# Projected Performance of a Baseline High Integrity GNSS Railway Architecture under Nominal and Faulted Conditions

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# **BIOGRAPHY (IES)**

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**Veronica PALMA** received the Laurea (Master of Science) in Electronic Engineering from Università degli Studi Roma Tre, Rome, Italy, in May 2007. From November 2007 to November 2010, she attended the "Biomedical electronics, Electromagnetics and Telecommunications" doctoral school in Engineering of the University "Roma TRE", achieving her Ph.D. degree in April, 2011 with the thesis entitled "Distributed Video Coding of 3D Sources". She is now collaborating with RadioLabs, where she has been involved in European projects like ESSOR (European Secure Software defined Radio), 3InSat (ESA project), a project on satellite navigation in railway environments and D-BOX (FP7), as project manager, on the demining tool-BOX for humanitarian clearing of large scale areas from anti-personnel landmines and cluster munitions. Currently, she is working in H2020 projects as: ERSAT EAV – "ERTMS on SATELLITE - Enabling Application Validation", RHINOS and STARS. She is involved in developing a system to provide the current position of a train/car/UAV in motion, based on GNSS measurements and augmentation networks corrections, with high-demanding requisites on reliability. She is the director of the Radiolabs laboratory at the headquarters in Rome. Her research interests are mainly focused on: routing protocol optimization in mobile networks, network coding and satellite navigation.

**Maurizio SALVITTI** is the current Program Manager of the RadioLabs Consortium (Consortium of Universities Industry – Communications Laboratories), responsible for managing the program for the entire portfolio of research projects at national, European and international level, in which the Consortium is involved. During the course of his long career (> 25 years) he has worked in many telecommunications companies (telecommunications operator and services provider, technology manufacturers and vendor ) operating both nationally and internationally where he held various managerial positions in the area of Engineering , Operations and Project Management Office as Officer responsible of the coordination of complex projects , these latter in their complete life cycle ( from feasibility study to implementation, to design, to development , to installation and testing ) and in a multicultural environment.

Before aforementioned experience in the Telecommunications he has worked (9 years) in the Defense and Space sector by covering several responsibilities in companies of the Finmeccanica group.

**Cosimo STALLO** obtained cum laude the Ph.D in Microelectronics and Telecommunications at Electronic Department of Engineering Faculty of University of Rome "Tor Vergata" in 2010. Since 2011 he is Professor for the course on Satellite Navigation at Master of Science on "Advanced Satellite Communication and Navigation Systems" of University of Rome Tor Vergata. Since 2013-14 he is tutor for the course on Communication Systems at University of Trento, Italy. Since February 2010, he is the Chair of the Space Systems Technical Panel of the IEEE AESS. Since 2012 he is a senior Researcher at RadioLabs Consortium, where he has been/is involved in the technical committees of different GNSS projects in the railway sector as ESA IAP 3InSat (Train Integrated Safety Satellite System), ESA IAP SBS-RailS (Space Based Services for Railway Signalling), H2020 GSA ERSAT-EAV and H2020 GSA RHINOS (Railway High Integrity Navigation Overlay System). Currently, he is the project manager of an Italian regional project VIRGILIO (Virtual InstRuments for GNSS AugmentatIon and LocalizatIOn) and ESA GSTP Element 2-Competiteveness DB4RAIL (Digital Beamforming for Rail). He is co-author of about 50 papers on international journals/transactions and proceedings of international conferences.

## ABSTRACT

GNSS is being gradually adopted for both navigation and control of many safety critical transportation system. This paper focuses on the important area of high integrity GNSS for railway applications which is critical for safe use of GNSS. While aviation has led the development of high-integrity GNSS applications, the Railway High Integrity Navigation Overlay System (RHINOS) effort aims to apply GNSS to railways utilizing similar integrity methodologies. In particular, it seeks to provide the accuracy necessary to support the most critical railway operations while assuring a very low probability of Hazardously Misleading Information (HMI). The RHINOS efforts are studying the most appropriate architectures (e.g., combinations of GNSS augmentations) and developing an integrity methodology suitable for the architecture that is chosen. This paper describes a reference RHINOS architecture and examines its performance under nominal and faulted conditions.

The performance analysis is conducted through simulation using the Matlab Algorithm Availability Simulation Tool (MAAST). MAAST, which was developed for aviation integrity analyses, was modified to support Protection Level (PL) calculations based on a proposed RHINOS reference architecture. It calculates PLs at representative locations throughout Europe for both nominal and faulted cases. The nominal case assumes that all GNSS range measurements are bounded by fault-free error models. Error models derived from accepted Satellite Based Augmentation System (SBAS) and Ground Based Augmentation System (GBAS) models are used. The main exception is multipath, which is known to be more severe for trains than for aircraft. The fault cases examined are those where either ionosphere gradients, satellite (ephemeris or clock) errors, or multipath exceed the nominal models. The integrity monitoring should detect and exclude the fault, if it is sufficiently large or not detected it, in which case it will bound its effect.

Finally, sensitivity analysis is conducted to provide insights for designing the system. Different multipath assumptions are tested and different levels of mitigation are examined what level of mitigation and monitoring should be targeted.

# INTRODUCTION

High integrity Global Navigation Satellite System (GNSS) position navigation and timing (PNT) is vital for safety of life applications. The growing use of GNSS for automation means that our GNSS-based navigation systems are being trusted at the

highest levels. While aviation has led in developing and using GNSS integrity system, these systems must soon come to transportation systems such as railways and automobile as these applications are increasingly adopting both GNSS and automation. GNSS integrity is especially vital when the navigation system is the primary means of guidance. This means that the navigation system has final trust in guiding the vehicle. Hence it makes sense that aviation is the leading adopter. Commercial flights generally occur under Instrument Flight Rules (IFR) which essentially means that pilots must trust their instruments even over their senses. However, automation in rail and automobile means that we will be placing similar levels of trust in the navigation systems of these vehicles with similar, deadly, consequences should there be a failure. RHINOS, a project under European Horizon 2020 research effort, aims to apply GNSS to railways utilizing similar integrity methodologies

While GNSS has been used in various railway systems such as the Electronic Train Management System (ETMS) and some US Positive Train Control (PTC) systems, RHINOS will make use of GNSS with very high integrity in mind. To achieve this level of integrity, RHINOS will leverage the work and experience developed in building such systems for aviation. The RHINOS project will investigate existing technology, develop a reference design, analyze significant threats and examine potential performance. This work will also ensure the design works with existing system and meets railway standards.

This paper is organized into two sections. The first section provides background on train control, the reference RHINOS architecture, and the models developed to implement a "proof of concept" version of the RHINOS architecture in the Stanford MAAST MATLAB simulation tool. The second section demonstrates the performance of this simplified RHINOS architecture under both nominal and faulted conditions. These results show the sensitivity of RHINOS performance to worst-case satellite exclusions (due to faults detected by the RHINOS algorithms) and severe multipath affecting trains. Means to mitigate onboard multipath are proposed, and their potential benefits are quantified.

