message) is about 50% (cf Figure 12), assuming moving in the urban area induces all encountered azimuth values (i.e. masking occurrences are evenly distributed in azimuth). Then, once a masking occurrence is encountered, if the SBAS loss lasts more than 4s , then a full reacquisition of the SBAS message shall be performed to achieve SBAS recovery. In particular, message DFMC MT32 shall be reacquired, while its maximum update interval is 120s, provided that no additional similar loss occurred during the 120s period.

Nevertheless, when GEO is masked, it may be possible to still track the GEO "thanks to" multipath, but the bit error rate (BER) would increase due to the reduced C/N0. It is estimated problematic for integrity (probability of wrong decoding several successive times during an alert may exceed the allocated budget in system/user budget apportionment).

To summarize: **it is strongly unlikely to get integrate position(s) involving the TLOBU functioning during long period in urban area, as the IMU will have to withstand without SBAS complete acquisition due to the visibility of the EGNOS satellites (only geostationary currently) being at ~30° elevation seen from Europe**.

In opposition to this finding and being a very positive opportunity, it is highlighted in the Figure 12 that any SBAS dissemination by satellite providing elevation higher than 65° seen in Europe enables a very low probability of masking occurrence (0% in this simplified model). Alternatives to GEO for SBAS dissemination exist already and will be studied in a coming H2020 study being in competition at the time of writing this version.

It has also to be highlighted that this summarized analysis apply also for non urban area due to mountains, side infrastructure, trees and forest.

At the end of this short analysis, current SBAS EGNOS dissemination by GEO is not adapted for SBAS terrestrial users such as railway sector (at least with current message structure), whereas GNSS (GPS+Galileo) are sufficiently available for PVT computation but missing SBAS augmentation capacity, and so Safety of Life capacity too. Therefore **the SBAS EGNOS dissemination has to be at least at the level of the GNSS availability on ground**. This dissemination can be based on ground network such as LTE (dedicated GSM-R, Euroradio: terrestrial safe telecom network) but also on Space dissemination if SBAS satellite(s) to user is(are) higher than about 65 to 70° elevation for Europe land latitudes. A point of attention regarding GSM-R is its bandwidth capacity to add EGNOS augmentation data with a specific CoS class of service versus latency requirement.

Satellite	PRN	Location (equatorial longitude)
GEO1 (SES-5)	136	5°E
GEO2 (SES Astra-5B)	123	31.5°E
GEO3 (Eutelsat W5b)	121	5°W

Figure 10: Orbital positions of the EGNOS geostationary satellites

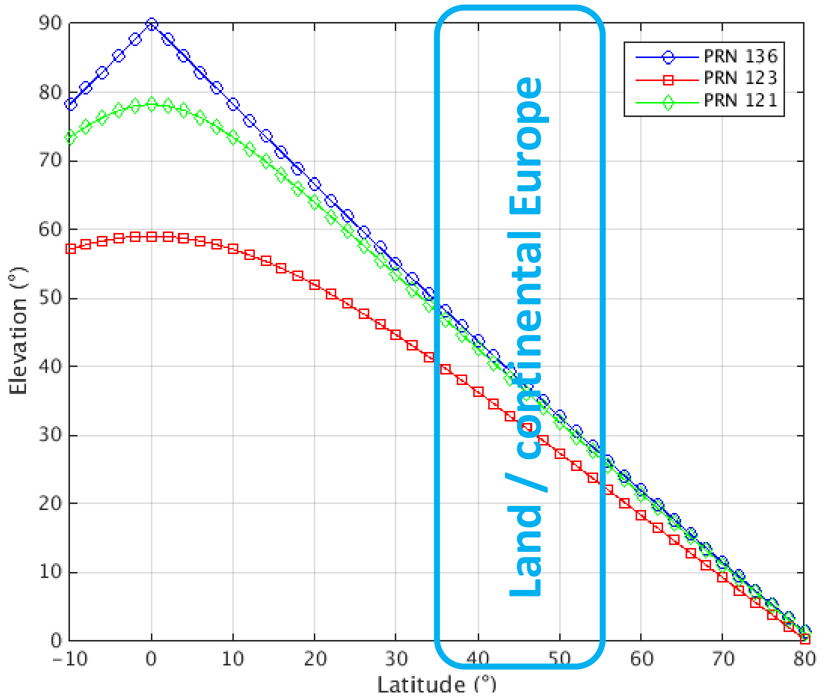


Figure 11: Elevation of EGNOS satellites versus Latitude in continental Europe for longitude 5°E (~Bruxelles)

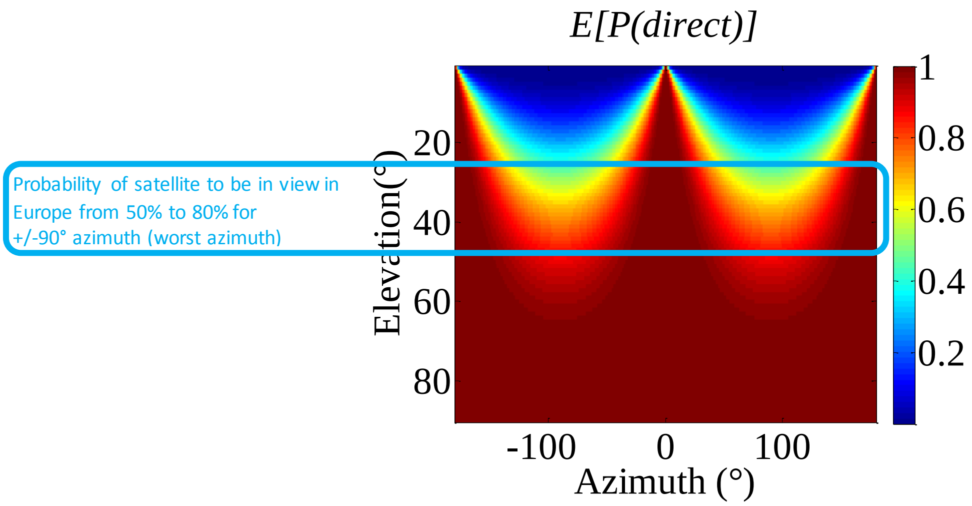


Figure 12: Probability of a satellite to be in view in urban environment from [Philippe Brocard. Integrity monitoring for mobile users in urban environment. Signal and Image processing. INP DE TOULOUSE, 2016.]

5 CONCLUSION

This document identified how SBAS augmentation could be used for train localization in 3 different approaches and made a preliminary assessment of the feasibility of train safe localization requirements following each of these approaches.

As a summary:

- Using the current version of EGNOS with a MOPS compliant receiver (Approach 1) does not fulfill successfully the railway requirements due to limitations of existing EGNOS and MOPS compliant receiver.
- Using Bayesian filtering capabilities at receiver level with existing EGNOS DFMC (Approach 2) will probably not be sufficient to fulfil railway needs. This has to be assessed through performances engineering.
- A dedicated Augmentation Service for Rail (Approach 3) associated with a Bayesian-based receiver is the most promising and preferred solution answering positively to train safe localization requirements.

- Further H2020 studies, driven by ESA together with European Commission & EU Space and being in competition at the time of writing this version, 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:
  - to target new Safety of Life services particularly for terrestrial users, including railway sector;
  - to target alternatives dissemination to GEO for SBAS dissemination with higher elevations and azimuth diversities for continental Europe latitudes.