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

D1.1 – Aeronautical Assumptions and Requirements

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Executive Summary

This report presents the work of ASTrail WP1 tasks 1.1 and 1.2 on the transfer of assumptions and requirements for the application of Global Navigation Satellite Systems (GNSS) from the civil aviation domain to the rail domain. The philosophy taken has not been to apply the civil aviation requirements, specified in terms of the four Signal-In-Space parameters of accuracy, integrity, continuity and availability. Rather, the approach is to use the railway formulation of requirements in terms of Reliability, Availability, Maintainability and Safety with guidance from the experience of civil aviation.

It is noted that in comparison to the reliability and safety of existing railway components, GNSS safety integrity, meaning the trust that the positioning and localisation solution is not subject to dangerous undetected errors, is a function of time. This is as a result of the non-stationary error distributions due to satellite motion. Furthermore, the Safety Integrity Level (SIL) must be achieved under all stated conditions as per the rail industry standards, this is interpreted to account for the worst-case conditions regarding the impact of a failure and other driving parameters relating to the measurement error model. In fact, what is known as *specific risk* in the aviation world, should be applied when safety is at stake. If a parameter's distribution is not well-known (overbounded correctly), or is predictable in some same, then the specific risk (worse case value) should be used.

The SIL in rail is referenced to a Tolerable Hazard Rate (THR) for a particular function, notably 10^{-9} per hour for SIL4 the most demanding level. This THR is the total risk during any hour of function. Since the probability distributions for the components are with conventional systems stationary, the designer only has to compare a computed hourly risk to the requirement to check compliance. With GNSS, since the real time risk varies, compliance must be verified in real time, unless it can be guaranteed that the requirement is met whatever the state of the system.

ASTRail accepts that the virtual balise concept is well established as a means to integrate a GNSS based positioning component to the rail localisation unit (LU) without a complete overhaul of the train architecture. This concept will then form the backbone of the architectures addressed in ASTRail. However, GNSS may also be used to provide a more frequent position update than provided by physical balises and thus relax requirements on the odometry function.

The approach setup in this document which will be followed throughout WP1 is to map RAMs requirements directly to the needs of the GNSS receiver requirements and not through the Signal-In-Space (SIS) requirements framework of civil aviation. This no doubt requires GNSS expertise, and it is critical when assessing the hazard of an incorrect GNSS location determination, that the correlation of errors be accounted for in order to model the duration of a fault condition. Similar with regards to the availability and reliability, it is shown herein that continuity is not the most appropriate means to quantify the performance at some SIS level since it is a measure of unpredictable events. Instead, system outages, or (non-hazardous) failures may be predictable due to the changing geometry of the constellation. It is therefore advised that a finer analysis of the up and down time with respect to all possible causes be performed for the use of GNSS in rail and that through this, the RAM requirements may be both set and validated. This will not obviate the need for a certain failure risk to be assigned to real-time monitors for threats in the same manner that the continuity budget is employed to compute the required probability of false alarm.

Studies of the current advances in civil aviation augmentation systems, which is being continued in T1.4, show that certain techniques may be applicable to the rail application. Namely, the multiple hypothesis approach of Advanced RAIM offers improved local integrity monitoring for the train's on-board function. Dual frequency positioning and monitoring techniques developed within the next generation GBAS work may help to inhibit some effects of ionosphere whilst reducing through smoothing the multipath. Such elements will be studied in greater detail in T1.6 and T1.7.

Table of Contents

1 Introduction

1.1 Scope and Structure

This deliverable contains the results and output of tasks T1.1 and T1.2 of the WP1 on Introducing GNSS in the Railway Sector. In section 2, a review of the requirements is made, beginning sith a descriptin of the documentation and policy of civil aviation, the assumptions and standards formed for GNSS use before looking at how rail requirements are defined. In section 3 a technical state of the art of previous GNSS in rail studies is performed with is critical to pick out acrhitectures for T1.6 and to begin to understand which requirements will be applicable. Section 4 selects the key assumptions and requirements for rail.

1.2 WP1 Planning

Figure 1 shows the dependencies within ASTRail and in particular WP1. Tasks T1.1 and T1.2 both contribute to the Architecture definition in T1.6 and there is a relationship with WP2, in particular the definition of the use cases in T2.1.

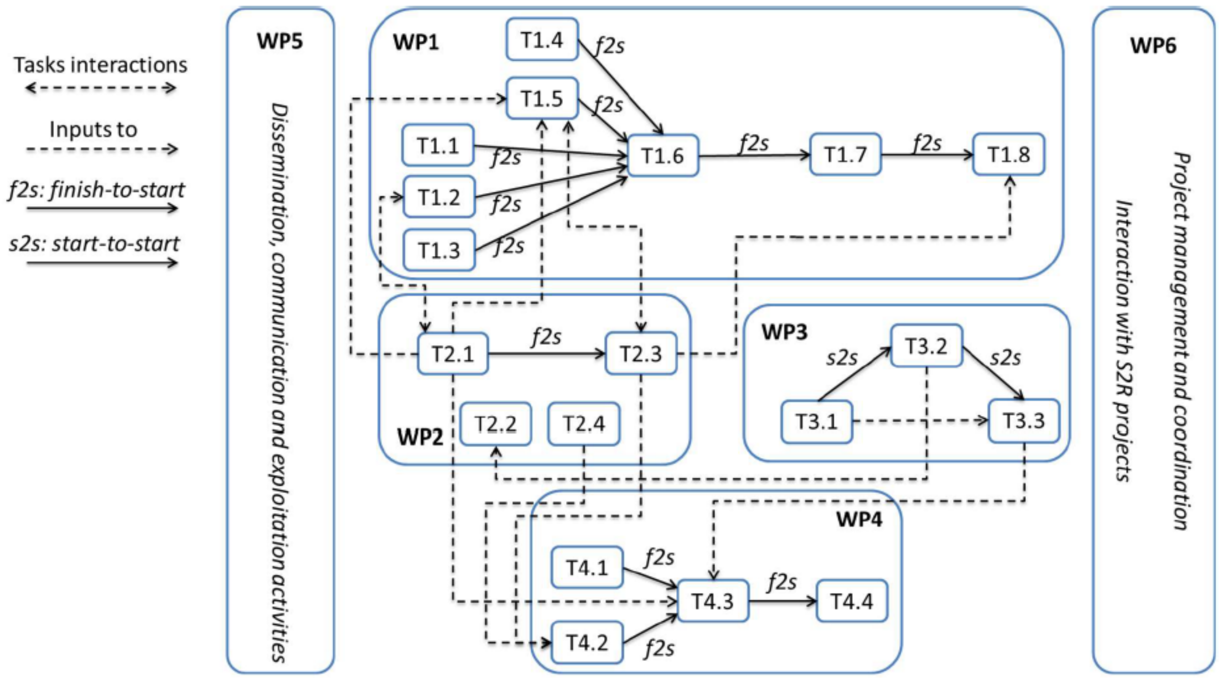

Figure 1 – ASTRail Interdependencies

Figure 2 shows the planning for T1.1 and T1.2.

			M1	M2	M3	M4	M5	M6	
Aeronautical Assumptions Review	**T1.1**	**ENAC**							**D1.1**
Identification and classification of aviation references	T1.1.1	ENAC							
Capture application and operational needs	T1.1.2	ENAC/ARD/SIRTI							
Extraction of Aviation Assumptions	T1.1.3	ENAC							
MCMF Standards Update	T1.1.4	ENAC							
Identfy Key Assumptions for Rail	T1.1.5	ENAC/ARD/SIRTI							

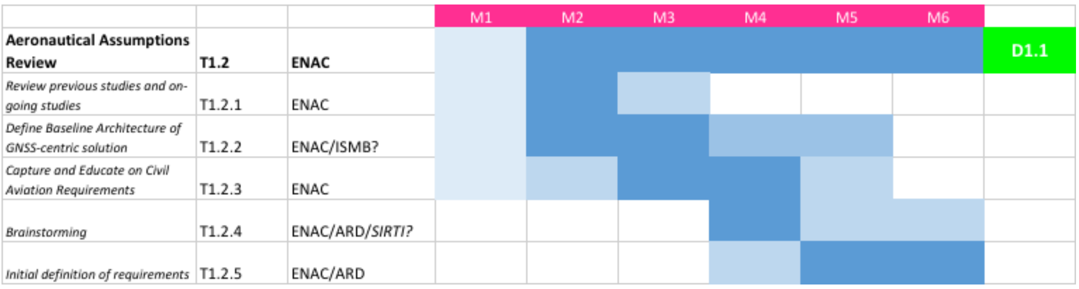

Figure 2 – T1.1 and T1.2 Planning

of related documents

1.3 Glossary

Term	Definition
CNS	Communications, Navigation and Surveillance
ATM	Air Traffic Management
DFMC	Dual Frequency Multi Constellation GNSS
ICAO	International Civil Aviation Organisation
RTCA	Radio Technical Commission for Aeronautics
ABAS	Aircraft Based Augmentation System
SBAS	Satellite Based Augmentation System
GBAS	Ground Based Augmentation System
RAIM	Receiver Autonomous Integrity Monitoring
ARAIM	Advanced RAIM
LAAS	Local Area Augmentation System
WAAS	Wide Area Augmentation System
RNP	Required Navigation Performance
A-SMGCS	Advanced Surface Movement Guidance Control System
ETCS	European Train Control System
GSM-R	Global System for Mobile Communication – Rail
VB	Virtual Balise
WGS-84	World Geodetic System of 1984
DG Mode	Directional Gyro Mode. A mode where valid heading output is determined through the use of inertial sensors without aiding from a magnetic sensing unit.

Table 1 – Glossary

2 Policy and Requirements State of the Art

2.1 Application Needs

GNSS is expected to provide in three ways:

1. Backward compatibility to physical balises and networks
2. Lower costs of ERTMS by removal of physical balises
3. Reduction of mission start time until ERTMS takes over driver responsibility

In order to achieve this the application needs must be specified and how GNSS use might depend on the various rail operations. Conditions such as the type of rolling stock, the density of traffic, system state (nominal, degraded, initialisation, recovery) and environmental conditions as well as the level of automation (GoA). The railway profiles may be high density, high speed, medium density, low density and regional lines.

Use cases for moving block signalling are defined in T2.2.

2.2 Classification of Aviation Standards (T1.1)

2.2.1 Aviation Stakeholders

Presented here is an overview of the stakeholders within civil aviation and the relationships regarding their activities, requirements setting and liability.

ICAO	The International Civil Aviation Organisation is a specialised agency of the United Nations (UN) which codifies standards and recommended practices outlining the principles and techniques of air navigation in the global setting.
RTCA	Formally the Radio Technical Commission for Aeronautics. A not-for-profit organisation that develops technical guidance for use by regulatory authorities in the aviation industry. Based in the United States with standards frequently referenced by the Federal Aviation Administration (FAA) Technical Standard Orders (TSOs).
EUROCAE	EURopean Organisation for Civil Aviation Equipment is a not-for-profit organisation which develops specifications for reference primarily within European aviation, in particular European Technical Standard Orders (ETSOs).
FAA	The Federal Aviation Administration (FAA) is the U.S national aviation authority which regulates and oversees all aspects of U.S civil aviation.
EASA	The European Aviation Safety Authority is an agency of the E.U with regulatory and executive tasks in civil aviation having taken over functions of the Joint Aviation Authorities. Note that a transition of some regulatory functions from national state Civil Aviation Authorities is being undertaken and has been one of the objectives of the Single European Skies (SESAR) programme.
SAE	A professional organisation which develops standards in the automotive and aerospace domains.
ARINC	A provider of transport systems engineering solutions and develops standards in particular for data communication. ARINC has developed the data standards and protocols for GPS receivers.

ECTL	EUROCONTROL, the European organisation for the safety of air navigations which coordinates and plans air traffic control throughout Europe. This includes the Air Traffic Control (ATC) functions for the Benelux region, coordinating flight plans and real traffic, providing a centralised Aeronautical Information Service (AIS), collecting en-route charges on behalf of Air Navigation Service Providers (ANSPs) and performing Air Traffic Management (ATIM) research and training.
IATA	The International Air Transport Association is a trade organisation of the world's airlines, whilst having no legislative power, it provides initiatives, standard and guidance on behalf of the industry.
ANSPs	Air Navigation Service Providers are organisations whose role is to
DSNA	The French ANSP, the Direction des Services de la Navigation Aérienne is a not-for-profit organisation with the role of air traffic control (ATC), air communications and information.
ATO	Air Traffic Organization (ATO) is the operational arm of the FAA responsible for providing safe and efficient air navigation services.

As shown in Figure 3, the framework of standards and regulations are in place to support the legislative bodies define the laws of the air, within the remit of their airspace. Each state, or association of states (to include the European Civil Aviation Conference (ECAC) region) sets laws which govern air traffic within the airspace it, or they, govern. These laws are set by the state's civil aviation authority (CAA) which is the regulator of civil aviation within that state's remit and holds the legislative power, meaning it is the legislative body with the means to prosecute if and when the laws are deemed to have been broken.

The state CAA however does not usually endeavour to develop all the laws in their technical detail in-house. Rather, standards are developed at regional and international level which are accepted by stakeholders (ICAO, airlines, airframe manufacturers, avionics manufacturers, ATMs systems designers, ANSPs) and referenced by technical orders issued by the state CAAs. Since standards are developed at both regional (e.g. RTCA, EUROCAE) and international level (ICAO), a process of harmonisation is often needed to align the standards rather than have contradictory standards in place.

Documentation published with this regard include both *standards*; specifications which are recognised as necessary to in the interests of safety, regularity and efficiency of air navigation and *recommended practices*; specifications which are desirable with regard to these performance indicators. In addition, *guidance material* may also be published including some less pertinent recommendations and explanatory background to explain the concepts used within the standards in greater depth.

In addition to the rules setting process, some regulators are tasked with issuing airworthiness certificates for aircraft implementations based on the standards in place. These are often acceptable for other states allowing the flight of aircraft within their airspace and within the operational framework laid out by the state (or regional) ANSP. Airframe (and other equipment) manufacturers must present a safety case to the regulator to prove the safe implementation with respect to the certification process.

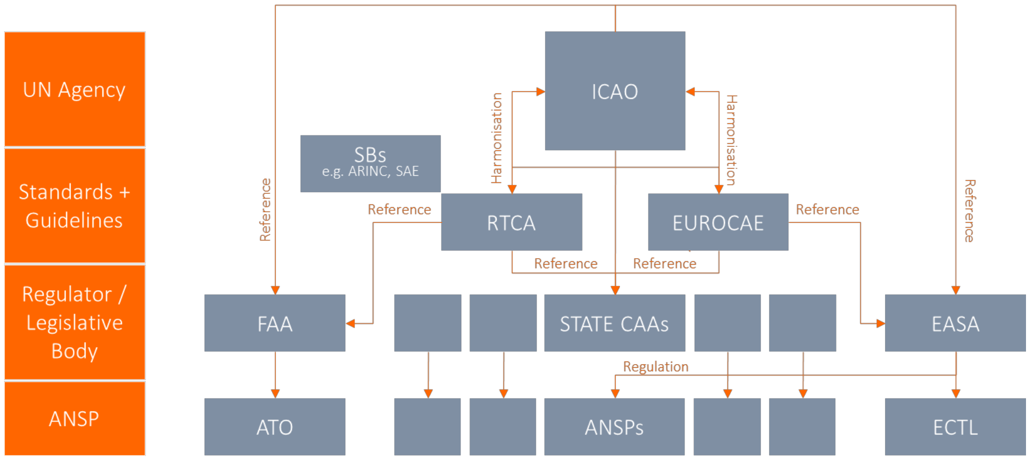

Figure 3 – Regulatory Structure

2.2.1 Reference Documents

2.2.1.1 ICAO References

The following table captures and classifies the ICAO documentation employed in this report.

Doc ID	Document Title	Description	Domain
Annex 04	Aeronautical Charts	Standards and Recommended Practices that define the obligations of States to make available certain ICAO aeronautical chart types, and specify chart coverage, format, identification and content, including standardized symbols and colour guides.	
Annex 06	Operation of Aircraft	Standards and Recommended Practices for the operation of aircraft in international general aviation,	
Annex 10 – Volume I	Aeronautical Telecommunications: Volume I Radio Navigation Aids (2010)	Standards and Recommended Practices for the use of radio navigation aids in civil aeronautical applications	System, Hardware, Software
Annex 11	Air Traffic Services – Air Traffic Control Service, Flight Information Service and Alerting Service	Standards and Recommended Practices for the Establishment and the Operation of the Air Traffic Control Services.	
Annex 14	Aerodromes	Standards and Recommended Practices for Aerodromes	
Annex 15	Aeronautical Information Services	Standards and Recommended Practices for Aeronautical Information Services	
Doc 8071	Manual on Testing of Radio Navigation Aids		
Doc 9613	Performance Based Navigation (PBN) Manual	Performance requirements for Area Navigation specified in generic terms	Operations, System

		without specific requirement for a single navigation aid	
Doc 9683	Human Factors Training Manual		
Doc 9750	Global Air Navigation Plan (2007)	Visionary operational concept to present ICAO objectives in terms of Communications, Navigation, Surveillance and Air Traffic Management	Operations, System, Policy
Doc 9849	Global Navigation Satellite System (GNSS) Manual	Information on the implementation aspects of GNSS to assist ANSPs, operators and manufacturers	Operations
Nagle PPT	ICAO Policy on GNSS, GNSS SARPs and Global GNSS Developments	Presentation providing overview of ICAO position of GNSS	Unofficial Policy

Table 2 – ICAO references

2.2.1.2 RTCA References

The following table captures and classifies the RTCA documentation.

Doc ID	Document Title	Description	Domain
DO-208	Minimum Operational Performance Specifications for Airborne Supplemental Navigation Equipment Using Global Positioning System (GPS)	Performance specifications for airborne software (and hardware)	Hardware, Software (Aircraft)
DO-217	Minimum Aviation System Performance Standards DGNSS Instrument Approach System Special Category I (SCAT-I)	Performance specifications for both ground and airborne equipment for the now-superseded SCAT-I system	Hardware, Software (Ground + Aircraft)
DO-228	Minimum Operational Performance Standards for Global Navigation Satellite Systems (GNSS) Airborne Antenna Equipment	MOPS for GNSS airborne antenna equipment designed to support GPS augmented with other techniques	Software, Hardware (Aircraft)
DO-229	MOPS for GPS/WAAS Airborne Equipment	MOPS for the U.S SBAS the Wide Area Augmentation System	System, Hardware, Software (Aircraft)
DO-236	MASPS for Required Navigation Performance for Area Navigation	Requirements for aircraft in an RNP environment, i.e. requiring an on-board monitoring function, and for vertical barometric navigation	System, Hardware, Software, Operations
DO-245	MASPS for the Local Area Augmentation System (LAAS)	Specifications of the interface between ground and airborne components of LAAS (U.S GBAS)	System, Software (Ground + Aircraft)
DO-246	GNSS-Based Precision Approach LAAS SIS ICD	Interface Control Document for LAAS	System, Software (Ground + Aircraft)
DO-247	The Role of the Global Navigation Satellite System	Addresses the proposed implementation of GNSS for Advanced Surface Movement Guidance and	Operations, Environment, System

	(GNSS) In Supporting Airport Surface Operations	Control System (A-SMGCS) for airport operations.	
DO-261	NAVSTAR GPS L5 Specification	Definition of the interface between NAVSTAR GPS L5 service and GPS users	System
DO-316	MOPS for GPS/ABAS Airborne Equipment	Specifications for the use of GPS with ABAS including RAIM and AAIM	System, Software (Aircraft)
DO-323	Safety, Performance and Interoperability Requirement Document for Enhanced Traffic Situational Awareness on the Airport Surface with Indicators and Alerts	ETSA is to aid pilots to operate on the airport surface. These specifications are for ETSA which does not provide a safety-critical guidance function for zero visibility conditions but for situational awareness	System, Operations
DO-334	MOPS for Strapdown Attitude and Heading Reference System (AHRS)	Specifications for the inertial navigation system AHRS employed on some aircraft	System, Hardware, Software

Table 3 – RTCA references

2.2.1.3 EUROCAE References

The following table captures and classifies the EUROCAE documentation.

Doc ID	Document Title	Description	Domain
ED-57	Minimum Operational Performance Specification for Distance Measurement Equipment	Specification for DME	System, Hardware, Software
ED-114	Minimum Operational Performance Specification For Global Navigation Satellite Ground Based Augmentation System Ground Equipment To Support Category I Operations	Specification for ground GBAS equipment	System, Hardware, Software

Table 4 – EUROCAE references

2.2.1.4 Requirements/Assumptions Taxonomy

The assumptions and requirements made within civil aviation have varying degrees of applicability to the proposed rail industry solutions. Table Table 5 presents a taxonomy for the applicability of such statements which I used below with a marker at the end of each requirement.

Letter	Action	
T	Requirement/Assumption transferred as is	
V	Requirement/Assumption to be transferred with modified values yet same form	
M	Requirement/Assumption must be modified but is applicable to rail application	

N	Requirement/Assumption is not applicable	
S	Supplementary requirement/assumption is needed	
U	Undecided, further investigation/results needed	

Table 5 – Requirements/Assumptions taxonomy

2.2.1.5 Terminology

Excerpts from RTCA DO229E and ED-114 which relate to the GNSS positioning function and the integrity monitoring as defined in 2.4. Readers are invited to section 2.4 for further details.

Accuracy: For an estimated position at a specific location, the probability the position error is within the accuracy requirement should be at least 95 per cent.

Alarm: An indication provided to the maintainer or operator to identify that the integrity and/or continuity requirements are not met or that the service is not available.

Alarm Limit: For a given parameter measurement, the error tolerance not to be exceeded without issuing an alarm.

Alert: For the definitions of missed alert, false alert, and time-to-alert, an alert is defined to be an indication that is provided by the GPS/SBAS equipment when the positioning performance achieved by the equipment does not meet the integrity requirements.

Alert Limit: For a given parameter measurement, the error tolerance not to be exceeded without issuing an alert.

Altitude: The vertical distance of a level, point or object considered as a point, measured from mean sea level.

Availability: The availability of a navigation system is the ability of the system to provide the required function and performance at the initiation of the intended operation. Availability is an indication of the ability of the system to provide usable service within the specified coverage area. Signal availability is the percentage of time that navigational signals transmitted from external sources are available for use. Availability is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities.

Continuity: The continuity of a system is the ability of the total system (comprising all elements necessary to maintain aircraft position within the defined airspace) to perform its function without interruption during the intended operation. More specifically, continuity is the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation and was predicted to operate throughout the operation.

Cyclic Redundancy Check (CRC): A very powerful form of parity check. The CRC algorithm associates a sequence of CRC code bits with a data block to preserve its integrity during storage and transmission operations.

Decision Altitude/Height (DA/H): A specified altitude or height in the precision approach at which a missed approach must be initiated if the required visual reference to continue the approach has not been established. Decision altitude (DA) is referenced to mean sea level, whereas decision height (DH) is referenced to the threshold elevation.

Failed Exclusion (exclusion not possible): A failed exclusion is defined to occur when a true positioning failure is detected and the detection condition is not eliminated within the time-to-alert (from the onset of the positioning failure). A failed exclusion would cause a navigation alert.

Fault Detection and Exclusion (FDE): Fault detection and exclusion is a receiver processing scheme that autonomously provides integrity monitoring for the position solution, using redundant range measurements. The FDE consists of two distinct parts: fault detection and fault exclusion. The fault detection part detects the presence of an unacceptably large position error for a given mode of flight. Upon the detection, fault exclusion follows and excludes the source of the unacceptably large position error, thereby allowing navigation to return to normal performance without an interruption in service. The fault detection aspects of FDE are referred to as Receiver Autonomous Integrity Monitoring (RAIM). However, FDE also includes the capability to isolate and exclude failed ranging sources so that navigation can continue in the presence of the failure.

Fault-Free: An operating condition of a given subsystem for which all functions are performed in a normal manner.

Final Approach Path: The prescribed straight three-dimensional path in space to be flown on final approach. For GBAS, this path is defined in the FAS Path Data by the Landing Threshold Point (LTP), the Threshold Crossing Height (TCH), the Flight Path Alignment Point (FPAP), and the Glide Path Angle.

Functional Requirement: A requirement other than those directly addressing one of the system performance parameters of accuracy, integrity, continuity, availability or coverage.

GBAS Aircraft Subsystem: The main functions of the GBAS aircraft subsystem are to receive and decode GNSS satellite signals and GBAS messages, determine the aircraft position and to provide guidance signals and integrity information.

Horizontal Alert Limit: The Horizontal Alert Limit (HAL) is the radius of a circle in the horizontal plane (the local plane tangent to the WGS-84 ellipsoid), with its center being at the true position, that describes the region that is required to contain the indicated horizontal position with the required probability for a particular navigation mode (e.g. 10^{7} per flight hour for en route), assuming the probability of a GPS satellite integrity failure being included in the position solution is less than or equal to 10-4 per hour.

Horizontal Figure of Merit: The HFOM is the radius of a circle in the horizontal plane (the local plane tangent to the WGS-84 ellipsoid), with its center being at the true position, that describes the region assured to contain the indicated horizontal position with at least a 95% probability under fault-free conditions at the time of applicability.

Horizontal Protection Level Fault Detection: The Horizontal Protection Level Fault Detection (HPLFD) is the radius of a circle in the horizontal plane (the local plane tangent to the WGS-84 ellipsoid), with its centre being at the true position, that describes the region assured to contain the indicated horizontal position. It is a horizontal region where the missed alert and false alert requirements are met for the chosen set of satellites when autonomous fault detection is used. It is a function of the satellite and user geometry and the expected error characteristics: it is not affected by actual measurements. Its value is predictable given reasonable assumptions regarding the expected error characteristics.