# BACKGROUND

The RHINOS effort seeks to leverage the experience in creating aviation GNSS integrity systems to develop a suitable railway GNSS-based control system with integrity. However, in developing a GNSS integrity system for railways, we need to be mindful of two key points. First, railways navigation and control are safety of life systems and have existing safety standards. We need to develop an architecture and integrity methodology that is mindful of existing standards and systems. In particular, the system envisioned by RHINOS must integrate with the existing European Train Control System (ETCS) and meet its integrity level of Safety Integrity Level (SIL) 4 [1]. Second, in utilizing aviation precedents to develop a thorough analysis of the hazards, we need to focus on the difference which can be driven by environmental factors and targeted performance. Many of the hazards and threat descriptions will be the same but there will also be some hazards, such as multipath and Radio Frequency Interference (RFI), whose impacts differ significantly from those in aviation. Design differences, such as carrier phase based positioning, also will result in additional hazards that need to be considered.

## **European Train Control System**

ETCS represents the state-of-the-art in train control and management. It uses a combination of a positioning system and odometry to determine the along track position of a train. The positioning system uses passive transponders, known as a balise, placed on the railway and a transponder reader, known as a Balise Transmission Module (BTM), on the train. Balises meeting ETCS specifications are termed Eurobalises and use a series of several transponders for each location. A certified odometry, such as one based on wheel rotation, is used to determine along track position between updates. This is shown in Figure 1. As ETCS is an existing and operational system, there are many standards that the system is designed to meet. And while it is currently a form of positive train control, where train movement is only allowed given a positive indication to the driver, it, when coupled with wireless communications, form the foundations of an automatic train control system. This makes high integrity positioning even more paramount.

GNSS can provide the absolute positioning function in ETCS and hence, can be a drop-in replacement to the system of balise and the onboard BTM. This is shown on the right of Figure 1. This development has global implications as ETCS is used worldwide. For example, the Chinese Train Control System (CTCS), versions 2 and 3, used on high speed rail lines, are also based on ETCS. However, for GNSS to be used, it needs to meet or exceed the performance of the current balise system. This means it must meet an Alert Limit (AL), essentially the limit on PLs where service can be provided, of about 10-30 meters through much of the operation to provide along-track positioning comparable to the fixed balise system<sup>1</sup>. Preferably, it would enable new capabilities such as rapid, track discrimination in railyards and stations. Track discrimination in railyards would require even lower ALs, likely around 1-2 m. This application will likely require the addition of carrier phase-based positioning. Additionally, it needs to demonstrate integrity of 10<sup>-9</sup>/hour/train, as specified by SIL-4. Table 1 shows some of these requirements. A preliminary fault tree was created to allocate the overall SIL-4 safety probability to the various components of the system and their fault modes. A reference architecture was developed to address the material hazards identified.



Figure 1. ETCS with Balise Transmission Module (BTM), European Vital Computer (EVC), Odometry and GSM-R (rail) communications (left) with balises (in yellow, picture on bottom) and ETCS concept with GNSS drop in replacement to balise system utilizing virtually defined balise based on GNSS positions. Picture courtesy of Wikipedia

Table 1. Target requirem	ents for Railway	positioning
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Requirement	Level	Source
Integrity	1e-9/hour/train	SIL-4
Alert Level (Bounds)	$\sim 10 - 30$ m (see footnote 1)	Along track control
Alert Level (Bounds)	~ 1 m	Track discrimination
Availability	To be defined	To be defined
Continuity	To be defined	To be defined

## **Reference Architecture**

A two-tier architecture based on a combination of existing Satellite-based Augmentation Systems (SBAS) and local area differential GNSS (LDGNSS) was used as the basis of the reference architecture [2]. Under this two-tier design, SBAS is responsible for wide area faults while LDGNSS is responsible for local errors and corrections [3]. For the initial study, each

<sup>&</sup>lt;sup>1</sup> In the ERSAT-EAV project AL was set to 30 m. During the RHINOS project, a goal of achieving AL = 12 m for full supervision and AL = 3 m for start of mission was determined.

LDGNSS reference station is assumed to have two independent receivers. The On Board Unit (OBU) on the train is responsible for errors affecting the user only, with the primary and most significant error being anomalous (un-modeled) multipath. Advanced Receiver Autonomous Integrity Monitoring (ARAIM) along with other measures will be employed to mitigate and bound these user errors. A simple illustration of this architecture is shown in Figure 2 with the primary purpose of various components given in Table 2.

The reference architecture assumes that the user employs single frequency GNSS for positioning. The rationale for this choice is multipath. The dual frequency ionosphere free range combination, while essentially eliminating ionosphere induced errors, effectively inflates other ranging errors such as troposphere, noise, signal deformation and multipath. These errors are inflated by as much as a factor of 3.5 when using L1 and L5. As multipath will be significantly larger than in the airborne environment, the penalty from using the ionosphere free combination is quite large unless large multipath errors can be significantly reduced. In addition, almost all ionospheric errors are removed by the application of local-area corrections in this architecture. As a result, single frequency is used for positioning, though additional frequencies can used for other functions such as multipath detection and mitigation. The reference architecture also uses code-based GNSS smoothed with carrier phase measurements. Carrier phase-based GNSS has additional threats and has traditionally been much harder to certify. While carrier phase-based GNSS may be needed for track discrimination, the design for this application is not analyzed in this paper.



#### Table 2. Reference RHINOS architecture components and purpose

	SBAS	LDGNSS	Multipath Mask	Measurement Tests	Residuals Tests	Destination Processing
Purpose	Detect wide area errors	Provide corrections, detect local errors, PL equation	Camera derived multipath mask for eliminating NLOS, inflated prior probability of multipath	Correlator or other measurement tests	Tests of residuals (ARAIM) & comp. of DD code (narrow) carrier (wide), Doppler	Independent integrity checks (accelerometer, others)
Hazard/Threat Mitigated	Iono Gradient, Ephemeris error	Iono, ephemeris, clock, corrections	Multipath	Multipath	Multipath	RFI



Figure 3. RHINOS Reference Architecture Integrity Monitoring and PL Calculation Flow

The reference architecture then yields the integrity processing flow shown in Figure 3. SBAS and LDGNSS monitors protect against wide area and local faults, excluding faulted signals, satellites, or entire satellite constellations if needed. LDGNSS provides differential corrections, removing all errors that are correlated between the OBU and the nearby reference stations. This information is then communicated to the OBU. Onboard, ARAIM can then provide further detection and exclusion for user level errors such as multipath. Then ARAIM and LDGNSS/Ground-based Augmentation System (GBAS) PLs are both calculated by the OBU, and the maximum PL among these is used to assess safety in real time.

## SIMULATING RHINOS PERFORMANCE

A simulation tool was created to understand the performance capabilities of the reference RHINOS architecture and to further develop the system. This section discusses the Matlab software tool developed and the modeling used to assess the nominal and faulted performance of the system.

# **MAAST for RHINOS**

The MAAST was developed at Stanford University to provide rapid performance analysis for aviation integrity systems, in particular SBAS [4] [5]. It simulates specified satellite constellations and calculates range error bounds based on a specified architecture and error models. It is not a signal simulator but rather a simulation of the geometry and model error experienced by each specified user. For our analysis, MAAST was modified to model the reference RHINOS architecture and calculate the ARAIM and LDGNSS PLs.

The LDGNSS protection level equations are derived from GBAS nominal (H0), single reference receiver fault (H1), and ephemeris fault (Heph) PL equations, [9], [10]. Single reference receiver fault PLs are calculated presuming the failure of one reference receiver weighted by an *a priori* likelihood of such a failure. This faulted PL is more significant with fewer reference stations. The ephemeris fault PL is based on the largest possible undetected ephemeris fault. This calculation is modified from traditional GBAS as the reference architecture may also utilize SBAS to catch such faults. Hence, the fault calculation will change depending on whether the user location is within the SBAS coverage area. In the analysis, all users are presumed to be within the SBAS coverage area unless otherwise specified.

ARAIM PLs are computed using the same methodology developed for aviation but with the RHINOS integrity allocations and prior probabilities [6]. ARAIM requires knowledge of several parameters which would either be known *a priori* or provide via an Integrity Support Message (ISM). The most critical of these are satellite and constellation fault probabilities ( $P_{sat}$  and  $P_{const}$ , respectively). Aviation ARAIM currently uses 10<sup>-5</sup> and 10<sup>-4</sup> for  $P_{sat}$  and  $P_{const}$ , respectively, for initial studies. These are derived from system guarantees and long term observations. These values are important as they determine the subsets needed to cross check in order to meet integrity levels. In the proof of concept architecture, satellite and constellation faults should be detected by the LDGNSS and SBAS components. Thus, we likely can reduce  $P_{const}$  greatly In this analysis,  $P_{const}$  of 10<sup>-11</sup> is used, which effectively credits SBAS and LDGNSS for catching constellation fault with a missed detection probability of 10<sup>-7</sup>. Multipath may also result in faulted satellite ranges, and the code is modified to use  $P_{sat}$  to account for the error. For RHINOS modeling, the value of  $P_{sat}$  is a combination of probability of satellite failure ( $P_{sat,1}$ ) and probability of satellite range fault due to multipath ( $P_{sat,2}$ ). Due to SBAS and LDGNSS monitoring,  $P_{sat,1}$  should be significantly lower than the aviation value of 10<sup>-5</sup>, and 10<sup>-9</sup> is used.

Provided an acceptable ephemeris file, any constellation configuration can be simulated within MAAST. For the analysis, an optimized 24 satellite constellation for GPS [7] and a published 24 satellite Galileo constellation is used [8]. The overall PL shown is the maximum over LDGNSS and ARAIM PLs. ARAIM PL typically dominates LDGNSS, as it incorporates user errors, such as multipath, that cannot be not completely captured by the LDGNSS PLs.

#### **Error Models**

Models for various range errors are used to calculate PL. These models are derived from aviation but have been modified to account for reference RHINOS architecture. Specifically, we model the residual errors of single frequency code pseudorange after corrections and monitoring for common local errors, such as ionosphere delay, are provided by the LDGNSS reference station. Hence, the error models are derived from locally corrected and monitored single frequency code pseudoranges. As this is essentially a variation of GBAS, the baseline error models generally derive from those accepted for GBAS. Table 4 shows the error model equations and the underlying sources from which the models are derived and modified [7] [9] [10] [11].

Ionospheric and tropospheric delays are mitigated by corrections from the LDGNSS reference stations along the trackside. Hence, only residual errors remain. There are two nominal cases that we consider for residual error: 1) nominal and 2) nominal ionosphere but anomalous troposphere. These are described using Vertical (or zenith direction) Ionospheric Gradient (VIG). The conservative one variance impact, in squared meters per squared km ( $m^2/km^2$ ), of nominal ionosphere and nominal troposphere (note that the latter is near negligible) and of nominal ionosphere and worst-case (undetected) troposphere are given in Equations (1) and (2), respectively:

$$\sigma_{vig\_nom}^2 = 0.004^2$$
 (1)  
 $\sigma_{vig\_nom}^2 = 0.0064^2$  (2)

The VIG value is converted to a residual ionosphere (and troposphere) vertical or zenith error by the equation (3). It incorporates the distance of the train from the nearest reference station ( $x_{train}$ ), the speed of the train toward that reference station ( $v_{train}$ ), and the carrier smoothing time of the train GNSS receiver ( $c_{smooth,tau}$ ):

$$\sigma_{iono\_vert} = \sigma_{vig\_nom} \left( x_{train} + \frac{2 * c_{smooth,tau} * v_{train}}{1000} \right)$$
(3)

For this analysis, we use a train speed of 36.1 m/s (130 km/hr) and a ground and airborne carrier smoothing time constant of 50 seconds. The one standard deviation ionospheric error is found using the obliquity factor as shown in equations (4) and (5) below, where  $R_e$  is the radius of the earth (6378 km) and h<sub>I</sub> is the assumed "thin-shell-height" of the ionosphere (350 km).

$$\sigma_{iono} = oblique_{factor}\sigma_{iono\_vert} \qquad (4)$$

$$oblique_{factor} = \frac{1}{\sqrt{1 + \left(\frac{R_e cos(el)}{R_e + h_I}\right)^2}}$$
(5)

The modeling of multipath differs more significantly from aviation though the nominal aviation Code Noise MultiPath (CNMP) model is used as a baseline. This model should be appropriate for a well-sited LDGNSS Reference Station (RS). The equation is shown in Table 4 below under "CNMP – User," in which the first two terms model multipath effects and the second two terms model receiver code noise. *el* represents the satellite elevation angle in degrees. As the basic aviation equation is likely optimistic for many rail environments, we inflate the standard deviation from CNMP model by a variable factor, *rail<sub>if</sub>*. Nominally, *rail<sub>if</sub>* of three is used to account for the higher multipath encountered in rail than in aviation. The standard deviation (variance) from the model is inflated by a rail inflation factor (rail<sub>if</sub>) of 3 (or 9 after squaring) for the baseline analysis. The CNMP model is not meant to catch extreme multipath errors. Extreme multipath errors represent faulted conditions and are accounted for both by ARAIM monitoring and *P<sub>sat</sub>*.

The CNMP for the reference station is based on the model shown in Table 4 under "CNMP – Red. Station," where M is the number of independent reference receivers. M is assumed to be the minimum number of 2 in the baseline architecture, giving only 1 trustworthy receiver in the M-1 or 1-receiver failure case. Actual installations will have generally have more than 2 reference receivers, so M = 2 is conservative.

The overall pseudorange error overbound variances are shown below for the nominal case and the one reference receiver faulted case.

$$\sigma_{nom}^2 = \sigma_{cnmp,rs}^2 + \sigma_{cnmp,user}^2 + \sigma_{iono}^2 \tag{6}$$

$$\sigma_{M-1}^2 = \sigma_{cnmp,rs,M-1}^2 + \sigma_{cnmp,user}^2 + \sigma_{iono}^2 \tag{7}$$

The overall model variance used for ARAIM is given by Equation (6) above. The same model is used as the accuracy variance  $(\sigma_{nom}^2)$ .