Horizontal Protection Level SBAS: The Horizontal Protection Level SBAS (HPLSBAS) is the radius of a circle in the horizontal plane (the plane tangent to the WGS-84 ellipsoid), with its centre being at the true position, that describes the region assured to contain the indicated horizontal position. It is the horizontal region where the missed alert requirement can be met. It is based upon the error estimates provided by SBAS.

Horizontal Exclusion Level Fault Detection: The Horizontal Exclusion Level Fault Detection (HELFD) is the radius of a circle in the horizontal plane, where the missed alert and failed exclusion requirements can be met when autonomous Fault Detection and Exclusion is used (i.e., exclusion is available). It is only a function of the satellite and user geometry and the expected error characteristics: it is not affected by actual measurements. Therefore, this value is predictable.

Integrity: is a measure of the trust that can be placed in the correctness of the information supplied by the total system. It includes the ability of a system to provide timely and valid warning to the user (alerts) when the system must not be used for the intended operation (or phase of flight)

Misleading Information: Any data which is output to other equipment or displayed to the pilot that has a navigation system error larger than the current protection level (LPL/VPL).

Missed Alert: Positioning failures that are not enunciated (as an alert) within the time-to- alert are defined to be missed alerts. Both missed detection and wrong exclusion conditions can cause missed alerts after the time-to-alert expires

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

Note: The term, missed detection, refers to internal processing of the FDE algorithm. It does not refer to an alert that is issued by the GPS/SBAS equipment.

Navigation System Error (NSE): Error that results from the residual composite errors from both the Ground Subsystem and aircraft receiver after correcting the ranging sources used to calculate deviations.

Performance Requirement: A requirement directly addressing one of the system performance parameters of accuracy, integrity, continuity, availability or coverage.

Positioning Failure: If the equipment is aware of the navigation mode/alert limit, a positioning failure is defined to occur whenever the difference between the true position and the indicated position exceeds the applicable alert limit. If the equipment is not aware of the navigation mode/alert limit, a positioning failure is defined to occur whenever the difference between the true position and the indicated position exceeds the applicable protection level (either horizontal or vertical as applicable).

Protection Level: The value (LPL/VPL) which bounds the actual error (NSE in particular) with a specified confidence.

Reception Mask: The nominal reception mask for each reference receiver defines the region in which the reference receiver can provide sufficient data to the Ground Subsystem such that measurement blocks can be calculated. It includes all elevations from 5° to 90° and all azimuths from 0° to 360°, excluding the blockage effects of any obstacle protruding from the horizontal plane.

Reference Receiver: A GNSS receiver incorporated into the GBAS Ground Subsystem, used to generate pseudo-range correction measurements.

Signal-in-Space (SIS): The aggregate of guidance signals arriving at the antennas of an aircraft. The GPS/GBAS SIS is comprised of the satellite signals and all signals emanating from the GBAS Ground Subsystem, including the VDB.

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

Vertical Alert Limit: The Vertical Alert Limit (VAL) is half the length of a segment on the vertical axis (perpendicular to the horizontal plane of WGS-84 ellipsoid), with its center being at the true position, that describes the region that is required to contain the indicated vertical position with a probability of 1-2x10-7 per approach, for a particular navigation mode, assuming the probability of a GPS satellite integrity failure being included in the position solution is less than or equal to 10^{-4} per hour.

Vertical Protection Level Fault Detection: The Vertical Protection Level Fault Detection (VPLFD) is half the length of a segment on the vertical axis (perpendicular to the horizontal plane of WGS-84 ellipsoid), with its center being at the true position, that describes the region assured to contain the indicated vertical position when autonomous fault detection is used. It defines the vertical region where the missed alert and false alert requirements are met for the chosen set of satellites when autonomous fault detection is used. (DO229E)

Vertical Protection Level SBAS: The Vertical Protection Level SBAS (VPLSBAS) is half the length of a segment on the vertical axis (perpendicular to the horizontal plane of WGS-84 ellipsoid), with its centre being at the true position, that describes the region assured to contain the indicated vertical position. It defines the vertical region where the missed alert requirement can be met. It is based upon the error estimates provided by SBAS. (DO229E)

Wrong Exclusion: A wrong exclusion is defined to occur when a detection occurs, and a positioning failure exists but is undetected after exclusion, resulting in a missed alert.

2.3 Aviation Assumptions (T1.1)

2.3.1 System Assumptions

System assumptions include those related to the total system design, incorporating the constellations and any augmentation systems. There are some subtle variations between assumptions taken between the three augmentations systems. The following constellation assumptions are taken within aviation, where such variations noted above are highlighted:

A.1 The prior probability of a single GPS satellite failure is no greater than 10^{-4} per hour per satellite.

(V) *Prior probabilities are needed as part of a Failure Modes and Effects Analysis and as a basis for the integrity monitoring design phase*

A.2 The prior probability of a single GPS satellite failure is no greater than 10^{-5} per hour per satellite.

(V) *Prior probabilities are needed as part of a Failure Modes and Effects Analysis and as a basis for the integrity monitoring design phase*

A.3 The prior probability of a single GLONASS satellite failure is no greater than 10^{-4} per hour per satellite.

(U) *Unclear if GLONASS could potentially be used as part of a multi-constellation solution within ERTMS.*

A.4 The distribution of ranging errors may be over-bounded by a zero-mean Gaussian model with determined and known standard deviation.

(M) *A Ranging Error model is clearly needed but a single zero-mean Gaussian model is not sufficient for land transportation application*

A.5 The distribution of ranging errors may be over-bounded by a non-zero-mean Gaussian model with determined and known bias and standard deviation.

(M) *A Ranging Error model is clearly needed but a single zero-mean Gaussian model is not sufficient for land transportation application*

A.6 The ranging errors of each pair of satellites may be considered to be mutually independent when using zero-differenced measurements.

(U) *Unclear if this assumption holds in an urban environment*

A.7 Satellite constellation availabilities are taken from the baseline constellations and accounting for possible depleted constellations

(U) *Unclear if it is appropriate to take the same approach in the rail domain*

A.8 The constellation slot (healthy) probabilities may be taken from the service commitments

(T) *Slot probabilities relate to availability statistics and as thus are not safety critical assumptions, following the service commitments as in aviation is reasonable.*

A.9 The maximum time for the GPS control segment to flag an unhealthy GPS satellite is 6 hours.

(T) *This is reasonable for a Major Service Failure type fault given the ground station coverage of GPS.*

A.10 The maximum time for the Galileo control segment to flag an unhealthy Galileo satellite is TBD.

(V) *As above, a similar service commitment may be taken once published by the relevant authority.*

A.11 A conservative estimate of the mean time to flag an unhealthy GPS satellite is 1 hour.

(V) *Specified in the requirements as Mean Time To Notify of 1 hour and supported by observed fault data (Department of Defense 2008)*

A.12 A conservative estimate of the mean time to flag an unhealthy Galileo satellite is 1 hour. **(V)**

(V) *Whilst no data is available for Galileo, the monitoring design processes are expected to be of similar performance to GPS. Possible modification of this value depending upon published commitments, observed data and analysis (for example at EU-US WG-C level).*

A.13 GPS satellite ephemeris are uploaded typically every 12 hours and modified every 2 hours

(T) *Highly unlikely to change in the near to medium term for fear of introducing new failure modes. (Department of Defense 2008)*

A.14 Galileo satellite ephemeris are uploaded typically every X hours and modified every X hours

(V) *Similar assumption needed as for A.13 but with likely shorter times (down to 10minutes has been published and observed).*

A.15 The discontinuation of a GNSS satellite service by a provider will be preceded by a minimum six year notification period

(T) *GPS provides a six year guarantee on the service level as a result of the funding programme cycles and satellite constellation backups. It is expected that Galileo may provide an equivalent commitment.*

A.16 The prior probability of a constellation (or wide) fault is zero

(V) *In some less stringent aviation applications this is assumed yet it is likely that a non zero value is used.*

A.17 The prior probability of a GPS constellation (or wide) fault is less than 10^{-6} per hour

(V) *In some studies for future aviation applications (ARAIM) this value or lower is used. An appropriate choice of value should be chosen for rail applications*

A.18 The prior probability of a Galileo constellation (or wide) fault is less than 10^{-4} per hour

(V) *In some studies for future aviation applications (ARAIM) this conservative value is used to account for lack of data of a new constellation (WG-C 2016)*

A.19 The prior probability of a Glonass constellation (or wide) fault is less than 10^{-3} per hour **(V)**

(V) *In some studies for future aviation applications (ARAIM) this conservative value is used to account for previously observed faults (Pullen and Enge 2013)*

A.20 The baseline GPS constellation consists of 24 satellites as given in DO316 B.1 (DO316)

(T) As stated.

A.21 The signal deformation threat model consists of both analog and digital failure components as given in ICAO Annex 10 and DO316 B.4.4. (DO316)

(T) The threat model has been well studied and agreed and defined at international level (ICAO 2010; Phelts et al. 2013)

A.22 Selective Availability, the voluntary degradation of the signal (noise like error with two-minute correlation time) is and will remain deactivated (DO316)

(T) Given the service history and service guarantees (RTCA 2009, 31)

A.23 Out of band interference can be as high as shown in DO316 Appendix C Figure C-1 (DO316)

(V) This model has been developed as appropriate for an aviation grade receiver and the aeronautical operating environment. A model must be assumed for the rail environment but is likely to differ.

A.24 The prior probability of a constellation outage is zero

(V) Unlike prior probability of failure this value is assumed zero in aviation studies. (WG-C 2016)

A.25 The probability of common constellation failure is zero

(T) Multiple detailed analyses of the risk of common Earth Orientation Prediction Parameters has been studied and concluded negligible risk of common constellation failure (WG-C 2015)

A.26 The correlation time of GPS ranging errors is two minutes (SA on)

(S) This assumption had been used in the development of RAIM requirements (Lee and Van Dyke 2002) but is no longer valid since SA is off. Alternative models are needed.

A.27 The temporal correlation of GNSS ranging errors may be modelled by a first order Gauss Markov process.

(M) This assumption is valid for most error sources (Department of Defense 2008) but an alternative may be needed for local errors

A.28 The correlation time of GPS clock and ephemeris errors is 30 minutes

(M) This assumption is given in (Department of Defense 2008)

A.29 The correlation time of GPS tropospheric errors is 15 minutes

(M) This assumption is given in (Department of Defense 2008)

A.30 The correlation time of GPS multipath and noise errors is X minutes **(M)**

(M) This assumption requires further study.

A.31 No *a priori* model of fault magnitude or fault profile may be assumed (ABAS only)

(M) In order to maintain conservatism, it is assumed that the fault may take any form. It is likely this assumption is employed in the rail domain. However it may also be the case that specific profiles are critical.

A.32 A constellation wide failure may impact all satellites and with any magnitudes

(T) As above but for all satellites. No previous knowledge of the form of faults on different satellites may be assumed. Earth Orientation Parameters could cause an apparent rotation of the reference frame.

A.33 The geodetic reference datum (i.e. WGS-84) employed for positioning shall remain stable

(T) No reason to expect any difference between applications

A.34 The conversion parameters between relevant geodetic reference data are known and remain stable over their period of applicability

(T) No reason to expect any difference between applications

A.35 The conversion parameters between constellation time references and UTC are known and stable over their period of applicability

(T) No reason to expect any difference between applications

A.36 GPS offers an L1 (1575.42MHz) signal in a protected ARNS band for safety-of-life applications

(T) This signal will remain as per the six year service guarantee.

A.37 GPS will offer an L5 (1176.45MHz) signal in a protected ARNS band for safety-of-life applications

(T) This signal will reach full operational capability in the medium term as per the service guarentees.

A.38 GPS L1 signal is modulated using bipolar phase shift key (BPSK) technique and a pseudo random noise (PRN) sequence (C/A code) at 1.023 Mchips/second which is repeated each millisecond. The transmitted PRN sequence is the modulo-2 addition of the C/A sequence and a 50bits per second navigation message

(T) No reason to expect any changes.

A.39 The GPS navigation message includes satellite ephemeris data, satellite health data, satellite clock corrections, propagation delay parameters (ionosphere) and UTC time transfer parameters

(T) No reason to expect any changes.

A.40 The constellations provide a health status for each satellite

(V) The merit given to health status may differ between applications

A.41 GPS time will be maintained to within 1 microsecond of UTC after accounting for the number of leap seconds

(T) No reason to expect any changes.

A.42 Short term frequency stability shall be better than an Allan deviation of 5×10^{-11} over 1 to 10 seconds when using SBAS. (Annex 10 App B 3.5.2)

(V) This figure governs the expected satellite clock noise that impacts how errors grow with longer latency. It presents a conservative value compared to expected future performance and may be of use for new differential GNSS applications.

A.43 Nominal code-carrier divergence shall be less than 5×10^{-11} over the short term 1-10s when using SBAS (Annex 10 App B 3.5.2.4)

(V) No reason to expect any changes to GPS, similar performance expected for other constellations

A.44 Availability of a navigation function depends upon both the physical characteristics of the environment and the technical capabilities of the transmitters (DO316)

(M) This remains true but the specifics differ with new signal technologies and of course the local rail environment

A.45 The assumed specification of the RF environment will be consistent with the real environment (DO316).

(M) The assumed specification will be different. It also remains to be assessed the impact of real time excess RF

A.46 Navigation Message sub-frames (critically 1, 2 and 3) may not be updated within the same frame (DO316).

(T) No reason to expect any changes.

A.47 Receivers' pseudorange step detection function should take into account satellite and aircraft dynamics

(M) If a pseudorange step detector is used a similar requirement is expected. It is likely a basic step detector would be employed.

A.48 ABAS SIS pseudorange error of 6m, ABAS avionics pseudorange error of up to 5m (rms), 7m (rms) ionospheric delay model error and 0.25m tropospheric delay model error

(M) Pseudorange error models will be used (before or after differential corrections depending upon the architecture used) and remain to be defined.

2.3.2 SBAS Assumptions

A.49 The satellite clock error grows linearly with time over the order of 1-10s (Annex 10 App B 3.5.5.2)

(M) Approximately true for any differential system thus likely applicable to a differential GNSS rail architecture

A.50 The satellite position error grows linearly with time over the order of 1-10s (Annex 10 App B 3.5.5.2)

(M) Approximately true for any differential system thus likely applicable to a differential GNSS rail architecture

A.51 The ionosphere may be modelled as a thin shell (Annex 10 App B 3.5.5.3) with mapping function to account for the obliquity factor (Annex 10 B.3.5.5)

(U) SBAS ionosphere corrections unlikely to be sufficient to rail requirements

A.52 The residual ionospheric error may be accurately modelled using a grid based approach with the using applying inverse square weights

(U) SBAS ionosphere corrections unlikely to be sufficient to rail requirements

A.53 The ionosphere's spatial variation is smooth between ionospheric grid points (IGPs) (Annex 10 App B 3.5.5.4)

(U) SBAS ionosphere corrections unlikely to be sufficient to rail requirements

A.54 Ionospheric features are on a scale larger than the set of Ionosphere Pierce Points (IPPs) generated by the ground network (Annex 10 App B 3.5.5.4) *caveat:* this is subject to the intended operation and the impact of finer resolution features not being captured, note that plasma bubble effects observed in Japan, potentially not captured by the ground network, restricted validation for more demanding operations.

(U) SBAS ionosphere corrections unlikely to be sufficient to rail requirements

A.55 The quality of corrections degrades over time and as such the quality metrics are subject to degradation parameters (Annex 10 App B 3.5.5.6.2)

(U) SBAS ionosphere corrections unlikely to be sufficient to rail requirements

A.56 GPS/SBAS is the only radio navigation system required on-board the aircraft to meet performance requirements for en-route to terminal and some vertically guided approach phases of flight (i.e. use as a primary means of navigation) (DO229E)

(N) This assumption is specific to an aviation operation

A.57 Failure of SBAS impacts *all* users of the service (DO229E)

(M) Further work is needed to assess how rail requirements will be set with regards to multiple users

A.58 Operational precautions are used to mitigate potentially hazardous situations (DO229E)

(M) Further work is needed to assess how the rail operations deal with a hazardous situation

A.59 Selection of the SBAS in use should be automatic (DO229E)

(U) SBAS ionosphere corrections unlikely to be sufficient to rail requirements

A.60 The receiver should select the SBAS satellite with the highest elevation since it provides the highest availability and reliability

(M) Further work is needed to assess the rail architecture and choice of SBAS GEO. It might be beneficial to select with respect to track heading.

2.3.3 GBAS Assumptions

A.61 The local area GNSS concept allows the strong mitigation of spatially and temporally correlated errors (satellite clock, ephemeris, ionosphere, troposphere)

(T) Independent of application.

A.62 The GBAS ground subsystem consists of 2 to 4 reference receivers

(U) Whilst the GBAS concept is useful to consider for rail, not the precise implementation

A.63 Satellite anomalies occur with a prior probability of 4.2×10-6 per approach.

(M) An approach lasts 150s which is not the applicable period for rail applications

A.64 Ground subsystem siting allows to mitigate significantly the multipath and interference impacts on the corrections.

(M) Not the same freedom for trackside site selection

2.3.4 GNSS aided IRS and GNSS-aided AHR Assumptions

A.65 Single-frequency (L1 C/A code) GPS-based sensors are the GNSS aiding source

(S)

A.66 The requirements will be updated when new standards exist for multi-frequency/multi-constellation sensors **(S)**

A.67 A pre-requisite for GPS sensors is compliance with TSO-C196. **(U)**

A.68 The requirements do not address GNSS augmentation, such as SBAS or GBAS differential corrections, for tightly-coupled hybrid integrations **(S)**

A.69 A pre-requisite for AHRS is compliance with TSO-C201 **(S)**

A.70 Equipment is categorized as follows: **(N)**

- Category A includes navigation-grade inertial components. When no GNSS is available, Category A is compliant with 14 CFR Part 121 appendix G; that is, unaided by GNSS Category A provides inertial coasting for positioning according to appendix G.
- Category B includes gyrocompass-grade inertial components meeting the requirements for heading performance category H1 in DO-334 with no external aiding, but is not compliant with 14 CFR Part 121 appendix G. When no GNSS is available Category B can coast for positioning over a period of time specified by the manufacturer.

- Category C includes AHRS-grade inertial components where DO-334 category H1 gyro compassing is not possible and additional aiding for heading is required. When GNSS is available, Category C is capable of providing positioning, velocity and enhanced attitude/heading.

A.71 Then the following sub-categories are intended to describe the integrated signal-in-space fault detection capability of the GNSS-aided inertial system. The intent for the subcategories is to differentiate how the equipment can support positioning operations. Subcategory 0 supports RNAV; subcategory 1 supports RNAV with RNP; and subcategory 2 supports RNAV with RNP during GNSS signal-in-space faults to enhance continuity. **(N)**

- Sub-category zero (0) GNSS integration provides no additional signal-in-space (SIS) fault detection-based integrity beyond what is provided by the GNSS receiver. This means the integrated system provides accuracy coasting only (i.e., horizontal figure of merit HFOM).
- Sub-category one (1) GNSS integration provides SIS fault detection-based integrity beyond what is provided by the GNSS receiver. This means that during operations where the GNSS receiver is not able to detect faulted satellites, the integrated system maintains a satellite fault detection capability referred to as detection or integrity coasting.
- Sub-category two (2) GNSS integration provides SIS fault detection-based integrity and exclusion-based continuity beyond what is provided by the GNSS receiver. This means that during operations where a faulted GNSS satellite is detected (detection coasting) the equipment in this sub-category maintains continuity by excluding the faulted satellite.

2.3.5 Operational Assumptions

A.72 The implementation of radio navigation aids does not obviate the need for visual aids for approach and landing (Annex 10)

(U) *The role of visual cues is part of aviation standards, remains to define the role of human element in the rail domain but it is expected to be entirely absent except for specific start of mission.*

A.73 There is safety risk from an unexpected outage (loss of continuity) which depends upon the intended operation, traffic density, airspace complexity and availability of alternative navigation aids

(U) *This is an aviation specific requirement due to the impossibility of parking an airborne aircraft.*

A.74 The requirements for system availability vary depending upon the possible existence of alternative navigation systems

(U) *The role of 'alternative' navigation systems for rail is to be discussed but the main goal here is to replace a system either entirely or in collaboration with, rather than having optional available systems deployed.*

A.75 GNSS use without augmentation using ground or space based methods (Aircraft Based Augmentation System – ABAS) is for supplementation navigation sensor equipment within designated continental airspace (U.S and Europe) and not intended to be the sole means of navigation. (DO316)

(N) *Aviation specific*

A.76 GNSS use without augmentation using ground or space based methods (Aircraft Based Augmentation System – ABAS) may be used for remote and oceanic operations as a sole means of navigation when no other means is available (DO316)

(N) *Aviation specific*

A.77 GNSS use without augmentation using ground or space based methods (ABAS) is for horizontal (also called lateral) navigation only and does not support a guidance function in the vertical domain. (DO316)

(U) *It is natural there is no vertical requirement for rail.*

2.3.6 Hardware Assumptions

A.78 For the purposes of GNSS signal-in-space performance specifications the receiver is assumed to be fault-free. It is a receiver with nominal accuracy and time-to-alert performance and has no failures which impact SISintegrity, continuity and availability

(M) *It is expected that a similar split between the localisation system and the receiver specifications is made in the rail domain, however details require further elaboration.*

A.79 Signal power levels of all requirements are stated prior to input to any preamplifier in use (DO316)

(U) *Likely similar for rail receiver specifications.*

A.80 Requirements are specified with respect to a 5 degree mask angle for GPS, any performance below which must account for the reduced gain.

(U) It is likely that 5 degrees is the bare minimum and possibly higher values may be needed for rail applications, or a dynamic mask.

A.81 The receiver is susceptible to distorted signals which could cause multiple correlation peaks.

(M) *This remains true but may be more severe in terrestrial domains*

A.82 The receiver is susceptible to correlation peak asymmetry due to multipath or spurious signal transmissions

(M) *This remains true but may be more severe in terrestrial domains*

A.83 The receiver is susceptible to flat correlation peaks causing excessive noise or drift

(M) *This remains true but may be more severe in terrestrial domains*

2.3.7 Software Assumptions

A.84 The bench tests defined for receiver algorithmic performance are representative of the performance over the population of space-time geometries and probability space (DO316)

(U) Whilst such tests are advisable for the rail industry it may be that local elements restrict the geometries and as such other factors may need to be taken in to account.

2.3.8 Environmental Assumptions

A.85 The ionosphere follows an eleven-year cycle with maximum at 2003, 2014, 2025.

(U) *Unclear what the ionosphere mitigation strategy will be for rail.*

A.86 2^{nd} order ionospheric delays are negligible (mm level)

(U) *Unclear what ionosphere mitigation approach will be used in the rail domain but it is likely that a differential system of some kind will be employed. 2nd order effects impact dual-frequency processing which is unlikely to be used since this inflates the local errors such as multipath.*

A.87 The ionosphere may be modelled for each of high-latitude, mid-latitude and low-latitude regions with respect to the geomagnetic equator

(M) *This split is used frequently in GNSS applications, aeronautical and elsewhere for ionosphere characterization. Specific modelling assumptions will have to be addressed.*

A.88 The ionosphere may be accurately modelled as a thin shell

(U) *The use of the thin shell model depends upon the architecture (dual frequency vs wide-area differential vs local area differential)*

A.89 The tropospheric delay may be accurately split between wet (~5%) and dry components (~95%)

(M) *The use of a dry-wet split model depends upon the architecture (wide-area differential vs local area differential)*

A.90 The dry tropospheric delay may be accurately mapped between the zenith and slant directions through the use of a mapping function (e.g. Neill mapping function)

(M) *The use of a dry-wet split model depends upon the architecture (wide-area differential vs local area differential)*

A.91 Tropospheric vertical decorrelation may be modelled using an empirical model with given refractivity index standard deviation and regional tropospheric scale height

(M) *The use of a dry-wet split model depends upon the architecture (wide-area differential vs local area differential)*

A.92 Tropospheric duct phenomena are rare and have minimal impact

(T) *As concluded within aeronautical studies.*

A.93 The correlation time of GNSS tropospheric errors is 30mins

(V) *Likely to be applied to rail domain since no change in tropospheric environment*

A.94 Out of band emissions shall not exceed those given in table 3.7.3.5-1 in Annex 10

(M) *A similar but rail and terrestrial specific bound will be needed.*

A.95 RNSS/ARNS within 1559-1610 MHz shall remain the only global allocation and emissions in this and adjacent bands are tightly controlled by national and international regulation

(T) *Clearly also applicable through international spectrum management rules*

A.96 Wind velocity and other environmental factors contribute to the avionic performance of following the desired track.

(U) *Whilst wind may impact braking capabilities or safety rules in rail, it is a less critical environmental condition.*

A.97 Spurious emissions shall be at least 40dB below the unmodulated carrier power over all frequencies (Annex 10)

(M) *Expect another similar assumption for the rail industry.*

A.98 SIS error models currently used in aviation are only applicable to an airborne receiver. Errors may be considerably different for an aircraft which is taxiing or stationary (DO316)

(T) *Local environment sure to be more challenging.*

A.99 Ionospheric error is the dominating error term for SBAS operations.