Another difference between the aviation and rail environment is RFI. RFI will also be a more significant hazard on railways, as train tracks are closer to potential sources of RFI. However, we do not explicitly include this in our current analysis, as there is no agreed upon threat model. For the PL equations, *S* is the transformation matrix (pseudoinverse matrix) from pseudorange measurements to position and time. *W* is the weighting matrix based on the inverse of the pseudorange variances. *S* is given by

$$S = (G^T * W * G)^{-1} * G^T * W$$
(8)

For the LDGNSS PL, three cases are shown in Table 4: nominal (H0), faulted reference receiver (H1), and ephemeris fault (Heph). If the geometry matrix is calculated in East/North/Up (ENU) coordinates, then the first row of *S*, *S*(1,:) or *S*<sub>*l*,*i*</sub>, is *S* in the East direction (*S*<sub>*E*</sub>). So, the lateral PL in the East-West direction is shown in equation (13). Similarly, the second row of *S*, *S*(2,:) or *S*<sub>2,i</sub>, is *S* in the North direction (*S*<sub>*N*</sub>) when using the ENU frame. From above,  $\sigma_i^2$  and  $\sigma_{M-1,i}^2$  are the variance of the nominal range error,  $\sigma_{nom}^2$ , and the range error with 1 faulted reference station,  $\sigma_{M-1}^2$ , on the ith satellite, respectively. The inflation factors (*K*) are shown in Table 3.

Name	Value	Integrity Level	Description
Kffmd,2D	6.79	10 <sup>-10</sup>	Fault-free missed detection multiplier (2-D)
K <sub>ffd,2D</sub>	5.26	10 <sup>-6</sup>	Fault-free detection multiplier (2-D)
K <sub>md,2D</sub>	4.29	2*10 <sup>-4</sup>	H1 (B-value) monitor missed detection multiplier (2-D)
K <sub>mde,2D</sub>	4.80	2*10 <sup>-5</sup>	Ephemeris monitor missed detection multiplier (2-D)

Table 3. Descriptio	n of 2-D Gaussian	K factors a	and their values
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For the H1 reference receiver fault case, we calculate two terms. The first (H<sub>1,bias</sub>) is the impact of B-values at their LDGNSS threshold values on EPL\_H1, and the second (H<sub>1, nom</sub>) is the impact of the remaining nominal error with one fewer reference receiver.  $\sigma_B$  is the standard deviation of the B-values, ignoring any residual correlation due to ground multipath, which should be small as the reference receiver sites will be separated by many kilometers. In the simulation, we use the worst-case threshold

values for the B-values in H1 rather than the actual values as would be done in a fielded system, where the real-time B-values would be included with the broadcast corrections. This results in larger H1 PLs than in the fielded system.

For the ARAIM HPL equation, Q is the statistical Q function that gives the tail probability of a standard Gaussian distribution (in Matlab: qfunc()). Q is one minus the cumulative distribution function of a standard normal/Gaussian. The first Q term in the equation accounts for the fault free case. Then, for each fault hypothesis k, we sum the probability of PL not protecting the error for all monitored faults ( $N_{fault,mon}$ ) weighted by the probability of that fault condition ( $P_{fault,k}$ ).  $T_k$  is the threshold for fault k calculated from the ARAIM model solution separation results.

In an implemented ARAIM system, the true solution separation is tested against this threshold to detect and exclude faults.  $\sigma$  and b are the model standard deviation and bias, respectively. q is the index to each direction.

PHMI is the total allocated probability of HMI ("Hazardously Misleading Information"), meaning an error that is not bounded by the resulting PL. PHMI needs to be modified by the probability that some satellite and constellation faults that are not monitored by ARAIM ( $P_{sat, not mon}$  and  $P_{const, not mon}$ , respectively). The first equation assumes a fraction allocation of f in the specified direction (q). The reader is directed to the Baseline ARAIM algorithm description in [6] for additional details.

Model (Error/PL)	Residual Error Model ( $\sigma^2$ ) or Protection Level	Source
lonosphere/ Troposphere (iono)	$\left[oblique_{factor}\sigma_{vig\_nom}\left(x_{train} + \frac{2 * c_{smooth,tau} * v_{train}}{1000}\right)\right]^{2}$	Modified from LAAS MOPS [9]
CNMP – User (cmnp, user)	$rail_{if}^{2} \left[ \left( .13 + .53 * e^{-el/10} \right)^{2} + \left( .15 + .43 * e^{-el/6.9} \right)^{2} \right]$	WAAS/LAAS CNMP model modified by rail <sub>if</sub> =3 [10][7]
CNMP – Ref. Station with M receivers (CMNP, RS, M)	$\left[\frac{1}{M}\left(0.16 + 1.07 * e^{-el/15.5}\right)^2 + (0.08)^2\right]$	LAAS GAD-B curve with no troposphere [9]
Overall	$\sigma_{nom}^2 = \sigma_{cnmp,rs}^2 + \sigma_{cnmp,user}^2 + \sigma_{iono}^2$ $\sigma_{M-1}^2 = \sigma_{cnmp,rs,M-1}^2 + \sigma_{cnmp,user}^2 + \sigma_{iono}^2$ $\sigma_{acc}^2 = \sigma_{nom}^2$	
LDGNSS HPL	$HPL_{H0} = K_{ffmd,2D} \sqrt{\sum_{i=1}^{N} \left(S_{1,i}^{2}\sigma_{i}^{2} + S_{2,i}^{2}\sigma_{i}^{2}\right)}$ $HPL_{H1} = K_{ffd,2D} \sqrt{\sum_{i=1}^{N} \left(S_{1,i}^{2}\sigma_{B,i}^{2} + S_{2,i}^{2}\sigma_{B,i}^{2}\right) + K_{md,2D}} \sqrt{\sum_{i=1}^{N} \left(S_{1,i}^{2}\sigma_{M-1,i}^{2} + S_{2,i}^{2}\sigma_{M-1,i}^{2}\right)}$ $HPL_{eph} = max \left(\sqrt{S(1,:)^{2} + S(2,:)^{2}}\right) * P_{value} * 1000 * x_{train} + K_{mde,2D} \sqrt{\sum_{i=1}^{N} \left(S_{1,i}^{2}\sigma_{i}^{2} + S_{2,i}^{2}\sigma_{i}^{2}\right)}$	LAAS MASPS [10]
ARAIM HPL	$HPL = \sqrt{HPL_1^2 + HPL_2^2}$ $2Q\left(\frac{HPL_q - b_q^{(k)}}{\sigma_q^{(k)}}\right)^{N_{faults,mon}} \sum_{k=1}^{N_{fault_k}} P_{fault_k}Q\left(\frac{HPL_q - T_{k,q} - b_q^{(k)}}{\sigma_q^{(k)}}\right)$ $= \frac{1}{2}PHMI\left(1 - \frac{P_{sat,not\ mon} - P_{const,not\ mon}}{PHMI}\right)$	Blanch, "Baseline ARAIM," [6]

Table 4. Summary of Error Models and Protection Level Equations Developed for RHINOS analysis

## Multipath Mitigation & Analysis Model

Multipath error is a major driver of railway performance and capabilities. The modeling and mitigation of multipath can have profound effects on performance. While the modified CNMP model above is used to represent and bound nominal multipath,

extreme multipath that violates this bound remains possible. ARAIM should find very large multipath errors and exclude them. However, there will be multipath faults that are severe but not large enough for ARAIM to detect. These are modeled by using  $P_{sat}$  so that it incorporates contributions from multipath faults,  $P_{sat,2}$ . For our modeling, we have  $P_{sat,2}$  depend on satellite elevation angle, as lower elevation angles tend to have more multipath. In the baseline analysis, we use values of  $10^{-1}$  to  $10^{-3}$  for  $P_{sat,2}$  at various elevation angles, as shown in Table 5. The elevation mask used for the nominal analysis is 10 degrees, again reflecting the fact that the terrestrial environment has more blockage than the air environment (which uses 5 degrees).

Table 5. Nominal Overall Probability of Satellite Signal Fault as a combination of Satellite & Multipath Fa	ıult
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<b>Elevation Angle</b>	P <sub>sat,1</sub>	P <sub>sat,2</sub>	P <sub>sat</sub>
Below 15°	10 <sup>-9</sup>	10-1	10 <sup>-1</sup> +10 <sup>-9</sup> ~ 10 <sup>-1</sup>
15 - 45°	10 <sup>-9</sup>	10-2	10 <sup>-2</sup> +10 <sup>-9</sup> ~ 10 <sup>-2</sup>
Above 45°	10 <sup>-9</sup>	10 <sup>-3</sup>	10 <sup>-3</sup> +10 <sup>-9</sup> ~ 10 <sup>-3</sup>

The RHINOS study is developing and assessing a variety of multipath mitigation methods and examining which ones should be used. The analysis supports this by determining the necessary level of multipath mitigation to achieve the desired performance goals. There are many reasonable methods that can be employed for detection: 1) multiple frequency combinations (L1/E1-L5/E5), 2) carrier phase-based detection, 3) multiple separated OBU antennas, and 4) skyview surveys [12]. The first three methods use measurements that should be uncorrelated from single antenna L1/E1 pseudorange to test for discrepancies from multipath. A skyview camera can be used to pre-survey the track to create location and azimuth dependent elevation mask to limit Non Line Of Sight (NLOS) satellites and multipath signals. Examples of these are shown in Figure 4. While many methods are being evaluated, the purpose of the analysis is not to prescribe the method but to determine the target level of mitigation. Hence, while the analysis examines the benefits of different levels of multipath mitigation, it does not indicate the means of achieving the proposed mitigation level.

We also examine the use of a mixed Gaussian model which postulates that multipath errors may be better represented by combination of two different Gaussian distributions than a simple Gaussian distribution. An improved nominal multipath model can reduce the incidence of faults, meaning conditions that fall outside the norm. It is hoped that, by accounting for more multipath conditions in the nominal model and reducing the fault probability, we can decrease PL while maintaining the targeted integrity levels



Figure 4. Using skyview camera (Left) and other means to mitigate multipath and non-line of sight signals (Right).

# **Modeling Faulted Performance**

Faulted conditions are obviously an important consideration in assessing integrity performance [13]. These conditions can cause ionosphere gradients, satellite (ephemeris or clock) errors, or multipath to violate the nominal models given above. Integrity monitoring will either detect the fault, if it is sufficiently large, or not detect it, in which case it needs to bound its effect. In the former case, the faulted satellite (SV) measurement is excluded. We had MAAST model the worst case exclusion by removing the satellite that has the greatest benefit for each PL. In the latter case, the ARAIM PL should protect against the fault. We instead determine the maximum (worst) undetectable error or Minimum Detectable Error (MDE). Analysis can determine the LDGNSS MDE *a priori*, while the ARAIM MDE depends on geometry. MAAST has been modified to determine the ARAIM MDE based on one undetected satellite fault. Table 6 shows the faulted conditions, the different cases that can result under the reference architecture, and the modeling, predominantly using MAAST, conducted to assess each faulted condition. The rationale for the modeling of each fault is explained next.

#### Table 6. Modeled Fault Cases

Fault	Mitigation cases	Modeling
Anomalous Ionosphere Gradient	Detection by SBAS Detection by LDGNSS Below LDGNSS Detection Threshold	1-2 satellite excluded Offline worst gradient analysis, Estimate range error under worst-case circumstance (gradient at MDE)
Ephemeris/Clock failure	Detection by SBAS Detection by LDGNSS Below LDGNSS Detection Threshold	1-2 satellite excluded Error at minimum detected error/threshold
Extreme Multipath (1)	Detection by ARAIM Below ARAIM Detection Threshold	1-2 satellite excluded ARAIM minimum detected error analysis
Extreme Multipath (2)	Bounding by ARAIM PLs	Sensitivity studies

In the case where there is an extreme ionospheric gradient, two physical conditions can occur. The gradient can exist either 1) within or 2) outside the SBAS coverage area. Within SBAS coverage, detection is conducted using SBAS information, and the affected satellite(s) is (are) removed. We assume that the SBAS detects the error before it significantly affects users – i.e., there are no effects beyond exclusion of faulted satellite(s). This assumption may need to be tested later, but the current study does not simulate the SBAS network. For this analysis, this impact is conservatively modeled by excluding the worst-case satellite, meaning the satellite that provides the maximum benefit to the user geometry in terms of reducing PLs. Outside SBAS coverage, the LDGNSS RSs are responsible for detection. LDGNSS will detect most extreme gradients and exclude the affected satellite(s). Again, this is conservatively modeled in the analysis as an exclusion of the worst-case (most-useful) satellite. However, there are possible scenarios where LDGNSS monitoring may not recognize the presence of an extreme gradient with the required missed-detection probability, depending on the size and geometry of the gradient relative to the train and nearby RSs. This worst-case period exists as the gradient passes by so its effects are experienced by the user and one reference station but not by other reference stations. An offline analysis was conducted to determine the worst-case ranging error condition under this scenario (when detection or warning does not occur). This can be compared to the ARAIM MDE which covers all undetected errors, regardless of source.

For ephemeris and clock failures, detection is performed by the SBAS and LDGNSS components, depending on the type and observability of the error. As with the ionosphere gradient, there are two cases – within and outside the SBAS coverage area. Within SBAS coverage, both SBAS and LDGNSS will detect, and it is expected that the detection is fast enough that the satellite is excluded before user errors are significantly affected. Outside SBAS coverage, LDGNSS will detect and exclude in a similar fashion, but with a larger MDE in the case of ephemeris errors (see the above discussion regarding the ephemeris PL). The SBAS or LDGNSS MDE is included in the ephemeris protection level computed for LDGNSS and thus contributes to OBU PL calculations.

For multipath faults, the baseline architecture utilizes ARAIM to detect multipath. For the faulted condition assessment, we consider several cases. The first case is where multipath is large enough that it is detected by ARAIM, thus the affected satellite(s) are excluded. As noted above, the ARAIM MDE gives the maximum undetectable error for multipath as well as any other fault mode that is limited to the subsets of satellites checked by ARAIM. More complex cases will be examined in future studies. For a given number of satellite measurements excluded, MAAST searches over all possible combinations of satellites to exclude to find the worst (largest) PL and the set of excluded satellites that results in that PL. In other words, this process

searches for and excludes the satellite(s) that provide the most benefit in terms of reducing PL by their presence in the navigation solution. This search procedure is conducted independently for each PL (LDGNSS H0, H1, eph, and ARAIM) and so a different excluded set may be used for each PL.

#### PERFORMANCE RESULTS

Assessment using MAAST for RHINOS was conducted using a 10 day simulation with two full constellations: GPS (optimized 24 satellite constellation [9]) and Galileo (projected full 24 satellite constellation [8]). No WAAS or EGNOS geostationary satellites are used in the initial simulation (except to relay SBAS corrections to the LDGNSS reference stations). While we assume the use of the L1 C/A and E1 OS (data/pilot) for GPS and Galileo, respectively, the error models used for each ranging signal are the essentially the same. Thirteen major European cities, spanning the anticipated breadth of the coverage area, were used for the assessment. The locations chosen are biased towards the edges of the coverage area of European Geostationary Navigation Overlay Service (EGNOS), the European SBAS. These locations should capture the worst-case areas for the selected architecture. These cities are shown in Figure 5. Singapore was used as a reference due it being located near the Equator and thus having nearly the best satellite geometry possible. It provides a means of examining the benefits of improved satellite geometry (via, e.g., additional satellites) in Europe.