(M) *Unlikely to remain true in an urban environment*

A.100 Ionospheric temporal correlation is of the order of 360s (6 minutes) (Roturier, Chatre, and Ventura-Traveset 2001)

(M) *This should be valid for SBAS single frequency system as of now. For a rail architecture it remains to be seen if additional elements will treat the ionospheric error.*

2.3.9 Inertial Navigation Assumptions

A.101 There is no requirement for excluding or annunciating a satellite from the tight coupled integrated solution if the protection level bounds the error. Error models may be used to compensate such errors (DO316 – R.2.1) **(U)**

A.102 All significant error sources are included in the error modelling to avoid in incorrect protection levels (DO316 – R.2.1.1) **(U)**

A.103 Satellite Failure Modes and Effects Analysis (FMEA) has been performed leading to the following failure models (with enlarged failure probabilities x3.448) **(M)**

Predicted MI Failure Type	Block I, II IIA Predicted MI Failure Probability in Units of 10^{-7}/hour/Satellite	Assigned Test Range	Assigned MI Failure Probability in Units of 10^{-6}/hour/Satellite
Ramp 0.01m/s	2	Ramp 0.01-0.05m/s	1
Ramp 0.1m/s	1	Ramp 0.05-0.25m/s	1
Ramp 0.5m/s	3	Ramp 0.25-0.75m/s	1
Ramp 1.0m/s	10	Ramp 0.75-2.5m/s	3.5
Ramp 5.0m/s	12	Ramp 2.5-5.0m/s	4.1
Step 300m	1	Step 300-700m	1
Step 3000m	34	Step 700-3000m	N/A

Table 6 – Summary of failure type probabilities (RTCA 2009, 316)

A.104 Acceleration faults need not be accounted since there is a negligible probability of accelerations above 0.1μg (less that 10^{-7}/hour/satellite) and accelerations below this value may be considered modelled by the ramp **(U)**

2.3.10 Integrity Monitoring Assumptions

A.105 Additional sensors (such as precise clocks, barometer, eLoran, or inertial sensors) may improve performance (availability of the navigation function for the intended operation) (DO316)

(U) *Unclear as of now what sensors will be available in addition to GNSS and odometry.*

A.106 Test procedures given in the standards are sufficient to prove the integrity and thus safety of the navigation function (DO316).

(S) *Unlikely that this alone will be sufficient since the rail domain is more sensitive to the precise environment through which the train is travelling.*

A.107 Intentional interference is a security issue rather than a safety issue and is not covered by the integrity requirement (DO316)

(U) *Unclear if rail safety will be treated in an equivalent manner.*

A.108 FDE algorithms weights are the same as those used to compute the position (DO-316)

(M) *Any FDE algorithm is of yet to be defined.*

A.109 ABAS equipment assumes only one satellite may be faulty at one time.

(S) *Unlikely that this assumption will be used, Advanced RAIM developments*

A.110 For FD prediction a URA index of 3 should be used (DO316)

(U) *Not applicable to a differential system as likely to be the case for rail.*

A.111 Performance assessed over space time points given in DO316 2.3.7.2 is considered sufficient to characterise the population of geometries (DO316 - 220)

(U) *Likely that additional tests are needed to account for local environment.*

2.4 Requirements, Standards,

2.4.1 Requirements

R.1 Radio navigation aids shall be subject to periodic ground and flight tests (Annex 10)

(M) *Periodic testing should be applicable to safety critical rail applications too. It remains to define in what form.*

R.2 Aerodrome control towers and approach control services shall be provided with information on the operational status of radio navigation services on a timely basis. (Annex 10)

(M) *Whilst there is no clear equivalent of the control tower and the focus of the GNSS 'operations' is to be defined.*

2.4.2 GNSS Receiver Requirements

R.3 ABAS Horizontal position error (95%) must not exceed 32m. (GPS ICD)

(V) Positioning accuracy requirements will be needed yet more stringent.

R.4 The receiver shall be able to track the carrier phase with an accuracy of 3mm (1 sigma)

(V) *Such a requirement will be needed, likely a similar value in line with technological capabilities.*

R.5 The receiver shall exclude any satellite designated unhealthy (Annex 10)

(T) Sure to be equally relevant.

R.6 When processing GPS and GLONASS measurements, the difference between time and coordinate reference systems shall be taken in to account (Annex 10 AppB 3.3.1)

(T) *Natural that any inter-constellation time reference differences must be accounted for.*

R.7 Receivers shall be tested under controlled environmental conditions (pressure, temperature, humidity etc.) within a lab to ascertain aeronautical suitability. (DO316)

(M) *A similar requirement will be needed for rail receivers.*

R.8 Receivers shall be bench tested to confirm conformance to the designed performance (DO316)

(M) *A similar requirement will be needed for rail receivers.*

R.9 Receivers shall be designed to be compliant with GPS SPS Performance Standard and the Interface Control Document (IS-GPS-200D) (DO316)

(T) *An equivalent requirement will be needed for rail receivers.*

R.10 Receivers shall decode continuously the navigation data (DO316)

(M) *A similar requirement will be needed for rail receivers taking in to account the presence of tunnels and signal blockages.*

R.11 Receivers shall use the clock and ephemeris data only after the data has been decoded a second time and matches exactly the first set (up to a maximum of 66seconds after receiver initialisation). (DO316)
(T) *An equivalent requirement will be needed for rail receivers.*

R.12 Receivers shall only use data when the IODE matches the 8 least-significant bits of the IODC. (DO316)
(T) *An equivalent requirement will be needed for rail receivers.*

R.13 Receivers shall designate all satellites as either healthy or unhealthy as per the broadcast flag (GPS in DO316)

(T) *An equivalent requirement will be needed for rail receivers.*

R.14 Receivers shall detect pseudorange steps greater than 700m on any satellite used in the position solution with a false alarm rate of 3.33×10^{-7} (DO316)

(M) *An equivalent requirement will be needed for rail receivers though with potentially different false alarm rate.*

R.15 A satellite shall be designated healthy only if all the conditions relating to the health word, parity checks, user range accuracy are met (DO316)

(T) *An equivalent requirement will be needed for rail receivers.*

R.16 The receiver shall use the same set of satellites for position computation and for integrity checking and shall select them automatically (without the need for human intervention) (DO316). It is recommended that no manual deselection of satellites is enabled. (DO316)

(T) *An equivalent requirement will be needed for rail receivers.*

R.17 The initialisation time (to first fix from cold start) shall be less than 5 minutes 95% of the time.

(M) *A similar requirement will be needed for rail receivers taking into account local signal blockage conditions.*

R.18 Incorporation of a new satellite shall be achieved within 80s (66s for the navigation message and 14s for acquisition search) (DO316).

(M) *A similar requirement will be needed for rail receivers taking into account local signal blockage conditions.*

R.19 For satellite signal losses of less than 30s the satellite shall be reacquired within 20s from the time the signal is reintroduced (possessing a minimum signal power as given in DO316 Appendix C). (DO316). **(M)** *A similar requirement will be needed for rail receivers taking into account local signal blockage conditions.*

R.20 Receivers shall use antennas that comply with RTCA DO-301 (active antenna with a preamplifier) or RTCA DO228, Change 1 (passive antenna without a preamplifier) (DO316)

(M) *A similar requirement will be needed for rail receivers taking into account local signal blockage conditions.*

R.21 Equipment shall accept GPS signals with the power range of -136.5 dBm and -115.5dBm for an active antenna or between -131 dBm and -119.5 dBm for a passive antenna

(M) *A similar requirement will be needed for rail receivers taking into account local signal blockage conditions.*

R.22 Equipment shall be able to track signals with a minimum signal in space power of -134dBm for active antennas (-128dBm for passive antenna) in the presence of antenna thermal noise density of -172.5 dBm/Hz and the interference conditions in DO316 Appendix C

(M) *A similar requirement will be needed for rail receivers taking into account local signal blockage conditions.*

R.23 Equipment shall be able to track GPS satellites with a maximum power of at least -121dBm (active) or -123dBm (passive) in the presence of SBAS satellites with a maximum power of at least.

(M) *A similar requirement will be needed for rail receivers taking into account local signal blockage conditions.*

R.24 The equipment shall be able to track in dynamic conditions up to 800kt of ground speed, 0.58g of *horizontal acceleration, 0.5g of vertical acceleration and 0.25g/s of jerk. (DO316 – 69)*

(M) *A similar requirement will be needed for rail receivers taking into account train dynamic ranges.*

R.25 A position shall be output at least once per second (DO316 – 79) with a latency less than 0.5s (DO316 – 80)

(V) *A similar requirement will be needed for rail receivers taking into account operational requirements with regards to communications intervals*

R.26 The use of carrier smoothing should achieve an error of less than 0.25m within 200s following initialisation in the presence of a code-carrier divergence rate up to 0.018m/s relative to the steady state of the standard filter (given in 2.1.2.6.4) (DO316 – 83)

(U) *Unclear if carrier smoothing will be used and what convergence is to be expected for terrestrial environments.*

R.27 The (ABAS) equipment shall provide and FD prediction algorithm for lateral operations

(U) *Unclear of the role of FD prediction, architecture and monitoring design dependent.*

R.28 If using receiver clock aiding, the 1-sigma of the frequency random walk shall not exceed 1ft/$\sqrt{s}$ in steady state conditions. The frequency drift shall not exceed 3ppm/°C in transient thermal conditions
(U) *Unclear if clock aiding is to be potentially employed*

R.29 Discriminator averaging (for an integrated Kalman Filter approach) shall consider the impact of temporal correlation and slowly varying errors. Fast errors relative to the averaging period shall also be considered (DO316 – 290).

(U) *Unclear what temporal models might be used for local errors or if a KF approach might be used.*

R.30 The satellite signal tracking quality shall be monitored for undetected cycle slips

(M) *Monitoring of cycle slips will be required in some form.*

R.31 The GPS receiver shall meet the tracking constraints shown in Figure 4 or Figure 5 depending upon which implementation is used (Further details given in (RTCA 2016)

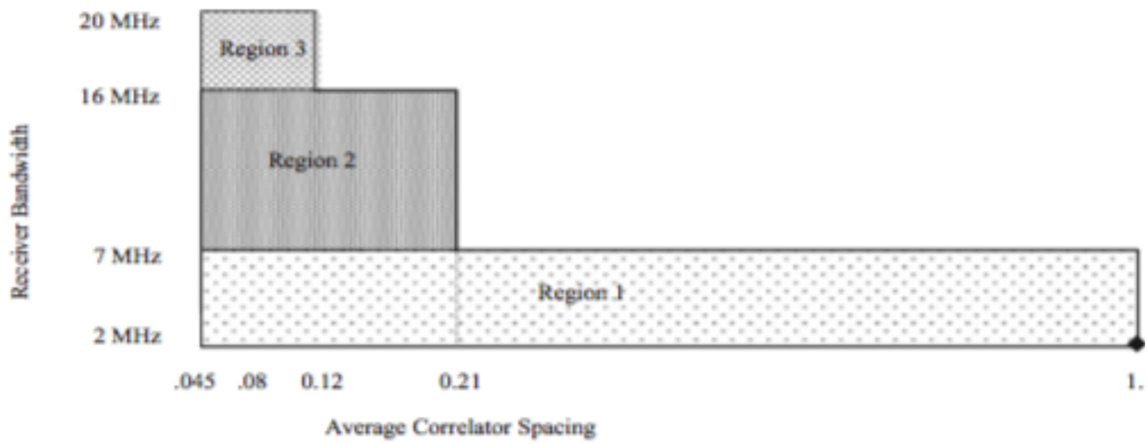

Figure 4 – Receiver Constraints for Early-Late Discriminator Tracking

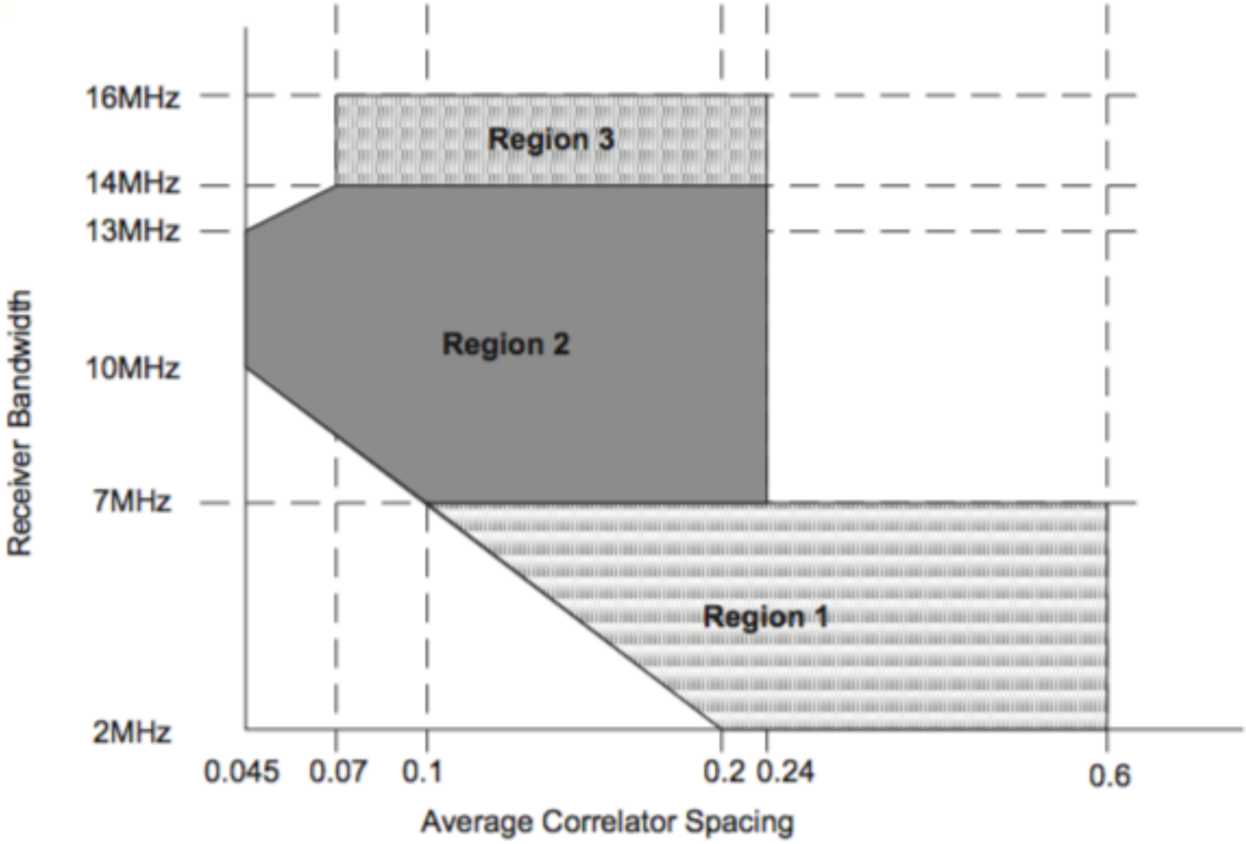

Figure 5 – Receiver Constraints for Double Delta Discriminator Tracking

(M) *Receiver parameters ideally limited to a narrow region or single point to limit variations in biases between differential reference station errors and train receiver errors.*

2.4.3 SBAS System Requirements

R.32 SBAS shall provide long term corrections including 4D satellite position and clock and 4D satellite velocity and clock drift (Annex 10 App B 3.5.4.4.1)

(U) *Unclear what if any elements of SBAS corrections will be employed.*

R.33 SBAS shall provide fast corrections for rapidly varying errors other than troposphere and ionosphere (Annex 10 App B 3.5.4.4.2)

(U) *Unclear what if any elements of SBAS corrections will be employed.*

R.34 SBAS shall provide integrity parameters relating to the fast and long-term corrections, namely the UDREI (User Differential Range Error Indicator) and degradation parameters (Annex 10 App B 3.5.4.5)
(U) *Unclear what if any elements of SBAS corrections will be employed.*

R.35 The SBAS messages must be broadcast with respect to the maximum intervals as specified in Annex 10 Table B-54 (Annex 10 App B)

(U) *Unclear what if any elements of SBAS corrections will be employed.*

R.36 The SBAS time to alert shall be 5.2 seconds for a precision approach or APV-II (APproach with Vertical guidance) user.

(U) *Unclear what if any elements of SBAS corrections will be employed.*

R.37 The SBAS message loss rate shall be less than 1 message in 1000 for the interference described in DO229E Appendix C

R.38 **(U)** *Unclear what if any elements of SBAS corrections will be employed.*

R.39 SBAS equipment shall process SBAS message types 0, 1, 2, 3, 4, 5, 6, 7, 9, 17, 24, 25, 27 and 28.

(U) *Unclear what if any elements of SBAS corrections will be employed.*

R.40 SBAS equipment shall only use data until it is timed out, starting at the end of message reception. (Time out intervals for fast corrections may be a low as 12s depending upon the indicator (RTCA 2006)

(U) *Unclear what if any elements of SBAS corrections will be employed.*

R.41 SBAS corrections shall be applied after pseudorange filtering and before computation of the position including pseudorange and range rate corrections (RTCA 2006).

(U) *Unclear what if any elements of SBAS corrections will be employed.*

R.42 The equipment shall perform code-carrier smoothing with an error less than 0.25m within 200s following initialisation (divergence up to 0.018m/s)

(U) *Unclear the expected performance of smoothing in the terrestrial urban environment*

R.43 SBAS equipment shall be able to compute and output protection level predictions

(U) *Unclear though unlikely that SBAS protection levels will be employed for the train localization envisaged.*

2.4.4 GBAS System Requirements

R.44 The GBAS (service) coverage shall be at least the segmented area given in ED-114 section 3.1.

(N) *GBAS service coverage related to aeronautical operations*

R.45 GBAS Ground Subsystem continuity shall be greater or equal to 1-8×10-6 per 15 seconds (to account for the final stage of approach) which includes VHR data broadcast failures.

(N) *GBAS service coverage related to aeronautical operations*

R.46 An allocation of the 2×10^{-7} integrity risk in any one approach is made between the protection level computed at the aircraft (0.5×10^{-7}) and the remaining risk under the responsibility of the ground subsystem (1.5×10^{-7})

(M) *A split of risk and responsibility between the user (train) and reference (trackside) infrastructure will be necessary with values to be defined.*

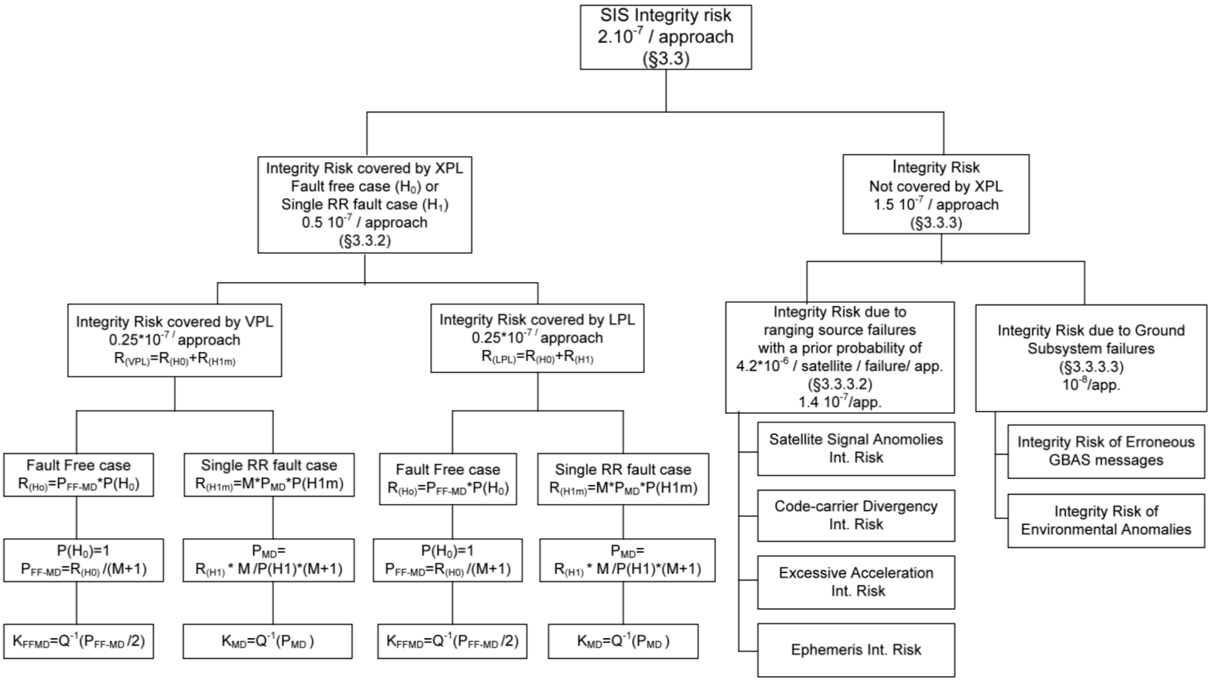

Figure 6: GBAS Integrity Risk Allocation (Eurocae 2007)

R.47 The alert limits for GBAS are at the most critical points, 40m and 10m in the lateral and vertical directions respectively.

(U) *An alert limit will be needed but values must be defined.*

R.48 Reference receiver failure shall occur with a probability less than 10^{-5} in any one approach.

(M) *A requirement for reference receiver failure will be needed.*

R.49 Ground corrections accuracy shall meet one of three designated levels given in ED-114.

(M) *Requirements for reference receiver accuracies will be required.*

R.50 GBAS integrity is not assured in the event that the airborne receiver fails to receiver three consecutive corrections messages (MT1)

(M) *Requirements for message reception will be required.*

R.51 The ground subsystem shall provide to the aircraft scalar pseudorange corrections every 0.5s with corresponding range rate correction

(M) *Requirements for message reception will be required.*

R.52 The ground subsystem shall provide integrity and quality data every 0.5s to the aircraft notifying of any satellite failures

(M) *Requirements for message reception will be required.*

R.53 The ground processing shall use the same code-carrier smoothing filter as the aircraft receiver

(M) *If smoothing is employed, this may be necessary to eliminate ionospheric divergence as done in aviation applications. Alternatively divergence free processing might be used if multiple frequency receivers are deployed.*

R.54 The ground processing shall use the same set of clock and ephemeris data as the aircraft receiver

(M) *For differential processing such requirements are to be expected.*

R.55 The ground subsystem shall provide ranging source availability information to the aircraft

(U) *To be defined the roles of train and trackside for a rail architecture.*

R.56 The ground subsystem is subject to site selection and qualification in order to mitigate the impact of obstacles on the multipath of GNSS signals

(M) *Less flexibility for any reference stations may severely limit an equivalent requirement.*

R.57 The ground subsystem shall perform Signal Quality Monitoring (SQM)

(M) *To be defined if the rail solution will perform its own SQM or rely upon existing (e.g. SBAS) SQM.*

R.58 The airborne receiver shall apply code-carrier divergence monitoring to aid ionosphere detection

(U) *Threats and monitors will require further development for the rail solution.*

2.4.5 Strapdown Attitude and Heading Reference Systems (AHRS) Performance Requirements (RTCA 2012)

R.59 The equipment shall output pitch, roll and heading data through all attitudes and headings.

(U) Required output ranges of equipment for rail needs to be defined

R.60 The equipment shall output data up to at least ±70deg/sec angular rates in each axis, at least ±2 g body axis longitudinal and lateral acceleration and at least ±4 g body axis normal acceleration.

(U) Required output ranges of equipment for rail needs to be defined

R.61 The equipment shall be categorized according to attitude accuracy performance as described in Table 7

Category	Attitude Accuracy	
	Static Conditions	Dynamic and Flight Conditions
A1	0.1°	0.2°
A2	0.2°	0.5°
A3	0.5°	1.0°
A4	1.0°	2.5°
A5	1.0°	2.5°

Table 7 – Attitude performance requirements for AHRS

(U) Requirements for inertial equipment for rail needs to be defined

R.62 The equipment shall meet the attitude static accuracy limits as defined in Table 7

(U) Requirements for inertial equipment for rail needs to be defined

R.63 The equipment shall meet the attitude dynamic and flight accuracy limits as defined in Table 7

(U) Requirements for inertial equipment for rail needs to be defined

R.64 The equipment shall be categorized according to heading accuracy performance as described in Table 8

Category	Source of Heading Information	Heading Accuracy	
		Static Conditions	Dynamic and Flight Conditions
H1	Non-Magnetic Heading Determination (i.e. Gyrocompassing system)	1.0°	2.0°
H2	Magnetic Slaving	1.0°	2.0°
H3	Magnetic Slaving	1.5°	4.0°
H4	Magnetic Slaving	2.0°	6.0°
H5	Magnetic Slaving	2.0°	6.0°
		Heading Drift Accuracy, Under Static and Dynamic and Flight Conditions	
H6	DG Mode	2° in 6 hours	
H7	DG Mode	2° in 3 hours	
H8	DG Mode	5° in 1 hour	
H9	DG Mode	30° in 1 hour	
H10	DG Mode	5° in 10 minutes	
H11	DG Mode	10° in 10 minutes	
HX	No heading capability	n/a	

Table 8 – Heading performance requirements for AHRS

R.65 The equipment shall start and provide valid attitude output within 3 minutes after normal rated power is applied.

(U) Requirements for inertial equipment for rail needs to be defined

R.66 The equipment shall start and provide valid turn and slip output within 3 minutes after normal rated power is applied.

(U) Requirements for inertial equipment for rail needs to be defined

R.67 For heading category H1, the equipment shall start and provide valid heading output within 10 minutes after normal rated power is applied, when operating in latitudes less than ± 60°. The manufacturer shall specify the alignment time above ± 60°.

(U) Requirements for inertial equipment for rail needs to be defined

R.68 For heading category H2 through H5, the equipment shall start and provide valid heading output within 3 minutes after normal rated power is applied.

(U) Requirements for inertial equipment for rail needs to be defined

R.69 For heading category H6 through H11, the availability of DG mode heading shall be within 5 minutes of start-up.

(U) Requirements for inertial equipment for rail needs to be defined

R.70 Conditions where the equipment does not meet the highest declared performance category shall be annunciated.

(U) Requirements for inertial equipment for rail needs to be defined

R.71 The three following conditions shall be annunciated:

- Loss of attitude, heading or turn and slip
- Operation in a DG mode is a non-DG mode is provided
- Operation in degraded mode

(U) Requirements for inertial equipment for rail needs to be defined

R.72 The update rate of output data shall be a minimum of 10Hz.