The PL results that follow are for trains in the selected locations moving in an arbitrary direction at an assumed speed of 36.1 m/s (130 km/hr). No specific track direction or alignment is assumed. Therefore, the results are generally shown as 2-D Horizontal PLs (HPLs). For the primary RHINOS train-control application, only 1-D lateral protection levels (LPLs) along the known track direction are needed, and GNSS train position is aligned along this known track direction. The benefits of this alignment in reducing the output 1-D along-track PL are not included in the simulated MAAST results. In [2] we have calculated the train position track-constrained from live testing in Sardinia and we have derived the value of PL epoch by epoch relative to that track-constrained position. Note that 2-D HPL overbounds the Lateral Protection Level (LPL) in any direction, even without the use of track constraints.



Figure 5 – European sites used for analysis

#### **Nominal Performance**

The analysis using the nominal conditions provides several informative results. First, the ARAIM HPL dominates the LDGNSS HPL (the maximum of the three LDGNSS PLs for H0, H1 and ephemeris) under these conditions. Figure 6 shows the HPL from ARAIM and LDGNSS for two locations (Berlin and Paris) over the first day. The ARAIM HPL is always larger, often significantly, than the LDGNSS HPL, and the ARAIM HPL is much more sensitive to GNSS satellite geometry. This is not surprising, as LDGNSS does not consider the likelihood of multipath anomalies at the OBU (a multipath anomaly at a single reference station is covered by the LDGNSS H1 PL). As OBU multipath faults dominate *P*<sub>sat</sub> in this case, the LDGNSS calculation cannot fully capture the hazard should the multipath fault rates be similar to that shown in Table 5.

To examine availability, a 10 day simulation is used to generate the cumulative distribution, specifically the Complementary Cumulative Distribution Function (CCDF), of the HPL, which gives the probability that HPL is at or below a specific value. In it, the HPL vectors over time for each user location are re-sorted and plotted from lowest (far right) to highest (far left). The x-axis gives the probability that a given HPL value on the y-axis is not exceeded. For example, in Figure 7, the HPL at the 99<sup>th</sup> percentile level for Singapore is about 12 m, meaning that 99% of all simulated HPLs at Singapore are at or below 12 m. Figure 7 shows that the 99% PL levels for European sites are at least 22 m and are generally over 30 m. This is a little higher than our target. One way to improve performance is by having better geometry. The HPL distribution is much better for Singapore due to better geometry which can better manage the satellite faults anticipated by  $P_{sat}$ . Another way to improve performance is to have better multipath mitigation.



Figure 6. ARAIM & LDGNSS HPL at Berlin (Left) & Paris (Right) over 24 hours - Base sensitivity case



Figure 7. HPL percentile plot for test locations calculated over 10 days – Base sensitivity case

#### **Multipath Mitigation**

MAAST is used to examine the effect of different levels of multipath on overall PLs. It can determine the approximate amount of multipath mitigation required to achieve targeted PL. For the initial multipath mitigation study, we select one level of mitigation performance. We assume that mitigation reduces the probability of multipath faults ( $P_{sat,2}$ ) by a factor of 100, as seen in Table 7. However, mitigation, such as a skyview camera, may reduce the amount of sky where usable satellites can reside. So we also assume higher elevation mask of 15 degrees in the "mitigated" scenario.

Table 7. Overall Probability of Satellite Signal Fault as a combination of Satellite & Multipath Fault: Multipath Mitigated Case

Elevation Angle	P <sub>sat,1</sub>	P <sub>sat,2</sub>	P <sub>sat</sub>
Below 15°	10 <sup>-9</sup>	10 <sup>-3</sup>	10 <sup>-3</sup> +10 <sup>-9</sup> ~ 10 <sup>-3</sup>
15 - 45°	10 <sup>-9</sup>	10-4	10 <sup>-4</sup> +10 <sup>-9</sup> ~ 10 <sup>-4</sup>
Above 45°	10 <sup>-9</sup>	10-5	10 <sup>-5</sup> +10 <sup>-9</sup> ~ 10 <sup>-5</sup>

Figure 8 shows the HPLs over the first day at Berlin and Paris. With the lower  $P_{sat}$ , the difference between ARAIM and LDGNSS HPLs is also much lower. There are a few exception where ARAIM HPLs are noticeably larger, and these are likely due to weaker satellite geometry. Figure 9 shows the HPL cumulative distribution for the assumed level of multipath mitigation. The overall HPLs are much lower, with 99% levels in Europe between 8-13 m, which are well within our target.

However, these results still represent nominal conditions without any satellite excluded other than by the elevation mask. We must also consider conditions where there are faults that result in satellite exclusion, and these are shown in the following section.



Figure 8. ARAIM & LDGNSS HPL at Berlin (Left) & Paris (Right) over 24 hours – Multipath mitigated sensitivity case



Figure 9. HPL percentile plot for test locations calculated over 10 days – Multipath mitigated case

#### **Faulted Performance**

We first consider the effect of detected and excluded faults under the multipath mitigated case. Specifically, assuming the same multipath mitigation approach shown above is used, we conducted an assessment of performance with one excluded satellite. For each given HPL, MAAST excludes the satellite that improves the HPL the most (if it were present in the navigation solution). These "worst case" excluded satellites lead to much weaker satellite geometry, and again the ARAIM HPL dominates. This is shown in Figure 10, which has the ARAIM and LDGNSS HPL for Berlin and Paris. Figure 11 shows the HPL cumulative distribution for all 14 locations. The overall HPLs in Europe at the 99% levels are around 30 m. So with the assumed multipath mitigation, the HPL distribution with the worst case satellite excluded is slightly better than that of the nominal case (without multipath mitigation or satellite exclusion). ARAIM weakness due to satellite geometry implies that three constellations may be useful under these conditions. Even the addition of a partially complete constellation is useful, since SBAS and LDGNSS provide protection against constellation-wide failures.



Figure 10. ARAIM & LDGNSS HPL at Berlin (Left) & Paris (Right) over 24 hours – Multipath mitigated sensitivity case & 1 satellite fault



Figure 11. HPL percentile plot for test locations calculated over 10 days – Multipath mitigated sensitivity case & 1 satellite fault

#### **Missed Detection**

If a fault is not detected and excluded, the worst case is for the fault to cause an error at the MDE, which means the largest fault magnitude that is not detected and excluded with the required false-alert and missed-detection probabilities. ARAIM examines all range errors regardless of source, and hence its MDE is only dependent on the number of satellites affected by the fault. The ARAIM MDE depends on satellite geometry and can be derived from the fundamental ARAIM equations. LDGNSS is primarily responsible for satellite and ionospheric errors. Offline analysis is used to determine the LDGNSS MDE from these errors. Since satellite errors experienced by LDGNSS and the user will be similar, only very large errors due to satellite-fault conditions will significantly affect users. Similarly, normal ionospheric gradients cause very small differences between RSs and users, but under anomalous conditions, ionospheric delays can differ significantly between the LDGNSS RSs and the user. LDGNSS monitors for this condition using, among other tests, the consistency of candidate corrections from individual reference receivers (these are used to create the "B-values" that drive the H1 PLs), making the most severe of these conditions detectable (the resulting B-values exceed the MDE). As shown below, we conduct modeling of severe ionospheric gradients affecting a user and two nearby RSs (the minimum number that would be present) to determine this MDE and then the resulting maximum differential error from LDGNSS monitoring.