(U) Requirements for inertial equipment for rail needs to be defined

R.73 The latency of output data shall be a maximum of 200msec. This does not include filter phase delay.

(U) Requirements for inertial equipment for rail needs to be defined

R.74 The DG mode shall include a mean for the operator to activate the DG mode and manually adjust the heading.

(U) Requirements for inertial equipment for rail needs to be defined

R.75 The equipment shall provide a degraded mode of operation. This mode shall only be permissible if the equipment provides at least one operational mode with a declared category of performance.

(U) Requirements for inertial equipment for rail needs to be defined

R.76 In degraded mode, the AHRS pitch and roll shall be stable, free of oscillations, steps, or other objectionable transients under all conditions.

(U) Requirements for inertial equipment for rail needs to be defined

R.77 During un-accelerated, straight and level flight, the degraded mode pitch accuracy shall be less than or equal to ± 3°. During accelerations or manoeuvres, and within the first 60 seconds following accelerations or manoeuvres, the pitch error shall be less than or equal to ± 6° in the range of ± 10° pitch. Outside of ± 10° pitch, the pitch shall be in the correct direction and not provide objectionable pitch information.

(U) Requirements for inertial equipment for rail needs to be defined

R.78 The range of the slip indicator shall be at least ± 7°. Its accuracy shall be within ± 2°.

(U) Requirements for inertial equipment for rail needs to be defined

2.4.6 GNSS-aided IRS and GNSS-aided AHRS Requirements

Note that sub-categories of equipment are defined with respect to variable operational goals and the type of equipment installation.

R.79 Sub category 0, 1 and 2 equipment shall be capable of computing the 95% horizontal figure of merit HFOM.

(U) Definition of categories for equipment for rail needs to be defined

R.80 Sub category 1 and 2 equipment shall also be capable of computing the horizontal protection level HPL conforming to the false alert rate and missed alert probability in Table 9

Parameter	Requirement
Missed detection probability (satellite positioning failure)	0.001
False detection probability (see note 2)	10^{-5}/hour
Probability (pMI) of exceeding HPLFD	10^{-7}/hour
Probability (pMI) of exceeding HPLFF	10^{-5}/hour
Failed exclusion probability (satellite positioning failure)	0.001
Time to alert	8 sec

Table 9 – Summary of positioning FDE requirements

(M) Similar definitions for rail applications needs to be defined

R.81 For Sub category 2, where in addition exclusion capability is claimed, the probability of failed exclusion shall be less than 10^{-3}. Failed exclusion is the inability to remove the satellite before the horizontal error exceeds HEL.

(M) Similar definitions for rail applications needs to be defined

R.82 *HFOM, HPLFD and HEL shall* be functions of measurement accuracy and geometry only and shall not depend on individual measurements.

(M) Similar definitions for rail applications needs to be defined

R.83 For subcategory 0, 1 and 2 the HFOM output shall continue to bound at a 95% level during an outage (accuracy coasting).

(M) Similar definitions for rail applications needs to be defined

R.84 For sub category 1 and 2 where the HPL outputs continue during the GPS outages the required probabilities must be maintained. The probability of missed alert due to a latent satellite fault shall remain less than 10^{-3} during outages (integrity coasting). A latent satellite fault is a fault that remains undetected prior to loss of GPS. In other words, an undetected satellite fault prior to the loss of one or several GPS satellite may miscalibrate the hybrid filter(s), and this impact must continue to be reflected in the HPL.

(U) Requirements applicable for aircraft operations

R.85 The false alert rate shall remain less than 10^{-5}/hour during outages.

(U) Requirements applicable for aircraft operations

R.86 For sub category 2, where in addition exclusion capability during integrity coasting is claimed, the probability of failed exclusion shall remain less than 10^{-3} during outages. Failed exclusion is the inability to remove the satellite before the horizontal error exceeds HEL.

(U) Requirements applicable for aircraft operations

R.87 x-FOM shall be a function of measurement accuracy and geometry only and shall not depend on individual measurements.

(T) Definition of x-FOM does not depend on application

R.88 If fault detection is claimed for a navigation parameter x the probability of missed detection P_{md} and false detection P_{fd} shall be specified by the manufacturer.

(T) Does not depend on application

R.89 The equipment shall be capable of computing the protection level x-PL.

(T) Does not depend on application

R.90 x-PL shall be a function of measurement accuracy and geometry only and shall not depend on individual measurements.

(T) Does not depend on application

R.91 If fault exclusion is claimed for a navigation parameter x the probability of failed exclusion P_{fe} shall be specified by the manufacturer.

(T) Does not depend on application

R.92 The equipment undergoing testing shall be capable of computing the exclusion level x-EL.

(T) Does not depend on application

R.93 x-EL shall be a function of measurement accuracy and geometry only and shall not depend on individual measurements.

(T) Does not depend on application

R.94 If receiver clock aiding is used to enhance integrity or exclusion capability, the algorithms that perform calibration shall be designed to prevent the satellite failure itself from affecting the integrity of the clock error state calibration. Conventional Kalman filter integrations using clock states for offset and drift rate with no further enhancements to protect these states in a failure situation will not meet this requirement.

(U) Depends on the architecture of the solution

R.95 If pressure altitude aiding is used to enhance integrity or exclusion capability, the algorithms that perform calibration shall be designed to prevent the satellite failure itself from affecting the integrity of the pressure altitude error state calibration. Conventional Kalman filter integrations using a bias error state with no further enhancements to protect this state in a failure situation will not meet this requirement.

(U) Depends on the architecture of the solution

R.96 If magnetometer aiding is used to enhance integrity or exclusion capability, the algorithms that perform calibration shall be designed to prevent the satellite failure itself from affecting the integrity of the magnetometer error state calibration. Conventional Kalman filter integrations using a magnetometer error state with no further enhancements to protect this state in a failure situation will not meet this requirement.

(U) Depends on the architecture of the solution

R.97 If dual antenna aiding is used to enhance integrity or exclusion capability, the algorithms that perform calibration shall be designed to prevent the satellite signal failure itself from affecting the integrity of the error state calibration. Conventional Kalman filter integrations using error states with no further enhancements to protect these states in a failure situation will not meet this requirement.

(U) Depends on the architecture of the solution

R.98 The receiver clock frequency random walk 1-sigma shall not exceed 1 $\mathrm{feet}/s/\sqrt{s}$ under steady state thermal conditions.

(U) Depends on the architecture of the solution

R.99 The frequency drift shall not exceed 3 ppm/°C under 5°C/minute transient thermal conditions (TBM).

(U) Depends on the architecture of the solution

R.100 The integrated system shall properly account for the local gravity anomalies and deflections such that the FOMs and PLs continues to bound the system errors while operating in areas of increased gravity anomaly/deflections, even when coasting. Suitable mechanisms include an appropriate subset of the following:

- Over-bounding using a standard model with an elevated sigma level.
- Compensation using a gravity map.
- Adjustment of the filter parameters (e.g. increase the process noise).

(U) Depends on the architecture of the solution

R.101 The gravity statistical model shall over-bound the tails of the residual error distribution.

(U) Depends on the architecture of the solution

R.102 Validation activities shall model pseudo range errors and carrier phase errors using statistical test data that represent all significant sources of measurement error. This data will be generated by the combination of five independent models: ionospheric, tropospheric, satellite clock & ephemeris, receiver noise, and multipath.

(M) Measurement errors might require other models for rail applications

R.103 Ionospheric error shall be modelled using the International Reference Ionosphere 2001 (IRI-2001) model (Bilitza 2001) and the depletion bubble model.

(M) Ionosphere errors might require other model for rail applications

R.104 The IRI-2001 model is deterministic and the location, date, and time model inputs shall be randomized to generate statistical test data that can be applied to Monte Carlo trials for missed alert, failed exclusion/compensation, and false alert/rare normal tests. The time and date should be randomized over one (eleven year) solar cycle.

(M) Ionosphere errors might require other model for rail applications

R.105 It is assumed that the receiver compensates for tropospheric error according to DO-316 (RTCA 2009) and residual errors shall be modelled using a first-order Gauss-Markov process with a 30 minute correlation time. The sigma shall be scaled per the troposphere residual error sigma equation defined in (RTCA 2009). Residual errors in simultaneous measurements from different satellites are assumed to be uncorrelated. Other troposphere models may be used, but they must be validated.

(M) Troposphere errors might require another model for rail applications

R.106 Satellite clock & ephemeris error shall be modelled using a first-order Gauss-Markov process with a 2 hour correlation time and a 2 m sigma. No correlation is assumed between satellites. Other clock & ephemeris models may be used, but they must be validated.

(M) Satellite clock and ephemeris errors might require another model for rail applications

R.107 Receiver and multipath error shall be modelled using the airborne receiver error model.

(M) Satellite clock and ephemeris errors might require another model for rail applications

R.108 If the tightly integrated inertial/GNSS function does not use carrier phase smoothing of the code, the code error model shall use a 25 second correlation time and adjust the sigma from 100 sec to 25 sec.

(U) Depends on the architecture of the solution

R.109 If carrier phase smoothing is used, the smoothing constant shall be used to adjust the sigma.

(T) Depends on the architecture of the solution

R.110 A system using discriminator averaging when determining the horizontal protection level (HPL) shall consider:

- The impact of the temporal correlation ρ, of the discriminator noise.
- The impact of slowly changing errors that are not reduced by averaging (e.g. ionospheric error).
- The reduction in detection performance for failures with dynamics that are fast relative to the averaging period.

(U) Depends on the architecture of the solution

The following requirements:

R.111 *The system fault free protection level (HPLFF x-PLFF) bounding and false alert rates for positioning and additional claimed navigation parameters shall not degrade more than 2 orders of magnitude when exposed to ionospheric storm conditions.*

R.112 *The system fault free protection level (HPLFF x-PLFF) bounding and false detection rate for positioning and additional claimed navigation parameters shall not degrade when exposed to ionospheric depletion bubble conditions. The detection and exclusion capability and corresponding bounding of the errors in position via HPL and any claimed parameters via x-PL shall remain unaltered when exposed to ionospheric depletion bubbles conditions.*

R.113 *The system fault free protection level (HPLFF x-PLFF) bounding and false detection rate for positioning and additional claimed navigation parameters shall not degrade when exposed to phase scintillation.*

The detection and exclusion capability and corresponding bounding of the errors in position via HPL and any claimed parameters via x-PL shall remain unaltered when exposed to ionospheric phase scintillation.

R.114 *The system fault free protection levels (HPLFF x-PLFF) bounding and false detection rate for positioning and additional claimed navigation parameters shall not degrade when exposed to ionospheric amplitude scintillation. The detection and exclusion capability and corresponding bounding of the errors in position via HPL and any claimed parameters via x-PL shall remain unaltered when exposed to ionospheric amplitude scintillation.*

R.115 *The system fault free protection levels (HPLFF x-PLFF) bounding and false detection rate for positioning and additional claimed navigation parameters shall not degrade when exposed to RFI at the standard mask. The detection and exclusion capability and corresponding bounding of the errors in position via HPL and any claimed parameters via x-PL shall remain unaltered when exposed to RFI at the standard mask.*

R.116 *The system fault free protection levels (HPLFF x-PLFF) bounding and false detection rate for positioning and additional claimed navigation parameters shall not degrade when exposed to broadband RFI above the standard mask. The detection and exclusion capability and corresponding bounding of the errors in position via HPL and any claimed parameters via x-PL shall remain unaltered when exposed to RFI above the standard mask.*

(U) Depends on the architecture of the solution

R.117 The probability per unit of time $\mathrm{p_{MI}}$, of exceeding HPLFD with no integrity alert (integrity risk) shall be defined as:

$$p_{MI} = \sum_{k=1}^{K} p_{f,k} p_{md,k} \tag{1}$$

Where $\mathrm{p_{md,k}}$ is the conditional probability of exceeding HPLFD for positioning failure mode k, $\mathrm{p_{f,k}}$ is the assigned MI failure probability per unit of time in Table 6 and K is the number of positioning failure modes.

(M) Similar definitions for rail applications needs to be defined

R.118 The continuity risk $\mathrm{p_{cont}}$ associated with a satellite failure that cannot be excluded before a loss of function occurs, shall be defined as**:**

$$p_{cont} = \sum_{k=1}^{K} p_{f,k} p_{fexl,k} \tag{2}$$

Where $\mathrm{p_{fexl,k}}$ is the conditional probability of failed exclusion for failure mode k.

(M) Similar definitions for rail applications needs to be defined

R.119 The tests for equipment shall be performed with correct or conservative:

- Inertial sensors (gyrometers and accelerometers) errors: bias, bias stability, noise, random walk, scale factor, misalignments, temperature effects etc…
- GPS receiver errors: clock, noise, temperature effects etc…

- GPS SIS errors: ionospheric, tropospheric, satellite clock, ephemeris, multipath etc…
- Airplane dynamics: horizontal accelerations, turns etc…

(M) Similar definitions for rail applications needs to be defined

R.120 Airplane dynamics shall include the following flight profiles:

- Terminal and non-precision approach.

For all parameters (position, velocity, attitude/heading), use straight and level flight during calibration (when failure is not present) and then use the following 3 flight profiles mimicking various approach configurations

i) One single 180 degree turn using a 1.5 degree/second turn rate started right after the failure is initiated.

ii) One single 45° turn using a 1.5 degree/second turn rate started right after the failure is initiated.

iii) Continue the straight and level flight (no turn or acceleration/deceleration).

The ground speed is approximately 200 knots in the three flight profiles.

- En route.

For position parameter, use straight and level flight during calibration (when failure is not present) and then use a 45 degree TBC turn mimicking a way point change using a 1.5 degree/second turn rate started right after the failure is initiated.

For velocity and attitude/heading parameters, use straight and level flight during calibration (when failure is not present) and then use the following 2 flight profiles mimicking various airplane dynamics:

i) A 45 degree (TBC) turn mimicking a way point change using a 1.5 degree/second turn rate started right after the failure is initiated.

ii) Continue the straight and level flight (no turn or acceleration/deceleration), as the absence of airplane dynamics has significant impact on attitude/heading errors observation and correction via GPS measurements.

(N) Aircraft only

R.121 If the position solution is updated at a low rate (such as a 2.5-min time step) the growth in the solution error between updates must be considered. The performance shall be measured and verified both before and after the measurement update.

(U) Depends on the architecture of the solution

R.122 The manufacturer shall categorize the failure detection [subcategory1, 2] and exclusion mechanisms [subcategory 2] employed by the monitor algorithms that are to be validated. The mechanisms identified are:

- Transient detection and exclusion (e.g. innovation screening)
- Satellite geometric redundancy (e.g. RAIM)

- Inertially propagated geometric redundancy (e.g. solution separation)
- Discriminator or residual time averaging (e.g. RAIM or extrapolation method)
- Gravity/Schuler coupling

(U) Depends on the architecture of the solution

R.123 The limitations and performance of each implemented detection/exclusion mechanism shall be demonstrated in test cases chosen by the manufacturer. This material will be used by the certification authority to assess the authenticity of the claimed improvements over normal RAIM.

(N) Depends on the architecture of the solution

R.124 When velocity and attitude/heading dependent parameters, x are bounded by a protection level x-PL the manufacturer shall similarly (e.g. mechanism a-d) categorize the failure detection and exclusion mechanisms employed and the limitations and performance of each implemented detection/exclusion mechanism shall be demonstrated in test cases chosen by the manufacturer.

(M) Similar definitions for rail applications needs to be defined

R.125 The Kalman filter technique provides a powerful verification tool referred to as covariance simulation. This type of prediction can be used for availability determination for different satellite constellations but shall not replace off line verification of the implemented algorithms.

(M) Depends on the architecture of the solution

R.126 The false detection rate shall be verified per section 2.3.7.4.2 of (RTCA 2009). The verification of the false detection rate can be performed by Monte Carlo simulation using flight trajectories with sufficient number of independent trials. If for an applicant the time required to achieve enough independent samples to test the required statistical limits may be impractical, so the detection and exclusion thresholds may be adjusted so that the test time is reduced to a reasonable level, such as days rather than weeks or months.

(M) Similar definitions for rail applications needs to be defined

R.127 All the detection mechanisms shall be active and tested at the same time.

(M) Depends on the architecture of the solution

R.128 All the exclusion mechanisms shall be active and tested at the same time.

(M) Depends on the architecture of the solution

R.129 The total amount of false detections and exclusions shall be verified.

(M) Depends on the architecture of the solution

R.130 If more satellite fault monitors are used the total false detection allocation shall reflect contributions from each additional monitoring mechanism.

(M) Depends on the architecture of the solution

R.131 The snapshot 95% horizontal accuracy test is defined in Section 2.3.3.3 of (RTCA 2009). If the inertial integration is performed by a recursive filter with memory, the scaling (1.5/HDOP) used in the test is not appropriate. The testing shall be performed versus the horizontal figure of merit HFOM that is provided by the integration filter. For a filter with position error in states 1, 2, 3 (North, East, Down) providing a covariance matrix this limit is expressed as:

$$2drms = 2\sqrt{p_{11} + p_{22}} \tag{3}$$

(N) Depends on the architecture of the solution

R.132 The accuracy test shall be performed using the signal error models and maximum thermal noise (minimum S/N0).

(V) Similar test can be applied for rail application

R.133 The accuracy test shall demonstrate that the instantaneous horizontal radial position error stays below HFOM, as defined above, 95% of the time (TBM).

(V) Similar test can be applied for rail application

R.134 The test shall evaluate at least 360 independent samples using the satellite constellation in Appendix B of (RTCA 2009).

(M) Similar test can be applied for rail application

R.135 A test shall be performed to verify that the fault-free rare normal HPL (H0) properly bounds the horizontal position error.

(M) Similar test can be applied for rail application

R.136 All position errors shall be evaluated relative to the HPL (subcategory 1 and 2) that is calculated by the equipment under test and if exclusion is tested (subcategory 2) the predicted HEL. The test first verifies normal (snap shot) RAIM performance and then moves on to test cases where the claimed HPL(HEL) performance is better than the performance provided by RAIM.

(M) Similar test can be applied for rail application

R.137 The corresponding RAIM baseline performance shall be provided for all test cases as a reference.

(M) Similar test can be applied for rail application

R.138 A failure to clearly identify and demonstrate the function of the mechanism responsible for the improved HPL or HEL (subcategory 2) relative to RAIM in a test case, shall render the test invalid.

(M) Similar test can be applied for rail application

R.139 The off-line detection/exclusion test procedure in Section 2.3.7.3.3 of (RTCA 2009) shall be performed to verify the RAIM equivalent performance, i.e. 1650 trials must be run for each of the 40 geometries (20 for detection and 20 for exclusion) with the (software) algorithm that is implemented in the equipment.

(M) Similar test can be applied for rail application

R.140 The RAIM equivalent performance shall be verified based on Section 2.3.7.3.3 of (RTCA 2009) using ramps that will not trigger any of the other detection/exclusion mechanisms augmenting the RAIM function.

(M) Similar test can be applied for rail application

R.141 The equipment manufacturer shall perform the following:

(U) Similar test can be defined for rail applications

R.142 For each failure mode, the magnitude of the ramps (step) shall be distributed uniformly in the interval designated in Table 10

Failure Type	Number of trials for each failure mode	Assumed MI Failure Probability in units of 10-5/h/satellite
Ramp 0.01-0.05 m/s	114	2/29
Ramp 0.05-0.25 m/s	57	1/29
Ramp 0.25-0.75 m/s	170	3/29
Ramp 0.75-2.5 m/s	569	10/29
Ramp 2.5-5.0 m/s	683	12/29
Step 300-700 m	57	1/29

Table 10 – Required number of trials for each failure mode

(M) Similar test can be defined for rail applications

R.143 The failure shall be introduced in the most difficult to detect/exclude satellite.

(M) Similar test can be defined for rail applications

R.144 For each failure mode, the failure ramp and the change in geometry shall be coordinated so that the desired HPL/HEL would have been exceeded if detection/ exclusion had not occurred.

(M) Similar test can be defined for rail applications

R.145 Evaluated over all 20 scenarios the number of missed detections shall be less than the 47 (33,000 trials).

(M) Similar test can be defined for rail applications

R.146 Evaluated over all 20 scenarios the number of missed exclusions shall be less than the 47 (33,000 trials). The total number of trials for detection and exclusion verification is 40 × 1650 = 66,000.

(M) Similar test can be defined for rail applications

R.147 The geometries that reflect a range of HPL/HEL values shall be chosen based on the solution separation HPL/HEL (HPLsolsep/HELsolsep) and not the RAIM related HPLraim (HELraim) (TBM).

(M) Similar test can be defined for rail applications

R.148 For pressure altitude calibration aiding, the reference is provided in Appendix G of (RTCA 2009). The RAIM algorithm used as a reference shall be tested according to Section 2.3.7 of (RTCA 2009).

(M) Similar test can be defined for rail applications

R.149 If claims of integrity coasting (TBM) are made, validation shall be performed for the false alert rate, missed alert probability and failed exclusion probability when all satellites are dropped.

(M) Similar test can be defined for rail applications

R.150 For validation of the false alert rate the tests in Section 2.3.7.3.2 of (RTCA 2009) shall be performed.

(M) Similar test can be defined for rail applications

R.151 For subcategory 1 20 coasting geometries of double duration shall be combined.

(M) Similar test can be defined for rail applications

R.152 For subcategory 2 40 coasting geometries shall be combined.

(M) Similar test can be defined for rail applications

R.153 The total number of false alerts shall be less than or equal to 47.

(M) Similar test can be defined for rail applications

R.154 For validation of the missed alert and failed exclusion probabilities 20 (sub category 1, 2) + 20 (sub category 2) coasting geometries shall be evaluated (TBM).

(M) Similar test can be defined for rail applications

R.155 Each coasting geometry shall include 1650 trials. A coasting geometry requires that all satellites have been removed such that the system is in an integrity coasting mode. In general, integrity coasting implies dropping to fewer than five measurements available, but all measurements except altitude must be dropped in this test.

(M) Similar test can be defined for rail applications

R.156 For each coasting geometry, the satellite error injection shall be timed such that detection/exclusion of the error occurs while the system is in the coasting condition and at the time of the claimed coasting duration. This verifies that the system can detect/exclude latent failures over the claimed duration.

(M) Similar test can be defined for rail applications

R.157 The total number of missed alerts shall be less than or equal to 47.

(M) Similar test can be defined for rail applications

R.158 The total number of missed exclusions be less than or equal to 47.

(M) Similar test can be defined for rail applications

R.159 The false-alert testing in section 2.5.3 of (RTCA 2017) can be modified to include all monitors which would mean it already includes any monitor used for these additional claimed parameters. As the tests performed the 95% performance, the rare normal performance (sub category 1,2) shall be used to verify compliance based on the same rules as is used for position and as the tests in 2.5.4-1.5.6 of (RTCA 2017) are performed based on a set of fault modes.

(M) Similar test can be defined for rail applications

R.160 The misdetection count, if detection is claimed, and the missed exclusion count, if exclusion is also claimed, shall be used to verify compliance based on the same rules as is used for position (this assumes the worst impact satellite is the same as for position TBC). This testing verifies that the parameters are protected for the expected threat defined by the standard fault modes and their probability of occurrence.

(M) Similar test can be defined for rail applications

R.161 The manufacturer shall categorize the failure detection and exclusion mechanisms employed by the parameter monitor algorithms that are to be validated.

(M) Similar test can be defined for rail applications

R.162 The limitations and performance of each implemented parameter detection/exclusion mechanism (as applicable) shall be demonstrated in test cases chosen by the manufacturer. This material will be used by the certification authority to assess the authenticity of the claimed performance.

(M) Similar test can be defined for rail applications

R.163 The applicant (sub category 0,1,2) shall demonstrate 95% bounding via x-FOM in tests equivalent to those in 2.5.4 of (RTCA 2017).

(M) Similar test can be defined for rail applications

R.164 The applicant (sub category 1,2) shall verify rare normal bounding by x-PL0 in tests equivalent to those in 2.5.5 of (RTCA 2017).

(M) Similar test can be defined for rail applications

R.165 The applicant (sub category 1,2) shall define 20/20 (as applicable) cases demonstrating the performance enhancement based on the method in (RTCA 2009)(different levels of protection) and perform testing equivalent to the testing in 2.5.6.2 of (RTCA 2017) for each claimed parameter.

(M) Similar test can be defined for rail applications

R.166 If coasting is claimed the applicant shall define 20/20 (as applicable) cases demonstrating the coasting performance in tests equivalent to those in 2.5.6.3 of (RTCA 2017).

(M) Similar test can be defined for rail applications

R.167 In method A, recorded storm data shall be used as the basis for the ionospheric component of pseudo range error in some trials.

(M) Similar test can be defined for rail applications

R.168 HPL shall bound position error to 10^{-3}/h during these trials and there shall be at the most 10^{-3}/h detections.

(M) Similar test can be defined for rail applications

R.169 For systems claiming bounding of additional parameters each x-PL shall bound the error to 10^{-3}/h in the parameter x during these trials and there shall be at the most 10^{-3}/h detections.

(M) Similar test can be defined for rail applications

R.170 Storms occurring on the following dates shall be processed: 06 November 2001, 24 November 2001, 30 October 2003, and 7-8 November 2004.

(M) Similar test can be defined for rail applications

R.171 In method B, the ionospheric storm model shall be used to demonstrate that HPL bound position error to 10^{-3}/h during these trials and there shall be at the most 10^{-3}/h detections.

(M) Similar test can be defined for rail applications

R.172 For systems claiming bounding of additional parameters each x-PL shall always bound the error to 10-3/h in the parameter x during these trials and there shall be at the most 10^{-3}/h detections.