#### Minimum detectable error for ARAIM

While the concept of a range domain MDE is not used in ARAIM, it can be derived from the ARAIM Solution Separation (SS) detection threshold and depends on satellite geometry. For the one-satellite faulted case, we start with the ARAIM missed detection equation. Essentially, the probability of missed detection,  $P_{MD}$ , is the probability that the calculated solution separation that targets the faulted scenario, plus an allocation for nominal error, falls below the specified threshold, T, and thus is not excluded by ARAIM. The threshold T is determined by the required false alarm rate. The derivation starts by assuming a fault causing a bias error on the ( $k^{th}$ ) satellite signal.  $S_{k,q}$ , again is S for the  $k^{th}$  measurement in the q direction with the superscript (0) indicating no satellites excluded.  $\sigma_{ss,int q}$  is the standard deviation in the  $q^{th}$  direction of the solution separation (ss) between the all in view and the solution with the  $k^{th}$  satellite excluded, hence the superscript (k). It uses weighting based on the integrity bound on range error variance. Later we will introduce  $\sigma_{ss q}$  which is similar except that the accuracy bound on range error variance [6] for the details and equation.

$$\left(S_{k,q}^{(0)}b_k + \varepsilon * \sigma_{ss,int q}^{(k)} \le T\right) = P_{MD} \tag{9}$$

Assuming a normal distribution of nominal error, where  $\Phi$  is the normal cumulative distribution function (cdf) and  $K_{MD}$  is the K-factor corresponding to  $P_{MD}$ .

$$\Phi\left(\frac{T-S_{k,q}^{(0)}b_k}{\sigma_{ss,\ int\ q}^{(k)}}\right) = \Phi(-K_{MD}) = P_{MD}$$
<sup>(10)</sup>

From equation (10), we can solve for the worst  $b_k$ , a bias from a fault on the  $k^{th}$  satellite, that would not cause an alert and a satellite exclusion. We replace T with its value based on  $K_{FA}$ . The result is shown in equation (11). Note that the probability of false alarm is not for protecting integrity but is instead to limit the number of unexpected losses of service (i.e., losses of continuity). Hence, the  $K_{FA}$  used is different than the K-factor used to protect integrity (e.g.,  $K_{MD}$ ).

$$S_{k,q}^{(0)}b_k - K_{MD} * \sigma_{ss,int q}^{(k)} \le T = K_{FA} * \sigma_{ss,q}^{(k)}$$
(11)

The MDE for a fault on satellite k and a given direction q,  $b_{MDE,k,q}$ , is calculated by the equation below (12):

$$S_{k,q}^{(0)}b_{MDE,k,q} = K_{FA} * \sigma_{ss,q}^{(k)} + K_{MD} * \sigma_{ss,int q}^{(k)}$$
(12)

The MDE for a fault on satellite k is the minimum  $b_{MDE,k,q}$  over all directions. In other words, this is the only error that will not be detected (with the required  $P_{EA}$  and  $P_{MD}$ ) in any direction. A larger value would be detected in at least one direction and hence would be excluded. The MDE for the user at that instant is then the maximum MDE over all satellites. Hence, Equation (13) shows the overall MDE.

(13)



 $b_{MDE} = \max_{k} \left[ \min_{q} \left( b_{MDE,k,q} \right) \right]$ 

Figure 12. MDE over 24 hours for base case



Figure 13. MDE over 10 days (240 hours) for base case with 1 worst case satellite excluded

This calculation is implemented into the MAAST simulation. Figure 12 shows the ARAIM MDE for one satellite fault. It generally ranges from 6 to 10 m. Of course, the ARAIM MDE depends on geometry, so if we had already detected and excluded the worst case satellite due to one failure, the MDE for another independent failure would be higher, as shown in Figure 13. The ARAIM MDE would be much higher with two (worst case) excluded satellites.

These ARAIM MDEs can be compared with those from SBAS and LDGNSS monitoring to determine the need, if any, for improved monitoring prior to ARAIM. The example of LDGSS monitoring of anomalous ionospheric gradients is a good example. As shown in the following subsection, the worst-case impact of these gradients after LDGNSS monitoring is a maximum differential error of about 3 meters. This is much smaller than the minimum ARAIM MDE of 6 meters shown here. Thus, unless the system design or assumptions change significantly, there appears to be little benefit of further improving LDGNSS monitoring against ionospheric gradients, as the user PLs will not improve and will still be dominated by ARAIM. Under different conditions, this might no longer be the case, and improvements to LDGNSS (or greater use of SBAS) might become advisable.

## Offline analysis of ionosphere faults

Ionospheric faults can be detected by SBAS, LDGNSS or ARAIM. The previous section shows the MDE calculation for ARAIM. This is applicable to ionospheric faults along with all other faults affecting individual satellites. In this section, we estimate the MDE for ionospheric faults using LDGNSS monitoring. We do not calculate an MDE value based on SBAS, as we do not want to rely on SBAS coverage in this architecture. In general, SBAS ionospheric monitoring (within the region covered by the network of SBAS reference stations) is much better than what can be done with LDGNSS, so the MDE that applies to users within SBAS coverage is lower than the value for LDGNSS computed here. For an anomalous ionospheric gradient case, analysis is conduct to determine, a priori, the largest undetected bias (maximum undetectable error or minimum detectable error). This bias is then used as the faulted bias bounds in calculating the PLs. The worst-case parameters of the ionospheric gradient are based on the model constructed for GBAS operations in mid-latitudes [15]. Figure 14 shows a simplified model of an extreme gradient. In this instance, the train is moving at 30 meters per second (m/s) and is halfway between the only two reference stations that are available to provide differential corrections. In this circumstance, the differential correction applied by the train is the average of the corrections generated by the two reference stations (morecommon scenarios would combine corrections from multiple RSs and would be less threatening). The gradient, modeled as a moving front in which a slant gradient of 400 mm/km exists within a width of 25 km between high and low delays, affects the measurements of the train and one of the two reference stations, but not the other. In this particular scenario, which is selected to be difficult to detect, the velocity of the front relative to the train and the (static) reference stations makes it difficult for Code-Carrier Divergence (CCD) monitoring to observe a large enough change of ionospheric delay over time to be able to detect. Instead, the most effective monitor is the comparison between candidate corrections generated at the two reference stations. This comparison generates "B-values" for each satellite that, as noted above, generates the B-values that are inputs to the LDGNSS H1 protection level calculations.