(M) Similar test can be defined for rail applications

R.173 The on-line validation for tightly integrated GPS/inertial systems follows the guidelines in Section 2.3.7.5 of (RTCA 2009). If the off-line simulation is not performed on the target processor using the same software used in the equipment, 40 satellite failure scenarios shall be run using the off-line simulation and the on-target software and the result evaluated according to Section 2.3.7.5.1 of (RTCA 2009).

(M) Similar test can be defined for rail applications

R.174 The 40 scenarios shall be chosen so that all types of detection/exclusion mechanisms subject to off-line testing are represented.

(M) Similar test can be defined for rail applications

R.175 If detection/exclusion for additional parameters are claimed 40 representative scenarios for velocity-based parameters and 40 representative scenarios for acceleration based parameters shall be run and picked so that all involved detection/exclusion mechanisms are tested.

(M) Similar test can be defined for rail applications

R.176 The behavioral test in Section 2.3.7.5.2 of (RTCA 2009) shall be performed as stated.

(M) Similar test can be defined for rail applications

R.177 The number of failure scenarios shall be 5 per detection/exclusion mechanisms and if detection/exclusion for additional parameters are claimed the tests shall be repeated for velocity-based parameters and for acceleration-based parameters as applicable (15 cases if all are claimed).

(M) Similar test can be defined for rail applications

2.4.7 Integrity Monitoring Requirements

R.178 An integrity monitoring solution shall be implemented in all solutions since the integrity of the core constellations is currently insufficient (Annex 10, DO316, DO229E)

(T) Follows from the service commitments

R.179 For the autonomous solution (without ground (GBAS) or satellite (SBAS) based augmentation), a Fault Detection and Exclusion (FDE) algorithm shall be employed

(S) This follows from the above (R.180)

R.180 Integrity shall be met in the presence of unintentional interference, although no false alarm requirement is stated (DO316).

(S) This follows from the above (R.180)

R.181 In the absence of a protection level, integrity is not provided (DO316).

(M) Probable that the integrity concept will be protection level based though not necessary

R.182 An ABAS receiver must provide a navigation alert within 8s for the presence of a fault leading to a position failure.

(M) A time to alert will be required for suc a function, TBD.

R.183 For an ABAS receiver the output of misleading information, considered to be a major failure condition shall be improbable.

(M) A similar requirement will be needed for rail receivers.

R.184 For equipment that support approach, arrival and departure phases of flight, EASA requires that hazardously misleading information shall be extremely remote (CS 25.1309 and AMC 25.1309)

(N) Air operation specific.

R.185 ABAS equipment shall compute a horizontal protection level using weighted FDE (DO316 – 56)

(U) Unknown integrity algorithm at this stage

R.186 For ABAS equipment the probability of missed alert shall be less than 0.001 for every geometry regardless of the faulty satellite (DO316 – 62).

(M) Missed alert of some kind would be required for autonomous monitoring solution

R.187 ABAS equipment false alert rate shall be less than 3.33×10^{-7}. (DO316 – 64)

(M) False alert rate of some value would be required for autonomous monitoring solution

R.188 ABAS equipment failed exclusion rate shall be less than 0.001. (DO316 – 65)

(M) False exclusion rate of some value would be required for autonomous monitoring solution

R.189 All SBAS and ABAS equipment shall provide a Fault Detection prediction algorithm to enable LNAV approach operations (RTCA 2016)

R.190 **(N)** Air operation specific.

2.4.1 Human Factors Requirements

R.191 The receiver shall facilitate use with regards to controls, operation, workload, display, discernibility, brightness, colour, contrast, view angle, symbology, moving mapping, labelling and annunciations

(RTCA 2016). Further details and requirements are found in (FAA, n.d.)(SAE 1988a, 1988b; Military Standard 1989)

(N) *Applicable to aviation crew and controllers.*

2.5 Civil Aviation SIS Requirements (T1.2)

Section 2.4 captured the majority of relevant requirements employed in civil aviation in relation to GNSS, based on the assumptions given in section 2.3. These included system, equipment, hardware, software and operational requirements for the use of civil aviation's augmentation systems (ABAS, SBAS, GBAS). Performance requirements for the navigation function in terms of accuracy, integrity, continuity and availability have been standardised at international level as provided in Table 11 and Table 12. The types of typical operation vary from the least stringent en-route operations at high altitude over oceanic regions to precision approaches down to runways at airports with high traffic and close aircraft separation. GNSS is only used to support horizontal guidance for the less stringent operations. Note that a range of values is stated for continuity since the traffic density and complexity may vary depending upon the guidance function and airspace. Furthermore, availability requirements will differ depending on whether the navigation system is employed as the sole system, the primary system with backup or as a complimentary system.

Typical Operation	Accuracy horizontal 95%	Accuracy vertical 95%	Integrity	Time-to-alert	Continuity	Availability
En-Route	3.7km (2.0NM)	N/A	$1 - 1\times10^{-7}$/h	5 min	$1 - 1\times10^{-4}$/h to $1 - 1\times10^{-8}$/h	0.99 to 0.99999
En-Route, Terminal	0.74km (0.4NM)	N/A	$1 - 1\times10^{-7}$/h	15s	$1 - 1\times10^{-4}$/h to $1 - 1\times10^{-8}$/h	0.99 to 0.99999
Initial approach, Intermediate approach, Non-precision approach (NPA), Departure	220m (720ft)	N/A	$1 - 1\times10^{-7}$/h	10s	$1 - 1\times10^{-4}$/h to $1 - 1\times10^{-8}$/h	0.99 to 0.99999
Approach operations with vertical guidance (AVP-I)	16.0m (52ft)	20m (66ft)	$1 - 2\times10^{-7}$ in any approach	10s	$1 - 8\times10^{-6}$ per 15s	0.99 to 0.99999
Approach operations with vertical guidance (AVP-I)	16.0m (52ft)	8.0m (26ft)	$1 - 2\times10^{-7}$ in any approach	6s	$1 - 8\times10^{-6}$ per 15s	0.99 to 0.99999
Category I precision approach	16.0m (52ft)	6.0m to 4.0m (20ft to 13ft)	$1 - 2\times10^{-7}$ in any approach	6s	$1 - 8\times10^{-6}$ per 15s	0.99 to 0.99999

Table 11 – Signal-In-Space performance requirements (ICAO 2006)

NOTES:

1) 95th percentile values for GNSS position errors are those required for the intended operation at the lowest height above threshold (HAT)

2) Integrity definition includes an alert limit

Typical Operation	Horizontal alert limit	Vertical alert limit
En-Route (Oceanic/continental low density)	7.4km (4NM)	N/A
En-Route (Continental)	3.7km (2NM)	N/A
En route, terminal	1.85km (1NM)	N/A
NPA	556m (0.3NM)	N/A
APV I	40m (130ft)	50m (164ft)
APV II	40m (130ft)	20.0m (66ft)
Category I PA	40m (130ft)	35.0m to 10.0m (115ft to 33ft)

Table 12 – Alert Limit (AL) requirements (ICAO 2006)

3) Range of values given for the continuity requirement

2.6 MCMF Standards (T1.1)

In this section, the developments of ongoing Multiple Constellation Multiple Frequency systems in civil aviation are described. Table 13 presents the primary active working groups. Whilst proceedings of working group meetings are not public documents, the developments made are often published in public peer reviewed journals, magazines and conference papers.

WG ID	Title	Domain
WG-C	E.U U.S Collaboration Working Group C	SBAS, ARAIM
WG-62	EUROCAE GALILEO	Galileo MOPS, DFMC SBAS
WG-28	EUROCAE GBAS	GBAS Ground ICD
WG-41	EUROCAE Surface Movement (SMGCS)	GNSS SMGCS Concept
SC-159	Navigation Equipment Using the Global Navigation Satellite System (GNSS)	GNSS
SC-227	Standards of Navigation Performance	RNP, PBN
NSP	ICAO Navigation Systems Panel	GNSS, Navigation

Table 13 – Working Groups

2.6.1 ARAIM

Advanced Receiver Autonomous Integrity Monitoring (ARAIM) (Blanch et al. 2012) is a concept of (pseudo) autonomous integrity monitoring whose aim is to supplement the performance in terms of availability for horizontal (lateral) guidance of aircraft to that of existing Receiver Autonomous Integrity Monitoring (RAIM). Furthermore, ultimately, the goal will be to support aircraft operations requiring vertical guidance, namely approach operations down to a decision height of 200ft.

Unlike SBAS and GBAS, the goal is not to provide corrections and integrity information at a high rate from a ground segment to the user (airborne) subsystem. Nor is the purpose for the ground subsystem to perform real time fault detection. Instead a light ground infrastructure is envisaged, potentially drawing on existing

GNSS networks in order to validate the assumptions taken to generate the Integrity Support Message (ISM) which is to be broadcast to aircraft providing the error model parameters of the nominal bias, standard deviation and fault probabilities.

ARAIM has yet to pass to the process of standardisation, thus any conclusions made must take into consideration that assumptions may change during the next phases of development. The following sections describe the assumptions and key decisions concerning: the threat model,

2.6.1.1 ARAIM Threat Model and Error Model

In ARAIM the threats, which include all possible events (natural, systematic, operational, random) that can lead to deviation of the navigation solution from the truth are categorised into three classes, expressed below. Threats have a probability of occurrence greater than a required integrity risk. In fact, the total threat space can be modelled by a nominal error plus a fault or residual error per satellite (Equation (5) below). The fault or residual errors may be considered either correlated or uncorrelated between satellites. This separates the faults into narrow faults which occur independently and wide fault which occur due to a common cause (i.e. constellation wide failure). The three classes are then (WG-C 2012):

1. Nominal errors occur when all systems (space, ground and user) are operating nominally. They are inherent to the system (e.g. receiver noise, multipath, nominal tropospheric delay, inter-frequency bias, nominal signal deformation, code noise, nominal orbit determination and clock errors). A Gaussian overbound with possible non-zero mean is used to model these errors $\boldsymbol{\varepsilon}$.

2. Narrow faults occur due to space or ground segment faults that affect just one satellite's signal/navigation message. This type of error reflects when errors occur with a greater frequency than predicted by the nominal model. The root cause might be satellite clock failures, code carrier divergence, incorrect ephemeris, excessive signal deformations etc.

3. Wide faults occur when a space or ground segment fault leads to multiple navigation signals or navigation messages being impact simultaneously and thus not a narrow failure. For example, EOP/EOPP faults and other threats which originate from ground operations that could lead to upload errors impact multiple satellites.

The list of errors/threats which might be classified into the above categories is:

1. Satellite clock errors
2. Satellite ephemeris errors
3. Code-Carrier Incoherence
4. Inter-Frequency Bias
5. Satellite Antenna Bias
6. Ionospheric delay
7. Tropospheric delay
8. Receiver Noise and Multipath

	Nominal	Narrow fault	Wide fault
1-Clock and Ephemeris	Orbit/clock estimation and prediction and broadcast limits	Includes clock runoffs, bad ephemeris, unflagged manoeuvres	Erroneous EOPP, inadequate manned ops, ground-inherent failures
2-Signal Deformation	Nominal differences in signals due to RF components, filters, and antennas waveform distortion	Failures in satellite payload signal generation components. Faulted signal model as described in ICAO	N/A
3-Code-Carrier Incoherence	e.g. incoherence observed in IIF L5 signal or GEO L1 signals	e.g. incoherence observed in IIF L5 signal or GEO L1 signals TBC	N/A
4-IFB	Delay differences in satellite payload signal paths	Delay differences in satellite payload signal paths TBC	N/A
5-Satellite Antenna Bias	Look-angle dependent biases caused at satellite antennas	Look-angle dependent biases caused at satellite antennas TBC	N/A
6-Ionospheric	N/A	Scintillation	Multiple scintillations at solar storms in certain latitudes
7-Tropospheric	Nominal troposphere error (after applying SBAS MOPS model for tropo correction)	N/A	N/A
8-Receiver Noise and Multipath	Nominal noise and multipath terms in airborne model (TBC Gailleo BOC(1,1) and L5/E5a))	e.g.: receiver tracking failure or multipath from onboard reflector. TBC	e.g.: receiver tracking multiple failure or multipath from onboard reflector. TBC

Table 14 – Feared Events (WG-C 2012)

Note that the above characterisation has been performed based primarily on GPS constellation experience. Application to the other constellations is well founded since the core principles of operation of each constellation are almost identical. However, minor variations in system design mean that care must be taken applying the outcome to all constellations.

As a result of the above analysis, the ARAIM nominal error model differs from previous GNSS assumptions used in civil aviation. Instead of the zero mean linear Gaussian model employed in RAIM, the presence of small nominal biases is allowed (Lee and McLaughlin 2007).

$$z = Hx + \varepsilon \quad (4)$$

Where $\boldsymbol{z}$ is an n-vector of measurements (following linearization), $\boldsymbol{H}$ is the observation matrix, $\boldsymbol{x}$ is the state vector composed of the three position states and any receiver clock biases (one per constellation nominally) and $\boldsymbol{\varepsilon}$ is the residual measurement noise vector.

In the presence of a fault, the model is thus as follows, where $\boldsymbol{\mu}$ is a non-zero fault vector.

$$z = Hx + \mu + \varepsilon \quad (5)$$

Note that the error model may be non-zero mean such that with nominal bias $\boldsymbol{b}$ and zero-mean residual noise $\boldsymbol{\upsilon}$ the following model is used

$$z = Hx + \mu + b + \upsilon \tag{6}$$

$$\varepsilon \sim \mathcal{N}(b, \Sigma) \tag{7}$$

Where Σ is the covariance matrix for $\boldsymbol{\upsilon}$ populated as follows:

$$\Sigma = \begin{pmatrix} \sigma_1^2 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \sigma_n^2 \end{pmatrix} \tag{8}$$

The standard deviations are set two possible values depending upon whether the covariance matrix is used for continuity and accuracy determination or to protect integrity.

$$\Sigma_{int}(i,i) = \sigma_{int,i}^2 = \sigma_{URA,i}^2 + \sigma_{tropo,i}^2 + \sigma_{user,i}^2 \tag{9}$$

$$\Sigma_{acc}(i,i) = \sigma_{int,i}^2 = \sigma_{URE,i}^2 + \sigma_{tropo,i}^2 + \sigma_{user,i}^2 \tag{10}$$

Error models for $\sigma_{tropo,i}^2$ and $\sigma_{user,i}^2$ are well established in civil aviation and are recalled in (WG-C 2012). Note that the user error model applies to an aircraft in flight.

Based on the above model, a number of inputs are needed by the airborne algorithm. These are summarized in Table 15.

Name	Description
$\sigma_{URA,i}$	Standard deviation of the clock and ephemeris error of satellite i used for integrity
$\sigma_{URE,i}$	Standard deviation of the clock and ephemeris error of satellite i used for continuity and accuracy
$b_{nom,i}$	Maximum nominal bias for satellite i used for integrity
$P_{sat,i}$	Prior probability of fault in satellite i per hour
$P_{const,j}$	Prior probability of fault affecting more than one satellite in constellation j per hour

Table 15 – ARAIM Airborne Inputs (WG-C 2012)

2.6.1.2 ARAIM Risk Allocation

ARAIM differs from existing SBAS, GBAS and ABAS implementations in that it applies the multiple hypothesis approach to integrity risk management. For example, the RAIM risk allocation was to a single possible system state (single satellite failure) for a horizontal positioning failure only, as shown in Figure 7. In this case the fault free case and multiple simultaneous faults have been determined to be negligible. This is since under the fault free condition (denoted as state H_0) the risk is given by:

$$P(PF\&NA|H_0) = 2\left(1 - Q\left(\frac{XAL}{\sigma_x}\right)\right) \quad (11)$$

Where Q is the Gaussian CDF, XAL is the alert limit in the coordinate of interest (x) and σ_x is the standard deviation of the position solution under the fault free condition. For RAIM the argument of the Gaussian CDF is extremely high, since a horizontal alert limit of 555m was the target for operations supported by RAIM. Multiple simultaneous faults were deemed to occur with a probability less than the intended integrity risk and thus not considered.

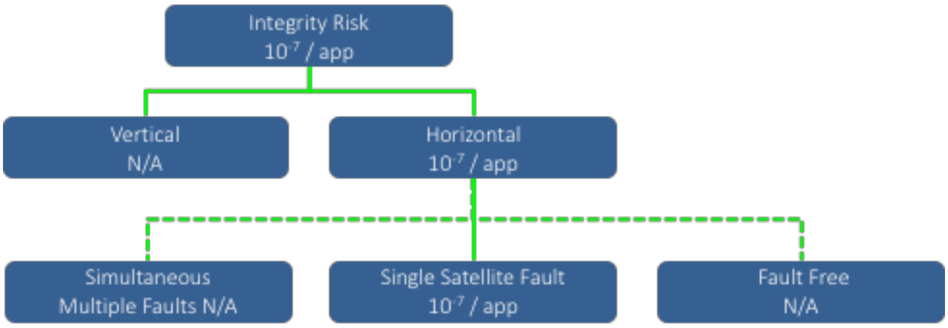

Figure 7 – RAIM Risk Allocation

In the case of ARAIM, risk is only allocated between unmonitored faults, threats to the vertical positioning solution and threats to the horizontal positioning solution.

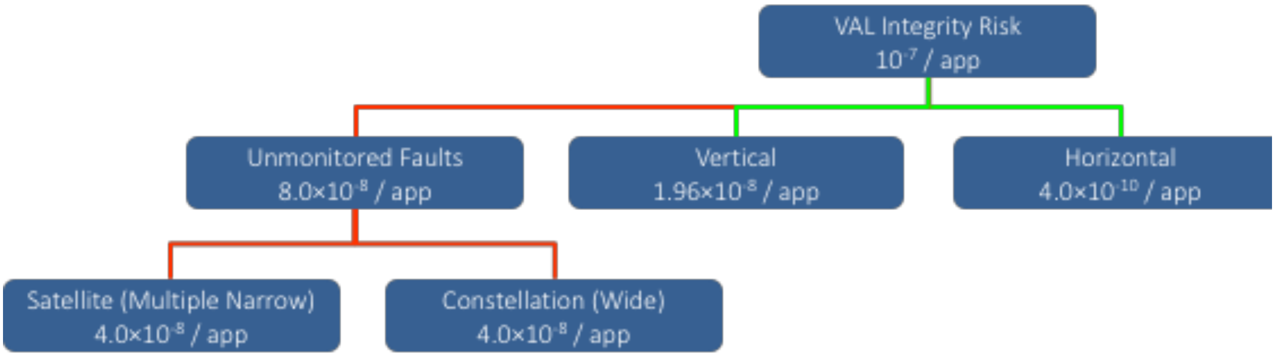

Figure 8 – ARAIM Risk Allocation

Instead of partitioning the risk between fault-free, single fault and multiple faults within the requirements framework, instead it is the ARAIM algorithm which will sum the respective risks from each fault mode and compare to the allocation.

$$P(HMI) = \sum_{i=0}^{n_H} P(HMI|H_i)P(H_i) < IR \quad (12)$$

Where $P(H_i)$ is the prior probability of the system lying in state H_i, $P(HMI|H_i)$ is the conditional probability of hazardously misleading information (HMI) given the system is in state H_i, and n_H is the number of monitored fault modes.

2.6.2 DFMC SBAS Developments

The working group on developing dual frequency multiple constellation SBAS within EUROCAE, so in particular EGNOS has developed draft standards, incorporating the following requirements which deal specifically with the DFMC component (EUROCAE 2018). The following requirements are extracted.

R.192 The equipment shall have the capability of acquiring and tracking Galileo E1-B/C signals with a minimum input signal power of -131.75 dBm in the presence of sky and antenna thermal noise density ($N_{sky,antenna}$) of -172.5 dBm/Hz (TBC) and under Normal Interference Conditions.

(M) *Interference condition may differ for a terrestrial rail application.*

R.193 The equipment shall have the capability of acquiring and tracking Galileo E1-B/C signals with a maximum power of at least -116 dBm.

(M) *Unlikely to differ yet receiver design for rail applications could introduce other constraints.*

R.194 The equipment shall have the capability of acquiring and tracking GPS L5 signals with a minimum input signal power of -129.4 dBm, SBAS L5 signals with a minimum input signal power of -133 dBm and Galileo E5a signals with a minimum input signal power of -129.75 dBm in the presence of sky and antenna thermal noise density ($N_{sky,antenna}$) of -172.5 dBm/Hz (TBC) and under Normal Interference Conditions.

(M) *Interference condition may differ for a terrestrial rail application.*

R.195 The equipment shall have the capability of acquiring and tracking GPS L5 signals with a maximum power of at least -116 dBm, SBAS L5 signals with a maximum power of at least -119 dBm and Galileo E5a signals with a maximum power of at least -114 dBm.

(M) *Interference condition may differ for a terrestrial rail application.*

R.196 The above requirements define the *Minimum Signal Conditions* and the *Maximum Signal Conditions* for GPS, Galileo and GEO SBAS satellites.

(T) *Such requirements will be needed for a rail application of SBAS.*

R.197 The equipment shall withstand, without damage, a CW signal, within the 3 dB L5 bandwidth of the equipment, of +20 dBm input to the preamplifier at the antenna port.

(M) *Interference condition may differ for a terrestrial rail application.*

R.198 The equipment shall be designed to process GPS L5 signals of PRN 1 to 32 and necessary L5 CNAV data described in IS-GPS-705D, under Normal Interference Conditions and under Minimum Signal Conditions.

(M) *Interference condition may differ for a terrestrial rail application.*

R.199 The equipment shall decode continuously the L5 CNAV bit train for each tracked GPS satellite.

(M) *Likely applied in the rail domain if L5 employed within the solution.*

R.200 With SBAS-L5 integrity monitoring, the equipment shall continuously compare the most recently decoded and validated L1 LNAV ephemeris and clock parameters set against the prior validated set and discard the previously validated set if the IODE/IODC values are the same, but there is a difference in the L1 LNAV clock or ephemeris parameters.

(U) *Unclear of the intended role of L1 and L5 frequencies in any rail solution.*

R.201 The equipment shall be designed to process the Galileo E1-B/C signals of SVIDs 1 to 36 and necessary E1 I/NAV data described in GAL OS-SIS-ICD, under Normal Interference Conditions and under the Minimum Signal Conditions.

(M) *Interference condition may differ for a terrestrial rail application.*

R.202 The equipment shall be designed to process the Galileo E5a signals of SVIDs 1 to 36 and necessary E5a F/NAV data described in GAL OS-SIS-ICD, under Normal Interference Conditions and under the Minimum Signal Conditions.

(M) *Interference condition may differ for a terrestrial rail application.*

R.203 The equipment shall decode continuously E5a F/NAV and E1 I/NAV navigation data streams for each tracked Galileo satellite.

(M) *Likely applied in the rail domain if Galileo E5a and E1 employed within the solution.*

R.204 The equipment shall continuously compare the most recently decoded E5a F/NAV ephemeris and clock parameters set against the prior set and discard the previously decoded set if the IOD_{nav} value is the same, but there is a difference in the E5a F/NAV clock or ephemeris parameters.

(M) *Likely applied in the rail domain if Galileo E5a and E1 employed within the solution.*

R.205 The equipment shall exclude or correct biased GAL E1 ranging data resulting from lock on side peaks of the correlation function within the time-to-alert (10 seconds for En route, Terminal and LNAV operations, and 6 seconds for LNAV/VNAV, LP and LPV approach operations) with a probability of missed detection lower than TBD and a probability of false alarm lower than TBD under Normal Interference Conditions and under Minimum Signal Conditions.

(M) *Likely applied in the rail domain if Galileo E5a and E1 employed within the solution.*

R.206 For Galileo E1/E5a signal outages of 30 seconds or less, the equipment shall include the satellite in the position solution within 20 seconds with 95% confidence from the end of the outage, given the following conditions:

i) The remaining satellites provide a GDOP of 6 or less;

ii) Under Normal Interference Conditions;

iii) With Minimum Signal Conditions;

iv) Aircraft dynamics within Normal Navigation Maneuvers Conditions.

(M) *Likely similar requirement yet modified to account for signal blockages and train dynamics.*

R.207 The equipment shall be designed to process the SBAS L5 signals of PRN 120 to 158 transmitted by GEO SBAS satellites, as described in Appendix A of MOPS for Galileo / GPS / SBAS L1/L5 Airborne Equipment, under Normal Interference Conditions and Minimum Signal Conditions.

(M) *Possible that SBAS data will be sent via the trackside infrastructure rather than by GEO*

R.208 The equipment shall not mistake one SBAS L5 signal resulting from cross-correlation effects during acquisition or reacquisition.

(M) *Likely applied in the rail domain if L5 employed within the solution*

R.209 The equipment shall be designed to decode the SBAS L5 data broadcast on the in-phase component of the signal, as described in Appendix A of MOPS for Galileo / GPS / SBAS L1/L5 Airborne Equipment. **(M)** *Likely applied in the rail domain if L5 employed within the solution*

R.210 The equipment shall decode SBAS L5 messages with a loss rate less 1 message in 1000 under Normal Interference Conditions and Minimum Signal Conditions.

(M) *Likely applied in the rail domain if L5 employed within the solution possibly with different rates*

R.211 For SBAS L1/L5 signal outages of 30 seconds or less, the equipment shall include the SBAS satellite in the position solution within 27 seconds with 95% confidence from the end of the outage, given the following conditions:

i) The remaining satellites provide a GDOP of 6 or less;

ii) Under Normal Interference Conditions;

iii) With Minimum Signal Conditions;

iv) Aircraft dynamics within Normal Navigation Maneuvers Conditions;

v) With $(I_{VALID})_{SBAS}$ and $(I_{VALID})_{GNSS}$ parameters equal to 241 seconds.

(M) *Likely similar requirement yet modified to account for signal blockages and train dynamics.*

R.212 The equipment shall apply the following receiver design constraints: **(M)**

i) 3-dB precorrelation bandwidth (BW) on L1: 12 ≤ BW ≤ 24 MHz;

ii) 3-dB precorrelation bandwidth (BW) on L5: 12 (TBC by ESA) ≤ BW ≤ 24 MHz;

iii) Differential group delay on L1: ≤ 150 nsec - D_A - D_C

iv) Differential group delay on L5: TBD

v) Instantaneous and average early – late correlator spacing (d) on L1: 0.08 ≤ d ≤ 0.12 L1 C/A chip;

vi) Instantaneous and average early – late correlator spacing (d) on L5: 0.9 ≤ d ≤ 1.1 L5 chip;

vii) Use of early minus late code loop discriminators only;

viii) For GPS measurements, use of BPSK(1) replica for L1 C/A signal and BPSK(10) replica for L5-Q signal;

ix) For GAL measurements, use of BOC(1,1) replica for E1-C signal and BPSK(10) replica for E5a-Q signal;

x) For SBAS measurements, use of BPSK(1) replica for L1 C/A signal and BPSK(10) replica for L5-I signal.

(M) *Likely similar conditions for rail application measurement usage.*

R.213 In addition, for LNAV/VNAV, LPV and LP operations, the equipment shall implement code tracking loops of L1/E1 and L5/E5a signals that are carrier driven, of first order or higher, and with a one-sided noise bandwidth greater than or equal to 0.125 Hz.

(M)

R.214 The equipment shall be able to use L1/L5 dual-frequency ionosphere-free pseudorange measurements from any GPS satellite only if the following conditions are all met:

i) Satellite position (including Earth's rotation correction) computed using the ephemeris parameters broadcast in subframes 2 and 3 of the L1 LNAV navigation message and corrected based on the satellite ephemeris correction parameters broadcast in MT 32 by the SBAS satellite providing the correction and integrity data in use; and

ii) Satellite clock corrections (including relativistic correction) applied based on the satellite clock parameters broadcast in Subframe 1 and the ephemeris parameters broadcast in Subframe 2 of the L1 LNAV navigation message, and on the satellite clock offset and drift error correction parameters broadcast in MT 32 by the SBAS satellite providing the correction and integrity data in use; and

iii) L1/L5 dual-frequency ionospheric-free pseudorange measurements obtained from L1 and L5 single-frequency uncorrected pseudorange measurements $PR_{L1C/A}$ and PR_{L5Q5} using the combination $PR = \frac{PR_{L5Q5} - \gamma_{15} PR_{L1C/A}}{1-\gamma_{15}}$ with $\gamma_{15} = \left(\frac{154}{115}\right)^2$; and

iv) Tropospheric correction applied; and

v) Group delay correction $-c \times T_{GD}$ applied (TBC), using parameter T_{GD} broadcast in Subframe 1 of the L1 LNAV navigation message.

(M) *Likely similar conditions for rail application measurement usage.*

R.215 The equipment shall be able to use E1/E5a dual-frequency ionospheric-free pseudorange measurements from any Galileo satellite only if the following conditions are all met:

i) Satellite position (including Earth's rotation correction) computed using the ephemeris parameters broadcast in Page Types 2, 3 and 4 of the E5a F/NAV navigation message and corrected based on the satellite ephemeris correction parameters broadcast in MT 32 by the SBAS satellite providing the correction and integrity data in use; and

ii) Satellite clock correction (including relativistic corrections) applied, based on the satellite clock parameters broadcast in Page Type 1 and the ephemeris parameters broadcast in Page Types 2 and 3 of the E5a F/NAV navigation message, and on the satellite clock offset and drift error correction parameters broadcast in MT 32 by the SBAS satellite providing the correction and integrity data in use; and

iii) E1/E5a dual-frequency ionospheric-free pseudorange measurements obtained from E1 and E5a single-frequency uncorrected pseudorange measurements PR_{E1} and PR_{E5a} using the combination $PR = \frac{PR_{E5a} - \gamma_{15} PR_{E1}}{1-\gamma_{15}}$ with $\gamma_{15} = \left(\frac{154}{115}\right)^2$; and

iv) Tropospheric correction applied.

(M) *Likely similar conditions for rail application measurement usage.*

R.216 The equipment shall be able to use L1/L5 dual-frequency ionosphere-free pseudorange measurements from any SBAS GEO satellite only if the following conditions are all met:

i) Satellite position (including Earth's rotation correction) computed using the ephemeris parameters broadcast in Message Types 39 and 40 of the SBAS L5 navigation message, and corrected based on the satellite ephemeris correction parameters broadcast in MT 32 by the SBAS satellite providing the correction and integrity data in use; and

ii) Satellite clock correction applied, based on the satellite clock parameters broadcast in the same Message Type 40, and on the satellite clock offset and drift error correction parameters broadcast in MT 32 by the SBAS satellite providing the correction and integrity data in use; and

iii) L1/L5 dual-frequency ionospheric-free pseudorange measurements obtained from L1 and L5 single-frequency uncorrected pseudorange measurements PR_{L1} and PR_{L5} using the combination $PR = \frac{PR_{L5} - \gamma_{15} PR_{L1}}{1 - \gamma_{15}}$ with $\gamma_{15} = \left(\frac{154}{115}\right)^2$; and

iv) Tropospheric correction applied.

(M) *Likely similar conditions for rail application measurement usage.*

R.217 The equipment shall exclude from the position computation pseudorange measurements from any satellite upon the occurrence of any of the following conditions:

i) DFREI = 15 decoded in any MT 32, 34, 35, 36 or 40 broadcast by the SBAS satellite providing the correction and integrity data in use;

ii) or DFRECI = 3 decoded in MT 34 broadcast by the SBAS satellite providing the correction and integrity data in use;

iii) or DFREI = 14 bumped by the reception of DFRECI = 2 in MT 34 broadcast by the SBAS satellite providing the correction and integrity data in use;

iv) or Valid correction and integrity data not available;

v) or DFREI table not available.

(M) *Likely similar conditions for rail application measurement usage.*

R.218 In addition, the equipment shall exclude from the position computation pseudorange measurements from any satellite upon the occurrence of any of the following conditions

i) For GPS satellites, failure of parity on five successive L1 LNAV words;

ii) or For GEO SBAS satellites, failure of parity on 4 successive L1 or 4 successive L5 messages.

(M) *Likely similar conditions for rail application measurement usage.*

R.219 The equipment shall be able to use in the position computation pseudorange measurements from any satellite when the conditions leading to satellite exclusion defined in [REQ-053] and [REQ-054] are all cleared.

(M) *Likely similar conditions for rail application measurement usage.*

R.220 In addition, before introducing or re-introducing a satellite in the navigation solution, the equipment shall ensure that the navigation data set used to compute the satellite position and clock offset corresponds to the navigation data set used by the SBAS service provider to generate correction and integrity data.

(M) *Likely similar conditions for rail application measurement usage.*

R.221 If used, the equipment shall be able to include L1/L5 dual-frequency pseudorange measurements from any GPS satellite only if the following conditions are all met:

i) Satellite position (including Earth's rotation correction) computed using the ephemeris parameters broadcast in message types 10 and 11 of the L5 CNAV navigation message; and

ii) Satellite clock correction (including relativistic correction) based on the satellite clock parameters broadcast in Message Type 30 and the ephemeris parameters broadcast in Message Type 10 of the L5 CNAV navigation message; and

iii) L1/L5 dual-frequency ionosphere-free measurements obtained from L1 and L5 single-frequency uncorrected pseudorange measurements $PR_{L1C/A}$ and PR_{L5X5} using the combination $PR = \frac{PR_{L5X5} - \gamma_{15} PR_{L1C/A}}{1-\gamma_{15}}$ with $\gamma_{15} = \left(\frac{154}{115}\right)^2$; and

iv) Tropospheric correction applied; and

v) Group delay correction $c \times \left(\frac{ISC_{L5X5} - \gamma_{15} ISC_{L1C/A}}{1-\gamma_{15}} - T_{GD}\right)$ applied, using parameters $T_{GD}, ISC_{L1C/A}$ and ISC_{L5X5} broadcast in L5 CNAV Message Type 30, X corresponding to the L5 signal component (I or Q) used to generate PR_{L5X5} measurements.

(M) *Likely similar conditions for rail application measurement usage.*

R.222 If used, the equipment shall be able to include L5 single-frequency pseudorange measurements from any GPS satellite only if the following conditions are all met: **(M)**

i) Satellite position (including Earth's rotation correction) computed using the ephemeris parameters broadcast in message types 10 and 11 of the L5 CNAV navigation message; and

ii) Satellite clock correction (including relativistic correction) based on the satellite clock parameters broadcast in Message Type 30 and the ephemeris parameters broadcast in Message Type 10 of the L5 CNAV navigation message; and

iii) Ionospheric correction applied by using the ionospheric coefficients broadcast in GPS navigation message (L1 LNAV or L5 CNAV) and used as detailed in IS-GPS-705D section 20.3.3.3.1.3; and

iv) Tropospheric correction applied; and

v) Group delay correction $c \times (ISC_{L5X5} - T_{GD})$ applied, using parameters T_{GD} and ISC_{L5X5} broadcast in L5 CNAV Message Type 30, X corresponding to the L5 signal component (I or Q) used to generate PR_{L5X5} measurements.

(M) *Likely similar conditions for rail application measurement usage.*

R.223 If used, the equipment shall exclude L5 single-frequency measurements from any GPS satellite upon the occurrence of any of the following conditions: **(M)**

i) The 1 bit L5 signal health in Message Type 10 different from 0 (as described in IS-GPS-705D section 20.3.3.1.1.2); or

ii) Non Elevation Dependent User range accuracy URANED0 index of 8 or more; or

iii) Non Elevation Dependent User range accuracy URANED0 index of -16; or

iv) L5 CNAV Message Type 30 T_{GD} parameter set to 1000000000000 ("not available"); or

v) ISC parameter ISC_{L5I5} or ISC_{L5Q5} (depends on the signal component, I or Q, used to generate measurements) set to 1000000000000 ("not available"); or

vi) "Alert" flag (bit 38) set to 1 (as described in IS-GPS-705D section 20.3.3); or

vii) L5 CNAV Message Type 0 (default message) (as described in IS-GPS-705D section 20.3.2); or

viii) The preamble does not equal 8B (hexadecimal) or 139 (decimal).

(M) *Likely similar conditions for rail application measurement usage.*

R.224 If used, the equipment shall exclude L1/L5 dual-frequency pseudorange measurements from any GPS satellite upon the occurrence of any of the following conditions: **(M)**

i) The 1 bit L5 signal health in Message Type 10 is different from 0 (as described in IS-GPS-705D section 20.3.3.1.1.2); or

ii) The 1 bit L1 signal health in Message Type 10 is different from 0 (as described in IS-GPS-705D section 20.3.3.1.1.2); or

iii) Non Elevation Dependent User range accuracy URANED0 index of 8 or more; or

iv) Non Elevation Dependent User range accuracy URANED0 index of -16; or

v) L5 CNAV Message Type 30 T_{GD} parameter set to 1000000000000 ("not available"); or

vi) ISC parameter $ISC_{L1C/A}$ set to 1000000000000 ("not available"); or

vii) ISC parameter ISC_{L5I5} or ISC_{L5Q5} or (depends on the signal component, I or Q, used to generate measurements) set to 1000000000000 ("not available"); or

viii) "Alert" flag (bit 38) set to 1 (as described in IS-GPS-705D section 20.3.3); or

ix) L5 CNAV Message Type 0 (default message) (as described in IS-GPS-705D section 20.3.2); or

x) The preamble does not equal 8B (hexadecimal) or 139 (decimal) in L5 CNAV message or L1 LNAV subframe; or

xi) Failure of parity on five successive L1 LNAV words.

(M) *Likely similar conditions for rail application measurement usage.*

R.225 If used, the equipment shall be able to include E1 single-frequency pseudorange measurements from any Galileo satellite only if the following conditions are all met:

i) Satellite position (including Earth's rotation correction) computed using the ephemeris parameters broadcast in Word Type 1, 2, 3 and 4 of the E1 I/NAV navigation message; and

ii) Satellite clock correction (including relativistic corrections) applied, based on the satellite clock parameters broadcast in Word Type 4 and the latest ephemeris parameters broadcast in Word Types 1 and 3 of the E1 I/NAV navigation message; and

iii) Ionospheric correction applied based on ionospheric coefficients broadcast in the GPS navigation message (L1 LNAV or L5 CNAV) and used as described in IS-GPS-200H section 20.3.3.5.2.5; and

iv) Tropospheric correction applied; and

v) Group delay correction applied by using the received BGD parameter broadcast in Word Type 5 of the E1 I/NAV navigation message as detailed in OS-SIS-ICD section 5.1.5.

(M) *Likely similar conditions for rail application measurement usage.*

R.226 If used, the equipment shall be able to include E1/E5a dual-frequency measurements from any Galileo satellite only if the following conditions are all met:

i) Satellite position (including Earth's rotation correction) computed using the ephemeris parameters broadcast in Page Types 2, 3 and 4 of the E5a F/NAV navigation message; and

ii) Satellite clock correction (including relativistic corrections) applied, based on the satellite clock parameters broadcast in Page Type 1 and the ephemeris parameters broadcast in Page Types 2 and 3 of the E5a F/NAV navigation message; and

iii) E1/E5a dual-frequency ionosphere-free measurements obtained from E1 and E5a single-frequency uncorrected pseudorange measurements PR_{E1} and PR_{E5} using the combination $PR = \frac{PR_{E5}-\gamma_{15}PR_{E1}}{1-\gamma_{15}}$ with $\gamma_{15} = \left(\frac{154}{115}\right)^2$; and

iv) Tropospheric correction applied.

(M) *Likely similar conditions for rail application measurement usage.*

R.227 If used, the equipment shall be able to include E5a single-frequency pseudorange measurements from any Galileo satellite only if the following conditions are all met:

i) Satellite position (including Earth's rotation correction) computed using the ephemeris parameters broadcast in Page Types 2, 3 and 4 of the E5a F/NAV navigation message; and

ii) Satellite clock correction (including relativistic corrections) applied, based on the satellite clock parameters broadcast in Page Type 1 and the ephemeris parameters broadcast in Page Types 2 and 3 of the E5a F/NAV navigation message; and

iii) Ionospheric correction applied, based on the ionospheric coefficients broadcast in the GPS navigation message (L1 LNAV or L5 CNAV) and used as detailed in IS-GPS-705D section 20.3.3.3.1.3; and

iv) Tropospheric correction applied; and

v) Group delay correction applied, based on the BGD parameter broadcast in Page Type 1 of the E5a F/NAV navigation message, as detailed in OS-SIS-ICD section 5.1.5.

(M) *Likely similar conditions for rail application measurement usage.*

R.228 If used, the equipment shall exclude E1/E5a dual-frequency pseudorange measurements from any Galileo satellite upon the occurrence of any of the following conditions:

i) Word Type 63 (E1 I/NAV dummy word) received; or

ii) Page Type 63 (E5a F/NAV dummy page) received; or

iii) E1-B/C signal health status ($E1\text{-}B_{HS}$) different from 0 (as described in OS SIS ICD section 5.1.9.3); or

iv) E5a signal health status ($E5a_{HS}$) different from 0 (as described in OS SIS ICD section 5.1.9.3); or

v) E1-B Data Validity Status ($E1\text{-}B_{DVS}$) different from 0 (as described in OS SIS ICD section 5.1.9.3); or

vi) E5a Data Validity Status ($E5a_{DVS}$) different from 0 (as described in OS SIS ICD section 5.1.9.3); or

vii) SISA(E1,E5a) index equal to 255 (or NAPA, as described in OS SIS ICD section 5.1.11).

(M) *Likely similar conditions for rail application measurement usage.*

R.229 If used, the equipment shall exclude E5a single-frequency pseudorange measurements from any Galileo satellite upon the occurrence of any of the following conditions:

i) Page Type 63 (E5a F/NAV dummy page) received; or

ii) E5a signal health status ($E5a_{HS}$) different from 0 (as described in OS SIS ICD section 5.1.9.3); or

iii) E5a Data Validity Status ($E5a_{DVS}$) different from 0 (as described in OS SIS ICD section 5.1.9.3); or

iv) SISA(E1,E5a) index equal to 255 (or NAPA, as described in OS SIS ICD section 5.1.11).

(M) *Likely similar conditions for rail application measurement usage.*

R.230 If used, the equipment shall exclude E1 single-frequency pseudorange measurements from any Galileo satellite upon the occurrence of any of the following conditions:

i) Word Type 63 (E1 I/NAV dummy word) received; or

ii) E1-B/C signal health status ($E1\text{-}B_{HS}$) different from 0 (as described in OS SIS ICD section 5.1.9.3); or

iii) E1-B Data Validity Status (E1-B_{DVS}) different from 0 (as described in OS SIS ICD section 5.1.9.3); or

iv) SISA(E1,E5b) index equal to 255 (or NAPA, as described in OS SIS ICD section 5.1.11).

(M) *Likely similar conditions for rail application measurement usage.*

R.231 If used, the equipment shall be able to include E1/E5a dual-frequency measurements from any Galileo satellite only if the following conditions are all met:

i) E5a F/NAV ephemeris, satellite clock correction and SISA(E1,E5a) parameters are available; and

ii) neither "SIS unhealthy" nor "SIS marginal" condition on E5a signal has occurred ever since the equipment collected these F/NAV parameters; and

iii) E1-$B_{HS} \neq 0$, E1-$B_{DVS} \neq 0$ and E1 I/NAV dummy word conditions are all cleared.

(M) *Likely similar conditions for rail application measurement usage.*

R.232 If used, the equipment shall be able to include E5a single-frequency pseudorange measurements from any Galileo satellite only if the following conditions are all met:

i) E5a F/NAV ephemeris, satellite clock correction, SISA(E1,E5a) and BGD parameters are available; and

ii) Neither "SIS unhealthy" nor "SIS marginal" condition on E5a signal has occurred ever since the equipment collected these F/NAV parameters.

(M) *Likely similar conditions for rail application measurement usage.*

R.233 If used, the equipment shall be able to include E1 single-frequency pseudorange measurements from any Galileo satellite only if the following conditions are all met:

i) E1 I/NAV ephemeris, satellite clock correction, SISA(E1,E5b) and BGD parameters are available; and

ii) Neither "SIS unhealthy" nor "SIS marginal" condition on E1 signal has occurred ever since the equipment collected these I/NAV parameters.

(M) *Likely similar conditions for rail application measurement usage.*

R.234 The equipment shall be able to process at least data from Message Types 0, 31, 32, 34, 35, 36, 37, 39, 40 and 47, as detailed in Appendix A of MOPS for Galileo / GPS / SBAS L1/L5 Airborne Equipment. **(M)** *If SBAS used in the rail solution, likely minimum set but subject to modification.*

R.235 The equipment shall only use SBAS L5 correction and integrity data if the time elapsed since the end of the reception of corresponding messages is less than or equal to their timeout interval defined in the following table.

(M) *Likely applied if system used in rail application.*

Contents	Associated Message Types	En route, Terminal Approach (LNAV) Timeout (s)	Approach (LNAV/VNAV, LP, LPV) Timeout (s)
Satellite Mask	31	600	600
Integrity Information (DFREI and DFRECI)	34 35 36 32 40	18	12
SV clock-ephemeris error corrections and covariance matrix	32	1.5 × (IVALID)MT 32 (defined in MT 37)	(IVALID)MT 32 (defined in MT 37)
SBAS SV ephemeris and clock-ephemeris covariance matrix	39 40	1.5 × (IVALID)MT 39/40 (defined in MT 37)	(IVALID)MT 39/40 (defined in MT 37)
Degradation parameters and DFREI scale table	37	360	240
Time Reference Identifier	37	360	240
Week Number Roll-Over Count	47	360	360
SBAS provider ID and ownership indicator	47	360	240

Table 16 – Timeout Intervals

R.236 The equipment shall only use SBAS L5 correction and integrity data obtained from the same SBAS L5 signal (PRN code)

(M) *Likely applied if system used in rail application*

R.237 The equipment shall satisfy the applicable integrity requirement within the time-to-alert (10 seconds for En route, Terminal and LNAV operations, and 6 seconds for LNAV/VNAV, LP and LPV approach operations) for the output of misleading information in the presence of interfering signals higher in power than *Normal Interference Conditions*. Under these extreme conditions, it is acceptable to output a navigation alert, but not to output misleading information.

(M) *Likely applied if system used in rail application*

R.238 If the equipment provides a time output, it shall be within 1 second of coordinated universal time (UTC).
(M) *Likely applied if system used in rail application.*

R.239 The equipment shall output the Horizontal Protection Level for the position solution (either the HPLSBAS or HPLDFSBAS applicable to En route through LNAV operations; or the HPLFD).

(M) *A protection level will be required, certainly in the along track direction*

R.240 If the position solution uses SBAS L5 corrected satellite measurements, the equipment shall compute the horizontal protection level HPLDFSBAS as defined in Appendix J of MOPS for Galileo / GPS / SBAS L1/L5 Airborne Equipment.

(M) *Likely applied if system used in rail application, however, DF operations in an urban environment are detrimental to multipath errors*

R.241 The latency of the SBAS-based protection level shall be less than or equal to 2.0 seconds, from the arrival at the antenna port of the last bit of an SBAS L5 message that affects the horizontal protection level to the display to pilot.

(M) *Latencies for rail applications must be set based on rail requirements*

R.242 The equipment shall alert within 8.0 seconds for FDE-provided integrity monitoring.

(M) *Times to alert for rail applications must be set based on rail requirements*

R.243 When reverting from HPLSBAS (or HPLDFSBAS) to HPLFD, the equipment must meet an 8.0 second time to alert requirement from the most recent valid computation of HPLSBAS (or HPLDFSBAS).

(M) *Times to alert for rail applications must be set based on rail requirements*

R.244 The equipment shall compute three-dimensional position and velocity.

(M) *In rail applications remains to be defined if the or which components of the system will produce velocity estimates and if both position and velocity will initially be in 3D or 1D.*

R.245 This position shall represent the WGS-84 position of the aircraft antenna (or centre of navigation) at the time of applicability.

(M) *As above, depends upon the architecture.*

R.246 The minimum update rate of "position output data" shall be once per second.

(M) *Latencies for rail applications must be set based on rail requirements*

R.247 The latency of the position, velocity outputs, defined as the interval between the time of the measurement and the time of applicability of the position and velocity, shall be less than or equal to 500 milliseconds.

(M) *Latencies for rail applications must be set based on rail requirements*

R.248 The "position output data" shall be output prior to 200 milliseconds after the time of applicability.

(M) *Latencies for rail applications must be set based on rail requirements*

R.249 The equipment shall indicate if the HPL cannot be calculated.

(M) *Unavailability situations to be defined for the rail industry.*

R.250 The equipment shall provide an indication or output the loss of navigation capability within 1.0 second on the onset of any of the following conditions:

i) The absence of power (loss of function is an acceptable indicator);

ii) Equipment malfunction or failure;

iii) The presence of a condition lasting 5 seconds or more where there are an inadequate number of usable satellites to compute a position solution (i.e., no computed data);

iv) The presence of a condition where fault detection detects a position failure that cannot be excluded within a 7.0 second time-to-alert.

(V) *Loss of function will require announcement within the bounds of rail operations.*

R.251 The equipment shall provide an FD prediction capability. If the equipment uses barometric altitude to improve availability, the availability of corrected barometric altitude (either by automatic or manual altimeter setting input) may be assumed for this purpose. For the purpose of this calculation, an acceptable value of the standard deviation of pressure altitude error is 50 meters. For FD prediction purposes only, means to manually identify a GPS or a Galileo satellite that is expected to be unavailable at the destination (for scheduled maintenance as identified in a NOTAM) or to identify a core constellation frequency the use of which is not allowed at the destination may be provided. In case the de-selection of core constellation frequency(ies) prevents the equipment from predicting valid HPLFD, the equipment may provide instead predicted HPLFD in accordance with RTCA/DO-229E section 2.1.3.2.2.3. When making FD predictions within 30 NM of the destination, current measurement weights may be used. For FD predictions, an acceptable value of the URA index for GPS satellites is 1 (whatever the origin of the almanacs used – L1 LNAV or L5 CNAV) and an acceptable value of the SISA index for Galileo satellites is 128. Acceptable values of ionospheric, tropospheric, and multipath and antenna group delay variation error are the values associated with the satellite elevation angle at the estimated location and time of arrival. Acceptable value for receiver noise contribution is the maximum value at Minimum Signal level. If range measurements do not have the same time reference, the difference between time references must be accounted for.