Figure 14. LDGNSS Model of Ionospheric Gradient

Based on the nominal error models for reference stations derived for GBAS and given in [10] and conservative  $K_{FA}$  and  $K_{MD}$  values that total 10, the minimum detectable error of B-value monitoring with only two reference stations is about 3 meters. This means that any ionospheric gradient that creates a B-value test statistic below 3 meters might not be detected by LDGNSS with the required  $P_{FA}$  and  $P_{MD}$ . In the "near-worst-case" scenario shown in Figure 14, where only B-value monitoring is deemed to be effective, this would occur if the gradient size is below about 240 mm/km, as that is the gradient size that would create a B-value roughly matching the MDE of 3 meters. If a gradient of this magnitude existed under the scenario shown in Figure 14 affected at least one satellite tracked by the train and was not excluded by LDGNSS, the resulting differential range error on each affected satellite would be approximately 3 meters, which is the same as the B-value MDE. This is due to the train using the average of the correction from reference receiver 0 (which is in error by 25 km × 240 mm/km × 0.001 m/mm = 6 m since it is on the "wrong side" of the gradient and from the unaffected reference receiver 1 (which has zero error). The result is a bias error of 3 meters. This error is a bias under the conditions shown in Figure 14, but will change with time as both the train and the gradient front move. Note that, once the front progresses past both the train and reference receiver 1, all three receivers will be on the same side of the front, with no gradient in between them, thus no differential error remains.

#### **Gaussian Mixture Multipath Model**

A Gaussian mixture model may provide a better representation of the distribution of multipath induced errors. It essentially postulates that the nominal multipath induced error can be well represented by a combination of two Gaussian distributions – a typical and a rare-typical condition. Hence, the model is a mixture of two Gaussian distributions with prior probabilities on each distribution. This is shown in Table 8, which gives the selected prior probability and multipath inflation factor, *rail*<sub>if</sub>, for both typical and rare typical conditions. The Gaussian mixture model is not meant to capture all multipath events, but it should

capture more of them than the nominal Gaussian model, which only applies the first of these two Gaussian distributions and gives it a probability of 1.

Again, we utilize  $P_{sat,2}$  to account for those cases not contained by either component of the mixture model. As the mixture model should capture more multipath events, we use a value of  $P_{sat,2}$  that is lower by one order of magnitude than that of the Gaussian multipath case. Hence, it is between  $10^{-2}$  and  $10^{-4}$  or  $10^{-4}$  and  $10^{-6}$  in the case of the baseline and multipath mitigated scenarios, respectively. The result of the baseline case, without multipath mitigation, is shown in Figure 15, which shows the HPL at Berlin over one day. As before, the HPL from ARAIM dominates that from LDGNSS.

Table 8. Gaussian Mixture Multipath Model Distribution Parameters Used

Conditions	Prior Probability	Standard Deviation Inflation off SBAS model ( <i>rail</i> ij) (equation 6)
Typical	0.97	3
Rare-Typical	0.03	8



Figure 15. Comparison of ARAIM & LDGNSS HPL (Gauss mix model off base sensitivity case) for rail<sub>if</sub> of 3 and 8 over 1 day at Berlin

The appropriate application of the Gaussian mixture model depends on its operational context. If the mixture of different multipath states occurs in a manner that is truly unpredictable to the user, then it might be appropriate to average their two different HPLs in real time, weighted by their prior probabilities, to get a single HPL that fairly represents both possibilities. Figure 16 shows the CCDF of HPLs calculated in this manner for all locations over 10 days (with all satellites present). Its results are quite good, with maximum HPLs below 15 meters for all locations, and 99.9<sup>th</sup>-percentile HPLs in the range of 10 to 12 meters. On the other hand, if we assume that the different scenarios (typical and rare-typical) are knowable beforehand, such as based on a map that divides suburban and rural track locations from urban ones, then we must create the HPL distribution without averaging the HPLs. In this case, we can take simulation results from typical and rare-typical case and then combine their HPL distributions weighted by the prior probabilities, thereby forming the baseline Gaussian mixture CCDF shown in Figure 17. The distribution sees a step jump at around the 97% level. This is not surprising, as the rare-typical case represents 3% of the instances and there is a large difference between the HPL of the typical and rare-typical conditions. Overall, HPL with the Gaussian mixture model is significantly better than the nominal performance shown in Figure 7. The one order of magnitude reduction of multipath induced satellite faults has a significant benefit that far outweighs the increased multipath error represented by the rare-typical component of the mixture model.



Figure 16. HPL percentile plot for test locations calculated over 10 days – Gaussian mixture model nominal case, Weighted average HPL



Figure 17. HPL percentile plot for test locations calculated over 10 days – Gaussian mixture model nominal case, Weighted average distribution

The above scenario assumes not multipath mitigation. In fact, we can use the multipath mitigation previously discussed with the mixture model (2 order of magnitude lower  $P_{sat,2}$  and 15 degree elevation mask). We assess the performance of using a mixture model assuming the multipath mitigation model in Table 7. Figure 18 compares the HPL from ARAIM and LDGNSS for this case at Berlin and shows that they are comparable. With lower likelihoods of OBU multipath faults, ARAIM and LDGNSS PLs become very similar. It also shows that reducing satellite fault probabilities or having more satellites and constellations can lower protection levels significantly.

Figure 19 and Figure 20 show the HPL cumulative distributions with the Gaussian mixture model assuming a weighted averaged HPL (see Figure 16) and separate HPL distributions (see Figure 17), respectively. For the average HPL shown in

Figure 19, the HPL performance very good at nearly all probabilities and is always below 12 m. In Figure 20, the HPL performance is slightly worse than the nominal multipath mitigated scenario of Figure 9 at the 99% level. The reason for this is that with multipath mitigation already reducing multipath faults by 2 orders of magnitude, the single order of magnitude decrease in multipath fault probability assumed for the mixture model is not as significant. And so the increased nominal multipath error that occurs 3 percent of the time in the mixture model causes a worse performance at 99%. However, the mixture model has lower HPLs at higher percentiles. Overall, the results show that better bounding and modeling can produce lower but still conservative protection levels.



Figure 18. Comparison of ARAIM & LDGNSS HPL (Gauss mix model with multipath mitigation) for rail<sub>if</sub> of 3 and 8 over 1 day at Berlin



Figure 19. HPL percentile plot for test locations calculated over 10 days – Gaussian mixture model with multipath mitigation, Weighted average HPL



Figure 20. HPL percentile plot for test locations calculated over 10 days – Gaussian mixture model with multipath mitigation, Weighted average distribution

# CONCLUSION

This paper examines the use development of high integrity GNSS for railway control as part of the RHINOS effort. It shows the reference architecture developed for RHINOS. It describes a bespoke version of MAAST developed to assess the RHINOS design. Error models and ARAIM and LDGNSS protection level equations were developed to reflect the design and were implemented in MAAST for RHINOS. MAAST was used to simulate various nominal and faulted cases to examine HPL and thus availability. The results show the projected performance of the RHINOS reference architecture for train positioning under nominal and faulted conditions. It also examined the performance improvements possible with better multipath modeling and mitigation. These results indicate that the system, with some degree of multipath mitigation, should achieve the objective of high availability of 12 m protection levels under nominal conditions. It is anticipated that an alert limit of 12 m is needed In Europe for full supervision for ERTMS/ETCS. Under the more severe variations of faulted conditions, such as when the most-useful satellite is excluded due to a detected fault, the availability of 12 m protection levels suffers. This work suggests several ways to achieve the availability targets in the presence of worst-case satellite exclusions, such as the addition of more satellites, other constellations, or further multipath mitigation.

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#### DISCLAIMER

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the European Commission.

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