(M) *Unavailability situations to be defined for the rail industry.*

R.252 For satellites used with SBAS L5-provided integrity monitoring, the equipment shall perform ionosphere-free L1/L5 carrier smoothing using the following filter, with one of the two acceptable approaches defined by item m) to compute the weighting function in the first 100 seconds since filter initialization:

$$P_{proj} = P_{n-1} + \frac{\frac{\lambda_{L5}}{2\pi}\left(\varphi_{L5,n} - \varphi_{L5,n-1}\right) - \gamma_{15}\frac{\lambda_{L1}}{2\pi}\left(\varphi_{L1,n} - \varphi_{L1,n-1}\right)}{1 - \gamma_{15}} \qquad (13)$$

Where:

- P_n is the ionosphere-free dual-frequency carrier-smoothed pseudorange in meters
- P_{n-1} is the previous ionosphere-free dual-frequency carrier-smoothed pseudorange in meters,
- P_{proj} is the projected ionosphere-free dual-frequency pseudorange in meters,
- $P_{L1,n}$ is the L1 or E1 raw pseudorange measurement in meters,
- $P_{L5,n}$ is the L5 or E5a raw pseudorange measurement in meters,
- $\varphi_{L1,n}$ is the accumulated L1 or E1 raw carrier phase measurement in radians,
- $\varphi_{L1,n-1}$ is the previous accumulated L1 or E1 raw carrier phase measurement in radians,
- $\varphi_{L5,n}$ is the accumulated L5 or E5a raw carrier phase measurement in radians,
- $\varphi_{L5,n-1}$ is the previous accumulated L5 or E5a raw carrier phase measurement in radians,
- λ_{L1} is the L1 wavelength in meters,
- λ_{L5} is the L5 wavelength in meters,
- $\gamma_{15} = \left(\frac{154}{115}\right)^2$ is the L1/E1 to L5/E5a frequency ratio, and

- α is the filter weighting function: after 100 seconds have elapsed since filter initialization, α is equal to the sample interval in seconds divided by the time constant of 100 seconds; in the first 100 seconds since filter initialization, α is equal to the sample interval in seconds divided either by the time constant of 100 seconds, or by the time in seconds since filter initialization

  (U) *Unlikely that DF ionosphere-free smoothing will be used due to multipath inflation, however, divergence-free smoothing could be if compatible with DFMC SBAS.*

R.253 The satellite signal tracking quality shall be monitored such that the allocated integrity risk due to undetected cycle slip or other undetected measurement fault is within the manufacturer's allocation. **(V)** *Such monitoring is required in all safety critical applications.*

R.254 The equipment contribution to the ionosphere-free dual-frequency pseudorange measurement error for a GPS or a Galileo satellite shall be less than or equal to 0.40 m (RMS) given the following conditions:

i) More than 360 seconds of continuous tracking of the dual-frequency signal;

ii) With L1/E1 and L5/E5a Minimum Signal Conditions;

iii) Under Normal Interference Conditions;

iv) Aircraft dynamics within Normal Approach Manoeuvres Conditions.

(V) *Likely similar conditions for rail application measurement usage.*

R.255 The equipment contribution to the ionosphere-free dual-frequency pseudorange measurement error for a GPS or a Galileo satellite shall be less than or equal to 0.30 m (RMS) given the following conditions:

i) More than 360 seconds of continuous tracking of the dual-frequency signal;

ii) With L1/E1 and L5/E5a Maximum Signal Conditions;

iii) Aircraft dynamics within Normal Approach Manoeuvres Conditions.

(V) *Likely similar conditions for rail application measurement usage.*

R.256 If integrity monitoring is provided by SBAS L5, the equipment shall compute a three-dimensional position using a linearized, weighted least-squares solution as defined in Appendix E of MOPS for Galileo / GPS / SBAS L1/L5 Airborne Equipment.

(M) *If DFMC SBAS is employed, such outputs will be needed.*

R.257 If integrity monitoring is provided by SBAS L5, the equipment shall compute Horizontal and Vertical Protection Level (HPLDFSBAS and VPLDFSBAS) as described in Appendix J of MOPS for Galileo / GPS / SBAS L1/L5 Airborne Equipment.

(M) *If DFMC SBAS is employed, such outputs will be needed.*

R.258 The equipment shall output SBAS-based protection levels (HPLSBAS and VPLSBAS for SBAS L1 integrity monitoring or HPLDFSBAS and VPLDFSBAS for SBAS L5 integrity monitoring) at least once per second.

(M) *Rates and latencies will ultimately depend upon the rail domain requirements.*

R.259 If integrity monitoring is provided by SBAS L5, the equipment shall perform in addition fault detection based on the redundancy of the SBAS-corrected ranging measurements used in the navigation solution.

(M) *If DFMC SBAS is employed, such fault detection outputs will be needed.*

R.260 The fault detection shall be performed at a rate of at least once per minute or within 6 seconds of a change in the set of satellites that are being used in the navigation solution.

(M) *Rates and latencies will ultimately depend upon the rail domain requirements.*

R.261 The probability of false alert shall be less than or equal to 1.6×10^{-5} per sample for every geometry.

(M) *It is likely that a false alert requirement be used for rail or any safety critical application with monitoring.*

R.262 For LNAV/VNAV approach, the equipment shall compute and output a position at a 1 Hz rate.

(M) *For rail applications, alternative output rates may be needed.*

R.263 For LPV or LP approach, the equipment shall compute and output a position at a 5 Hz rate to support an unaided navigator.

(M) *If DFMC SBAS is employed, such outputs will be needed.*

R.264 The equipment shall apply the tropospheric delay correction specified in RTCA/DO-229E Appendix A, Section A.4.2.4.

(M) *Depends upon the architecture, if wide area (SBAS) or local area differential system to determine if an empirical tropospheric correction is required.*

R.265 The equipment shall indicate if the HPL/VPL corresponding to the active integrity monitoring (SBAS L1 or SBAS L5 provided) cannot be calculated.

(M) *If DFMC SBAS is employed, such outputs will be needed.*

2.6.3 DFMC GBAS Developments

Dual Frequency Multiple Constellation (DFMC) GBAS has been investigated under the frame of the Single European Skies ATM Research (SESAR) programme, notably WP 15.3.7 of that funding programme. Under Horizon 2020, the SESAR 2020 PJ 14.03.01 is continuing this work of DFMC GBAS definition. The following subsections describe the main decisions taken.

2.6.4 DFMC GBAS Assumptions and Technical Contributions

The European solution will utilise the GPS and Galileo constellation on frequencies L1/L5 and E1/E5a respectively though without constraining any prospective standardisation activities to particular constellations. Whilst SF GBAS is based on a ground to air transmission rate of 2Hz, due to the available transmission space the addition of corrections on new signals requires a lower rate of transmission. Studies have selected a nominal transmission interval of around 2-3s (Guilbert, Milner, and Macabiau 2014) for these new corrections whilst providing a separate integrity message at the same 2Hz of existing GBAS.

Whilst DFMC SBAS has been fixed on the basis of the ionosphere free combination measurement processing mode (refer to R.252) the nominal processing mode for DF GBAS has not been finalised. Both an ionosphere-free and a single-frequency (L1) positioning with DF ionosphere monitoring have been proposed (Felux et al.

2015). The arguments against using the ionosphere-free smoothed combination are that nominal performance will be slightly reduced, resulting from the inflated multipath of this combination, whereas ionospheric events which could lead to potential positioning failure are monitored using a dual frequency ionospheric refraction technique (Konno 2007).

In addition to the positioning methodology, the use of new signals within GBAS necessitates a reassessment of the failure modes:

- Ionospheric gradients
- Incorrect ephemeris parameters
- Excessive acceleration (clock run-off)
- Code Carrier Divergence (CCD)
- Anomalous signal deformation
- Anomalous tropospheric gradients.

These topics have been studied and presented in a number of papers on DFMC GBAS (Guilbert 2015; Jiang, Milner, and Macabiau 2017), (Rotondo et al. 2014), (Jing et al. 2014).

2.7 Rail Requirements Transfer (T1.1)

In this section the question of a requirements transfer from aviation to the rail industry is considered. Firstly, as has been undertaken in previous studies (Lu 2014; Marais 2010), requirements in the different industries and domains are defined recalling in the case of civil aviation those terms from section 2.5.

2.7.1 Signal-In-Space Requirements

Signal-In-Space (SIS) requirements refer to the performance requirements on navigation system assuming a fault-free receiver subject to nominal errors. As described in the ICAO SARPs (ICAO 2006)

> « 3.7.2.4.1 The combination of GNSS elements and a fault-free GNSS user receiver shall meet the signal-in-space requirements defined in Table 3.7.2.4-1 (located at the end of section 3.7).
>
> *Note: The concept of a fault-free user receiver is applied only as a means of defining the performance of combinations of different GNSS elements. The fault-free receiver is assumed to be a receiver with nominal accuracy and time-to-alert performance. Such a receiver is assumed to have no failures that affect the integrity, availability and continuity performance. »*

This relationship is shown in Figure 9 where the GNSS receiver (RX) fault modes are covered by the safety risk apportioned to the aircraft. It is therefore the under the responsibility of the airframe manufacturer, subcontracted to an avionics manufacturer and not under the remit of the Air Navigation Services Provider (ANSP). In fact, this split of responsibility is the very reason for this apportionment. It must be decided if a similar approach is taken in the rail industry, noting that RAMS requirements have been stated apportioned between on-board requirement, lineside and centralised trackside equipment.

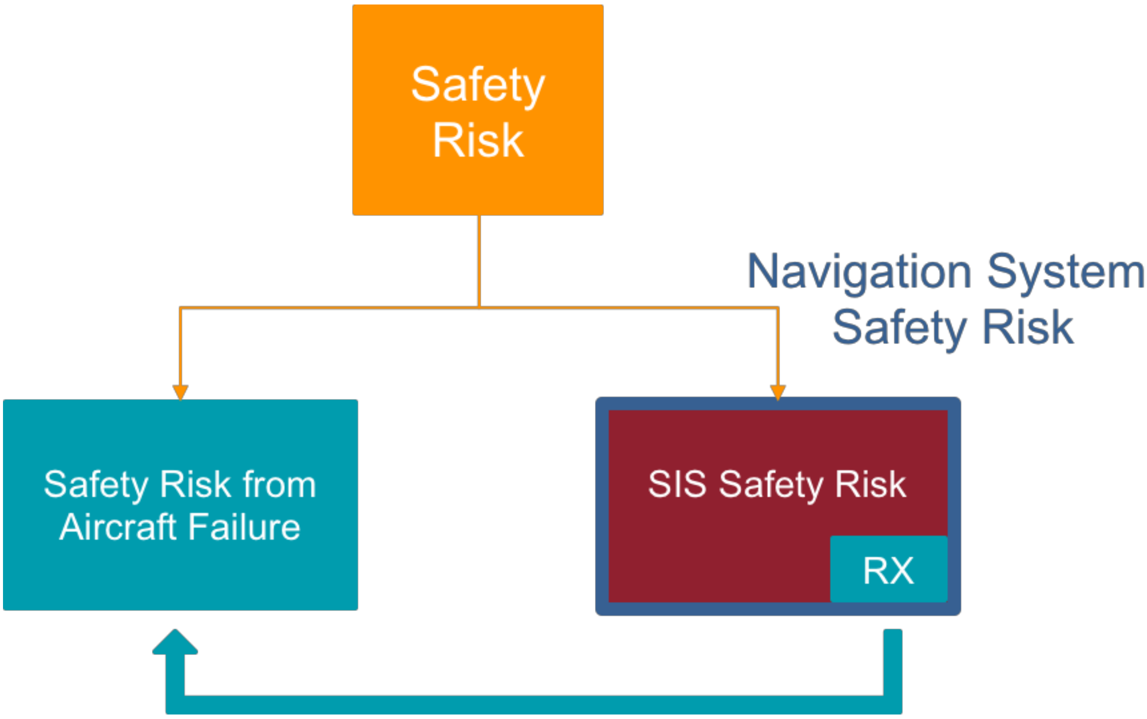

Figure 9 – Safety Apportionment in Civil Aviation (Simplification)

2.7.1.1 Accuracy

(Absolute) **Accuracy** The degree of conformance between the estimated position and the true position of the craft (vehicle, aircraft, vessel) at a given time (95% 2σ)

This definition is the most conservative and most likely definition to be used in the rail industry.

Predictable Accuracy The accuracy of a PNT systems position solution with respect to the charted solution

This definition is close to absolute accuracy and could be used in rail if the chart suffers from systematic errors which are equivalent to those of the surveyed railtrack network.

Repeatable Accuracy The accuracy which a user can return to a location whose coordinate has been measured at a previous time

Not to be used in the rail industry since systematic errors are not constant with time.

Relative Accuracy The accuracy with which a user can measure position relative to that of another user at the same time

Unlikely but possible application in moving block signalling system, in particular under the advanced virtual coupling concept.

Any accuracy requirement applies to all aircraft at all times and locations under the relevant operating conditions.

2.7.1.2 Integrity

2.7.1.2.1 Integrity Definition

The following definitions are used to define civil aviation's integrity concept.

Integrity The measure of trust that can be placed in the information provided by the PNT system, including the ability to provide timely warnings when the system should not be used

Time-to-Alert (TTA) Allowable time from the onset of an unsafe condition to the alarm indication.

Integrity Risk (IR) The allowable probability of an undetected unsafe condition over the period of operation of interest

Alert Limit The maximum allowable positioning error for which the aircraft remains safe.

Positioning Failure The state in which a positioning error (PE) exceeds the alert limit (AL).

HMI Hazardous Misleading Information (HMI) is defined as the state of a positioning failure occurring and no alert being issued (within the TTA).

The integrity requirement may be quantified as follows:

$$P_{hmi} = P(PF\&NA) < IR \quad (14)$$

2.7.1.2.2 Integrity per Sample

Actually equation (14) is a simplification since both the positioning failure and no alert conditions are states, defined for a particular point in time. A more precise definition may make two changes. Firstly, the PF and NA conditions may be understood to be states present for a duration at least as long as the TTA. Secondly, the requirement is over the duration not at each epoch.

$$P\left(\bigcup_{k=1}^{k=K} P(hmi@k)\right) = \sum_{k=1}^{K} P(hmi@k|no\ hmi@1\ to\ k-1) < IR \quad (15)$$

If the probabilities are independent between k then the relation may be expressed as a product:

$$\sum_{k=1}^{K} P_{hmi}(k)\left(\prod_{j=1}^{k-1} 1 - P_{hmi}(j)\right) < IR \quad (16)$$

Where K is the number of epochs during the period of operation.

Often, to simplify, since $P_{hmi}(j)$ are small numbers, then the conservative bound may be used.

$$\sum_{k=1}^{K} P_{hmi}(k) < IR \quad (17)$$

When the probability of HMI is correlated in time (between k), one approach is to consider a subset of time points k_n representing N independent tests.

$$\sum_{n=1}^{N} P_{hmi}(k_n) < IR \tag{18}$$

Using this approach a requirement for each independent test may be determined which applies to each epoch during the period of operation.

$$P_{hmi}(k) < \frac{IR}{N} \tag{19}$$

The correlation of P_{hmi} over k depends upon the threat considered and the monitoring solution, since these elements determine the positioning failure and no alert conditions, as well as the temporal properties of noise in the system. In the SBAS case, the aircraft protection level is designed to protect against positioning failures under the fault free condition accounting for nominal errors only. As shown in Table 11, the terminal area operations allowable integrity risk is $10^{-7}/h$. Under the assumptions taken for current single frequency SBAS (see A.99 and A.100) the dominating error term is the ionosphere with a correlation time of 6 minutes. Therefore, the allocated integrity risk is:

$$P_{hmi}(k) < \frac{IR_0}{10} = 5 \times 10^{-9} \tag{20}$$

Where IR_0 is half the full integrity requirement as described below. Note that in the faulty case independence of the P_{hmi} is also a function of the fault bias.

2.7.1.2.3 *Integrity Allocation*

Civil aviation has implemented three augmentation systems in order to meet the integrity requirements specified in the previous sections. Considering that system failures may then be a result of the payload, the constellation control segment, the augmentation system, the environment, then the total system may be partitioned into states H_i.

Law of total probability says (Zwillinger and Kokoska 2000):

$$P_{hmi} = \sum_{i=0}^{N_H} P_{hmi|H_i} P_{H_i} \tag{21}$$

This allocation is most often handled prior to the allocation with respect to time detailed in section 2.7.1.2.2. There are two methods for handling this partition. Firstly, a multiple hypotheses approach may be taken in which the total probability of HMI is determined at the aircraft and compared to the total integrity risk.

$$P_{hmi} = \sum_{i=0}^{N_H} P_{hmi|H_i} P_{H_i} < IR \tag{22}$$

Alternatively the total risk may be partitioned to specific states such that:

$$IR = \sum_{i=0}^{N_H} IR_{H_i} \quad (23)$$

Parts of the system are then allocated the responsibility to check that for certain i that (see Figure 10):

$$P_{hmi|H_i} P_{H_i} < IR_{H_i} \quad (24)$$

Civil aviation has mostly employed the second approach (Roturier, Chatre, and Ventura-Traveset 2001). However, recent developments under the Advanced RAIM (ARAIM) concept are based on the multiple hypothesis approach (Blanch et al. 2015).

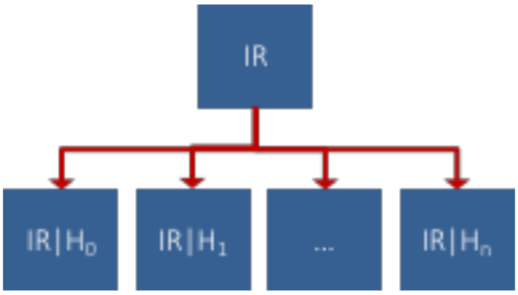

Figure 10 – Integrity Risk Allocation

2.7.1.2.4 *Protection Level*

One further topic to consider under the banner of civil aviation's integrity is the protection level. The protection level is a key concept since it places a bound (for H_i) on the maximum undetected error that may occur with the allocated probability (ICAO 2006).

The protection level is designed such that there is an equivalence between:

$$P_{hmi|H_i} P_{H_i} < IR_{H_i} \quad (25)$$

And the relation:

$$PL_{H_i} < AL \quad (26)$$

In other words, under the system state H_i, when the protection level does not exceed the alert limit, the system is safe for that particular case H_i.

2.7.1.2.5 *Specific Risk vs Average Risk*

Aviation employs two different notions of risk when developing requirements and integrity solutions. They are namely specific risk and average risk.

Specific risk has been defined as follows (Pullen, Walter, and Enge 2011):

The probability of unsafe conditions subject to the assumption that all credible unknown events that could be known occur with a probability of one.

An alternative definition is given in (Clark and DeCleene 2006):

The approach integrity requirements apply in any one landing and require fail-safe design. If the specific risk on a given approach is known to exceed this requirement, the operation should not be conducted.

In civil aviation, a specific risk approach has been taken for integrity developments, whilst average risk is agreed to be valid for continuity applications. Average risk is defined as follows (Pullen, Walter, and Enge 2011):

The probability of unsafe conditions based upon the convolved estimated probabilities of all unknown events.

The essential difference here is that certain conditions may be considered random, since they are firstly not predictable and secondly the distribution is known. One clear example is the multipath experienced by a GNSS receiver as a result of reflections from the fuselage. In other cases, it may be that the distribution is unknown, for example in the case of ionospheric front magnitudes (Datta-Barua, Bust, and Crowley 2010) or that the error values might be predicted (Montloin et al. 2013).

2.7.1.3 Continuity and Availability

The continuity of the system is a critical performance parameter for aviation. It is defined as (ICAO 2006):

Continuity of a system is the ability of the system to perform its function without interruption during the intended operation i.e. the probability that the specified performance will be maintained for the duration of a phase of operation.

The continuity requirement should be applied as applying the average risk of loss of service.

Availability The percentage of time that the services of a system are available (accuracy and integrity are met, in some interpretations also continuity)

2.7.1.4 SIS Requirements Summary

Figure 11 presents the four SIS requirements and their respective parameters (note that protection level is not usually used to express the required integrity but is used for the receiver compliance assessment, so in practice, the protection level is the maximum error that may be allowed with the probability equal to the integrity risk requirement).

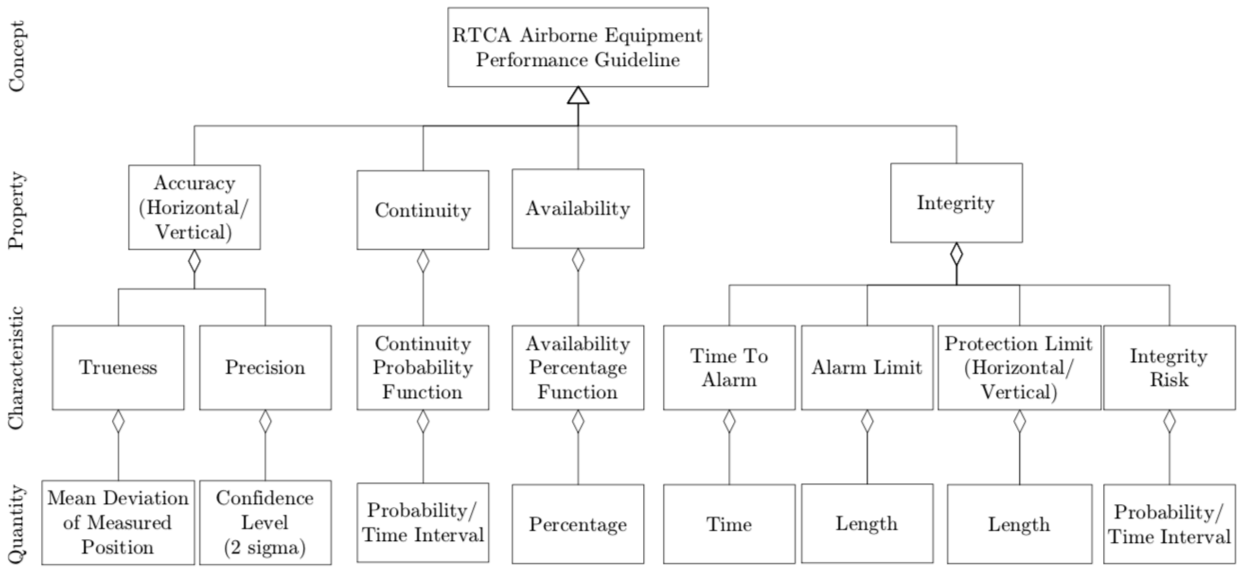

Figure 11 – SIS Requirements

2.7.2 RAMS Requirements

2.7.2.1 *Safety*

The primary goal of any system which supports human transportation, is that it be safe. Safety and safety functions are well-defined within the RAMS framework used in the rail industry. The following definitions are employed.

Safety Freedom from unacceptable risk of harm

Risk The probable rate of occurrence of a hazard causing harm and the degree of severity of harm

$$Risk = probability\ of\ occurence \times severity\ of\ harm$$

Safety Integrity Likelihood of a system satisfactorily performing the required safety functions under all the stated conditions within a stated period of time

The safety integrity is therefore a probabilistic term relating to the likelihood that the system remains safe given that safety functions are operational. It is specified over a period of time.

SIL Safety Integrity Level

THR Tolerable Hazard Rate

2.7.2.2 *Reliability, Availability and Maintainability*

Section 2.7.2.1 presented the requirement relating to safety integrity. However, safety is not the only performance metric of relevance. The rail industry also defines some quality of service metrics under the reliability, availability and maintainability (RAM) framework. These are defined as follows:

Reliability The probability that a system can perform a required function under given conditions for a given time interval

$R = e^{-\lambda T}$ for an interval T if failure rate λ is constant

MTTF Mean Time To Failure (MTTF) which for a constant rate is equal to $1/\lambda$

Maintainability The probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval when maintenance is performed under stated conditions and using stated procedures

$$M = 1 - e^{-\mu T} = 1 - e^{-\frac{T}{MTTR}}$$

MTTR Mean Time To Repair $MTTR = \frac{1}{\mu}$

Availability The ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval

$$A = \frac{MTTF}{MTTF+MTTR} = \frac{\mu}{\mu+\lambda}$$ (If constant rates)

Up State The state of being available (nominal state, following any maintenance after failure)

Down State The state of being unavailable following a failure (reliability event)

Dependability Collective term used to describe the availability performance and its influencing factors

Note that there is a cyclical relationship between availability, reliability and maintainability in the case that the failure and maintenance rates are constant. Such an assumption regarding the rates λ and μ is reasonable for electronic and mechanical components where the impact of the bathtub type curve is mitigated through specified design life.

The overall quality of service may be measured in a variety of metrics depending upon the application and intended service. For example, a railway may set an objective on the percentage of trains arriving with delay less than X minutes as a result of the PNT function

Note that under the RAMS formulation a failure is any event which leads to an outage

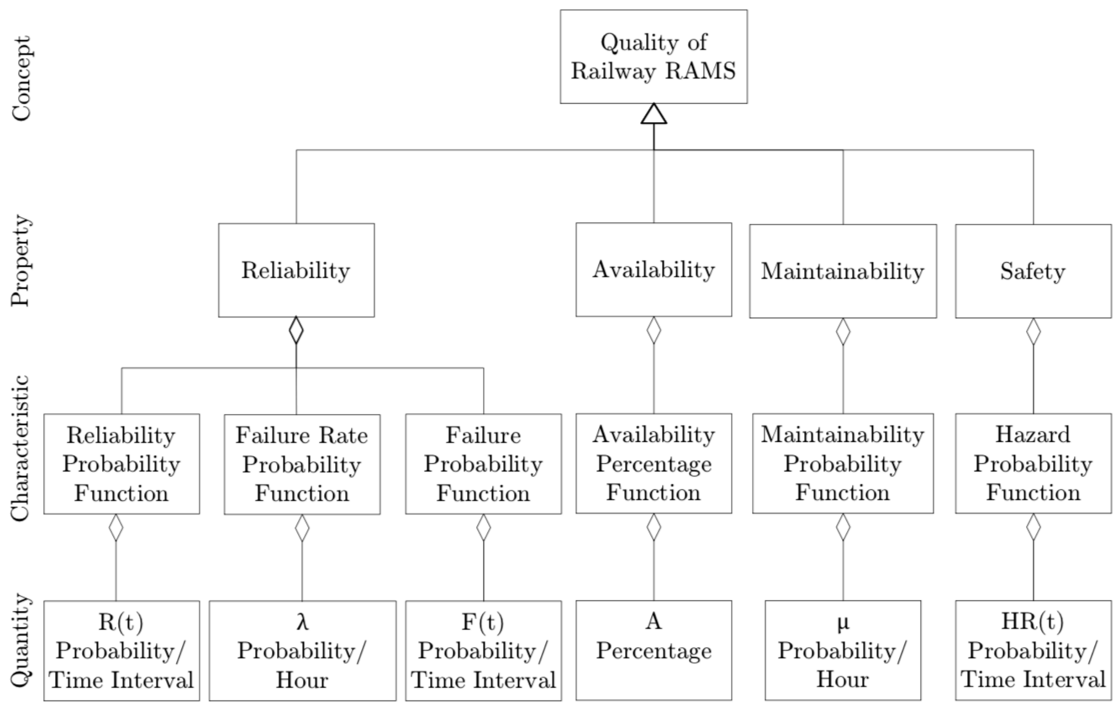

Figure 12 – RAMS

2.7.3 Mapping of RAMS and SIS Requirements

2.7.3.1 Overview of States

Under the RAMS framework, the system may be in three states:

- Available (Up State) and Safe

- Available but unsafe
- Unavailable (Down State)

The transition from the available and safe to the unsafe condition must be guaranteed to occur with a rate less than the THR. Requirements (RAM) are also made on the percentage of time the system spends in the down state (unavailable) and on the likelihood of this transition (failure rate) as well as the time taken to repair the system (repair rate). These relations are shown in Figure 13.

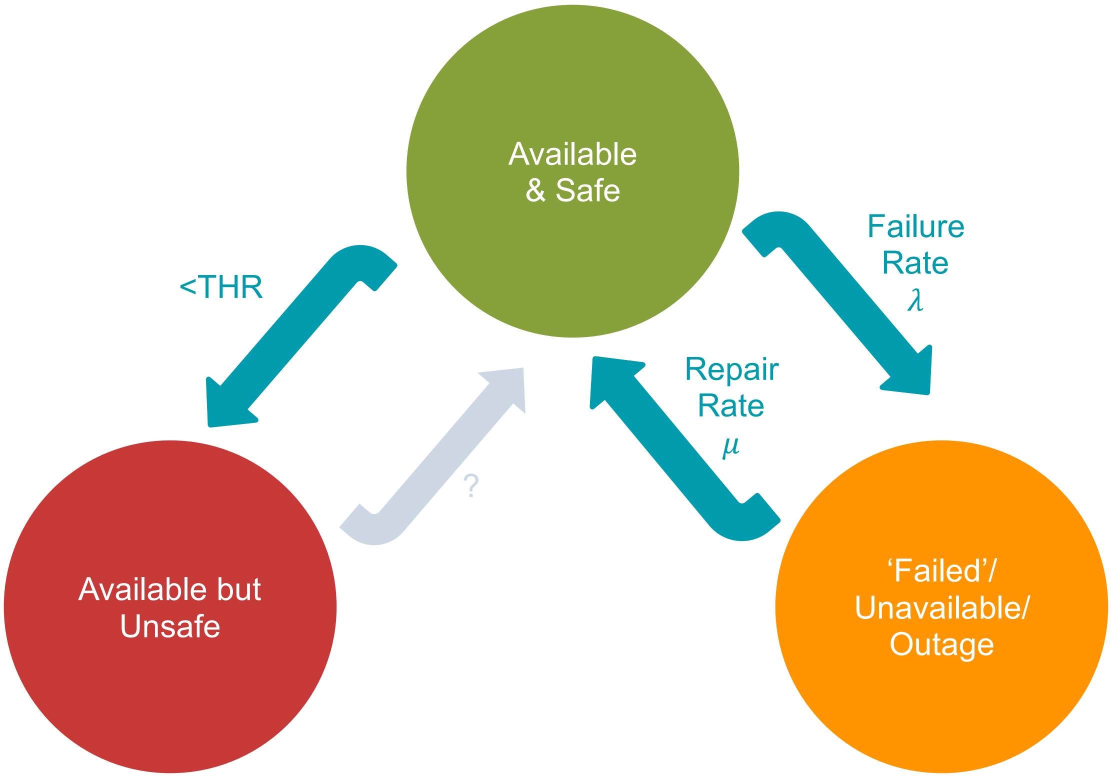

Figure 13 – RAMS States

2.7.3.2 *Safety Perspectives*

In section 2.7.1 it was noted that there is a critical mapping between the operational requirements, defined as SIS requirements in civil aviation and the algorithmic requirements allocated to components (or subsystems). The reason for this, is that certain requirements are assessed in real-time, notably the SIS integrity. This is necessary since the actual integrity (denoted P_{hmi}) varies with time (constellation geometry and error models) and the worst-case performance is insufficient. If it were proven that under worst case conditions, the level of integrity is sufficient, then no real time monitoring would be required, only a design level proof of safety, as confirmed by validation activities. Applications of GNSS to rail positioning inevitably suffer from the same temporal performance variation and as such real time assessment is needed.

The first step that the rail industry must take is a decision as to what high level requirements will take precedence and secondly a mapping must be performed from such high-level requirements to the component level or algorithmic level requirements which are applied at each sample. This mapping depends upon the architecture of the GNSS centric positioning solution and thus cannot be completed within T1.2 of ASTRail but only at the completion of WP1. However, initial steps may be taken to setup the process in advance, as will be described hereafter.

2.7.3.3 *Existing Mappings*

Some previous work has looked to map the SIS performance requirements used in civil aviation to the RAMS requirements used in the rail industry. Figure 14 shows such a simple mapping from (Lu 2014). There appears a natural relationship between GNSS continuity and RAMS reliability, since both deal with the rate of occurrence of observed failures (or outages). However, continuity is designed to protect against unexpected failures due to the impact this places on flight crew and ATC workload and stress. It is a safety issue and the result is a loss of continuity. RAMS reliability rather deals with the frequency of being unavailable and relates to the quality of service, where poor reliability leads to delays and unsatisfied customers of the rail network.

There is a natural correspondence in availability, although in light of the differences with regards to continuity, it should be highlighted that GNSS availability is often measured by the predictable availability since performance varies with time as the constellation geometry cycles. Prediction of an up or down state is not defined as plausible under the railway RAMS framework.

The rail industry uses *integrity* in two forms, both for train integrity – the train is connected – and the safety integrity relating to safety including the positioning function and movement authorities. It is this safety integrity which is often translated to the GNSS integrity. This equivalence will also be used here, but care will be taken regarding the mapping between algorithmic requirements relating to the validity of the protection level and the system level requirements in terms of THR (for safety integrity).

Finally, the accuracy of the GNSS solution is key in specifying the nominal level of positioning performance. Whilst no direct equivalent exists in the RAMS framework, accuracy requirements are specified in other parts of the rail standards.

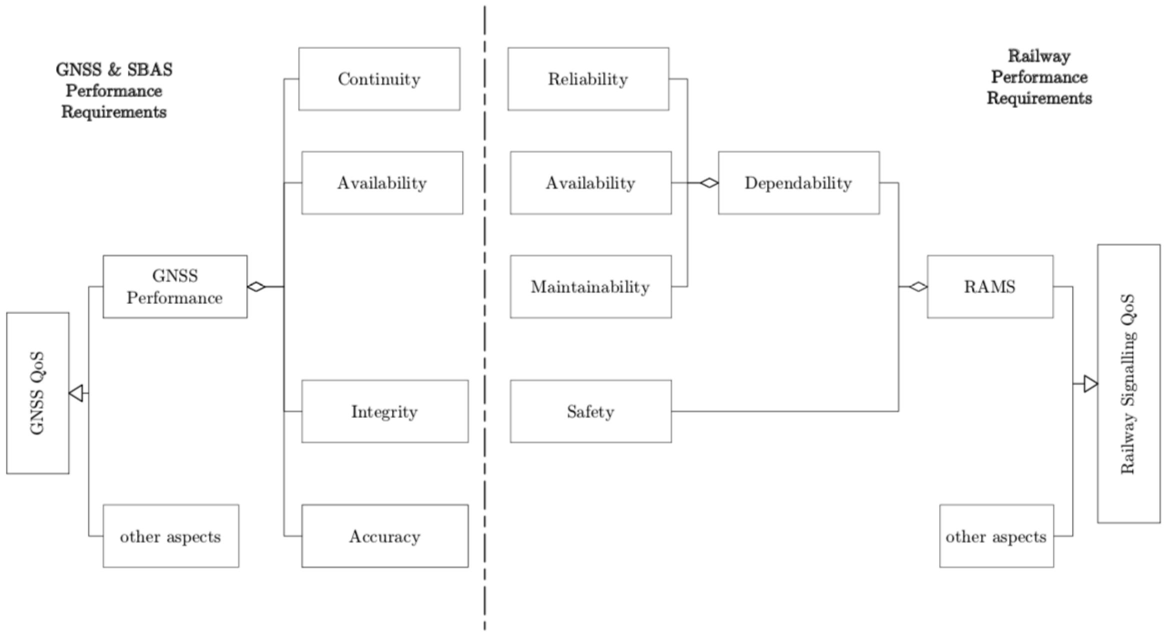

Figure 14 – Initial Mapping (Lu 2014)

2.7.3.4 *ASTRail Proposition for RAM aspect*

The proposal in ASTRail is to take a different approach to attempting to match Civil Aviation and RAMS railway requirements. Instead, the methodology will be to derive receiver requirements through an assessment of the expected RAMS (as well as the dependability and quality of service). Naturally, GNSS integrity will still be mapped to safety integrity, but accounting for the correlation time as described in 2.7.1.2.2.

In order to assess the RAM aspect of RAMS for GNSS in rail, the possible causes of a *failure* or *outage* in the language of GNSS in civil aviation must be captured. Table 17 presents such events.

Name	Cause	Repair Action	Predictable
Slow Geometry	Increased protection level as a result of slow changes in the satellite geometry as a result of nominal satellite orbital motion	Employ odometry / Wait for improved geometry / Revert to degraded mode with lower speed and larger protection level to exceed the alert limit	Yes
Setting Satellite	Satellite setting by passing below the horizon leading to one less satellite and thus worse geometry	Employ odometry / Wait for improved geometry / Revert to degraded mode with lower speed and larger protection level to exceed the alert limit	Yes
Satellite loss due to planned manoeuvre/maintenance	Satellite is set to unhealthy for a period of nominally up to a few hours whilst constellation control segment performs necessary actions. A NANU in the case of GPS (or equivalent for other constellations) is provided.	Employ odometry / Wait for improved geometry / Revert to degraded mode with lower speed and larger protection level to exceed the alert limit	Yes
Masking	Loss of tracking of a signal due to masking from buildings resulting in geometry change and increased protection level	Employ odometry / Wait for improved geometry / Revert to degraded mode with lower speed and larger protection level to exceed the alert limit	Yes
False Alarm	Trackside or Onboard integrity monitoring incorrectly detects a fault due to increased residual noise errors leading to a failed attempt to exclude the responsible measurements	Employ odometry / Wait for improved geometry or end of perceived failure / Revert to degraded mode with lower speed and larger protection level to exceed the alert limit	No
Satellite Failure	Trackside or Onboard integrity monitoring correctly detects a satellite payload or ground segment fault leading to a failed attempt to exclude the responsible measurements	Employ odometry / Wait for improved geometry or end of perceived failure / Revert to degraded mode with lower speed and larger protection level to exceed the alert limit	No
Ionospheric Gradient	Trackside or Onboard integrity monitoring correctly detects the impact of an ionospheric gradient fault leading to the removal of measurements and increased protection level above the alert limit	Employ odometry / Wait for improved geometry or end of perceived failure / Revert to degraded mode with lower speed and larger protection level to exceed the alert limit	No
Interference	Loss of tracking of a signal due to interference resulting in geometry change and increased protection level	Employ odometry / Wait for improved geometry or end of perceived failure / Revert to degraded mode with lower speed and larger protection level to exceed the alert limit	No
Jamming	Loss of tracking of a signal or signals due to intentional jamming resulting in geometry change and increased protection level or unavailable position solution	Employ odometry / Wait for improved geometry or end of perceived failure / Revert to degraded mode with lower speed and larger protection level to exceed the alert limit	No

Scintillation	Loss of tracking of a signal or signals due to ionospheric scintillation resulting in geometry change and increased protection level or unavailable position solution	Employ odometry / Wait for improved geometry or end of perceived failure / Revert to backup frequency / Revert to degraded mode with lower speed and larger protection level to exceed the alert limit	No
Shadowing	Loss of tracking of a signal due to shadowing from trees and other partially diffuse materials resulting in geometry change and increased protection level	Employ odometry / Wait for improved geometry or end of perceived failure / Revert to degraded mode with lower speed and larger protection level to exceed the alert limit	No
Error Model Change	Modification of the broadcast standard deviations relating to corrections in a DGNSS architecture and thus leading to increased protection levels	Employ odometry / Wait for improved geometry or end of perceived failure / Revert to degraded mode with lower speed and larger protection level to exceed the alert limit	No

Table 17 – GNSS Availability Outages/Failures

In light of the array of events given in Table 17 the following instantaneous availability probability equation may be given.

$$p(d;s) = \sum_{k=0}^{K} p_k(V_k;s)\delta(V_k,s,\dots) \quad (27)$$

Where:

- $\boldsymbol{s} = [\boldsymbol{x}, t]$ the space-time geometry with $\boldsymbol{x}$ is the true train location and t is the time
- V_k is the set of satellites (where all such subsets are numerated by k up to K
- δ is the binary availability function

Equation (27) may be equally stated in discrete time for a particular train movement. For now, the continuous space-time model is used.

The satellite subset parameter V_k may be further decomposed with respect to the events listed in Table 17.

$$p_k(V_k;s) = \sum_{l=0}^{L} p_{kl}(V_k;s,l) \quad (28)$$

Where :

$p_{kl}(V_k;\boldsymbol{s},l)$ is the state probability of satellite set V_k being available as a result of the phenomena l which is the index up to L of the events (including combinations of multiple events) in Table 17.

The proposed way forward with respect to this assessment is to determine an expected RAM performance level by taking the average of equation (27) over the space-time geometries. Since reliability and availability are not safety critical, it is acceptable to apply and average risk method to this.

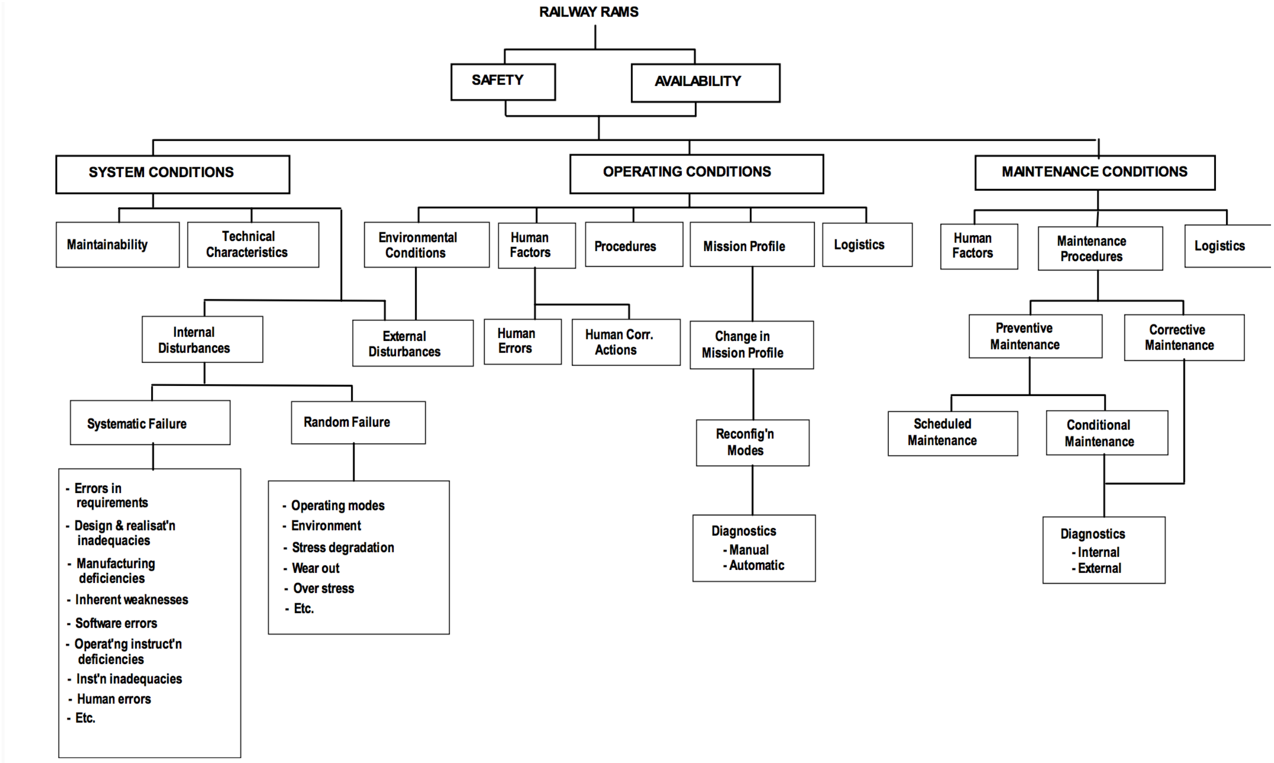

Figure 15 – Railway RAMS Conditions

It may be that p_{kl} is inlfuenced by some deterministic elements at certain spacetime geometries, this may be taken into account in the listing of V_k. Note that $p_{kl}(V_k; \boldsymbol{s}, l)$ are for the most part not under the control of the rail system designer. They are not faults within the system which is being designed. Instead they must be considered events borne of the ‘environment’. Figure 15 presents a typical set of conditions which influence the RAMS performance. They are split into the categories of *System, Operating* and *Maintenance* conditions. Under current rail and train systems engineering methods, the failures and maintenance activities occur predominantly within the system. However, since many parts of the GNSS service are not under the control of the rail system designer, such parts must be considered nominally as the *environment*. Consider Figure 16 which presents an abstraction of the RHINOS project concept described in 3.1.19 using the virtual balise concept from 3.1.17. Notably the components not under the control of the rail system designer are marked as *environment* in purple. This includes the SBAS data provided by EGNOS.

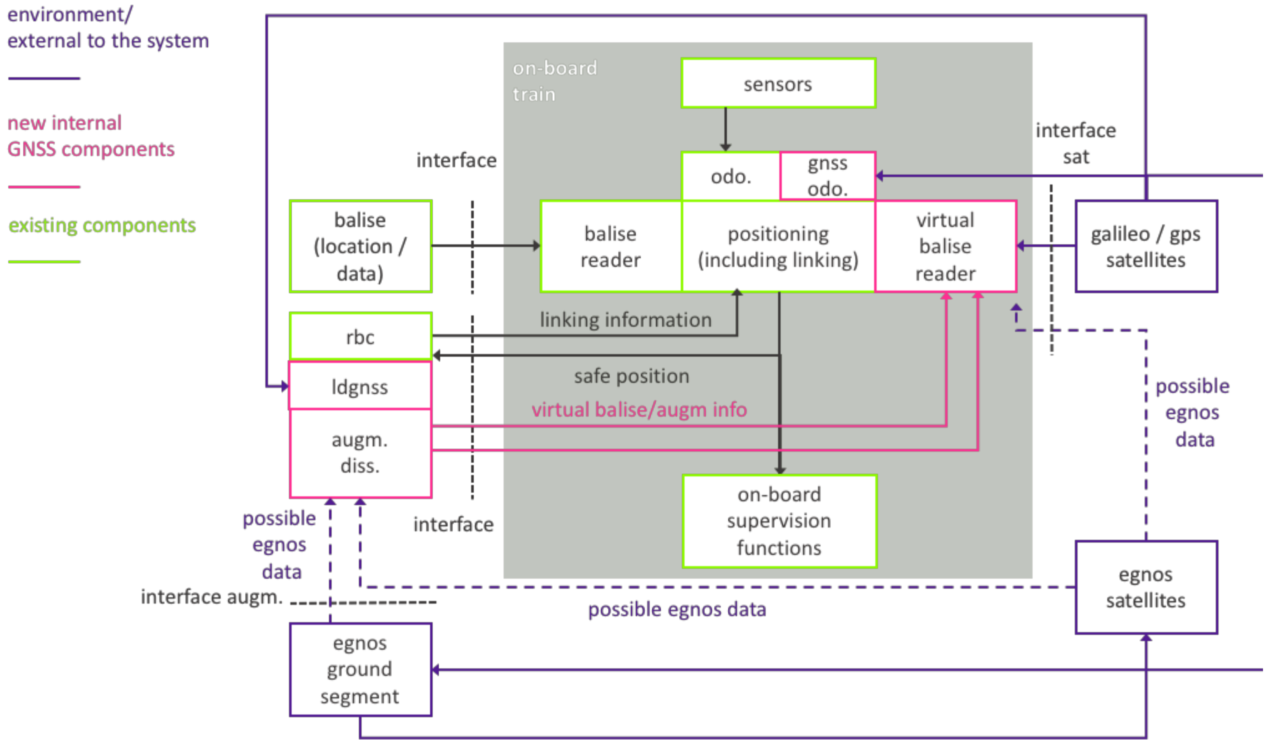

Figure 16 – System Partition

2.7.3.5 Integrity Mapping

There are three scenarios for the application of GNSS in rail. The first is that the GNSS is only used as part of a virtual balise reader in order to provide a position fix at the virtual balise locations and thus determine the passing of the virtual balise. The second scenario is that the virtual balise concept is not employed and in place the GNSS is integrated more centrally within the localisation unit, determining a position fix which is used at each communication cycle with the trackside infrastructure. This is a more traditional use of GNSS with respect to other transport domains but does not respect the legacy demands of the rail industry. Thirdly, the GNSS might be used as both virtual balise reader and as an aid to odometry. As the baseline, the first scenario is considered within ASTRail.

In order to develop the integrity mapping to the GNSS receiver, it will be necessary to look more closely at the hazard. This work has been attempted in T1.1 of WP1 but the conclusion has been to return to the question in T1.5 once more steps have been taken with regards to the hazard analysis. However, some insights are given here.

1. The duration of failure is important

The derivation of requirements for the balise and balise reader given in UNISIG Subset 88 Part 3 (UNISIG, n.d.) are a function of the duration of hazardous failure events.

2. The dependency of failure between virtual balises is important

The use of linking information is critical to mitigate the impact of a missed or *deleted* information point (balise or balise group). However, for GNSS, the failure is not to miss the virtual balise but to have the incorrect position. Therefore, at the next virtual balise, it is not possible to fully mitigate a fault at the previous virtual balise. It may be that the position error is now reduced. However, note that positioning integrity failures in GNSS are often correlated in time. A more thorough analysis will be performed in later tasks. For now, note that the effective number of samples n_{eff} that occur during a 1-hour period, which may need to be computed for both faulty states and fault-free states is given as:

$$n_{eff} = \frac{P\left(\bigcup_{i=1}^{i=n} h_{vbr,i}\right)}{P\left(h_{vbr,1}\right)} \tag{29}$$

Where $h_{vbr,i}$ is the hazardous failure event at virtual balise reading i of n over the hour. The event of the denominator is the single epoch hazardous failure event $h_{vbr,1}$.

Note that when the errors are highly correlated in time then $n_{eff} \cong 1$ since then events expressed in the numerator depend strongly on each other. However when error sources with short correlation times are dominant then n_{eff} can be particularly large. This risk cannot be divided indefinitely though, and since only at the virtual balise reading points is it relevant to assess the integrity (when are position solution is employed), the minimum of the effective number of samples and the number of balises read per hour (note this may depend on the speed of the train) is used.

$$n_{alloc} = min\left(n_{eff}, \bar{n}_{balise}\right) \tag{30}$$

3. The total balise risk allocation is assigned to the virtual balise reader

Note that in the virtual balise case there are no transmission errors which can lead to missing a balise. However, some architectures (see section 3) involve a certain level of trackside infrastructure providing GNSS corrections. Any risk budget may be further allocated amongst on-board and trackside components.

This number n_{alloc}, is then the number of samples over which to allocate the risk in order to obtain a requirement for the GNSS positioning function on the train. Note that under a multiple hypothesis approach, this derivation would be more complex. The effective requirement for the integrity of the GNSS positioning function is then:

$$P(hmi_{vbr})|_i \leq \frac{10^{-9}}{n_{alloc}} \tag{31}$$

The use and role of the above equation will be further elaborated in T1.4 and T1.6. Clearly $\bar{n}_{balise}$ is an assumption based on the operational framework, whilst n_{eff} will depend on the positioning architecture and the positioning integrity monitoring architecture. In section 3 that follows, the positioning architectures proposed in previous work is addressed.

3 Technical State of the Art

3.1 Review of Previous Studies

Name	Title	Description of Work	References
3inSat	Train Integrated Safety Satellite System	3InSat is a project aiming at developing and verifying a new satellite-based platform, based on the ASTS ERTMS system, to support the train localisation function. This satellite supported solution is not yet available on the market because of the very challenging safety requirements (Safety Integrity Level 4 SIL4 requirement) that a railway signalling system shall comply with.	(Rispoli 2016)
APOLO	Advanced Position Locator system	The APOLO solution is based on GNSS receivers (GPS with differential EGNOS corrections), integrated with inertial sensors and on-board odometers, in an "intelligent" system of mutual calibration, error filtering and error correction.	(APOLO 1999)
DITPOS RAIL	Demonstrate the Integrity of Train Positioning at the Railway	Development of an integrated solution for train positioning that incorporates tailor-made integrity calculations for future safety critical train based location systems.	(DITPOS RAIL 2015)
EATS	ETCS Advanced Testing and Smart Train Positioning System	The EATS project aimed to develop new on-board location systems by combining Global Navigation Satellite Systems (GNSS), Universal Mobile Telecommunications System (UMTS) and Global System for Mobile Communications – Railway (GSM-R) technologies, as well as including multi-antenna configurations on the train. This would allow for the migration from ETCS level 2 to level 3 which would improve the overall efficiency of European railways.	(EATS 2016)
ECORAIL	EGNOS Controlled Railway Equipment	The EGNOS Controlled Railway Equipment (ECORAIL) project deals with the implementation of satellite navigation into the railway domain to demonstrate the feasibility and benefits of GNSS in combination with the European Train Control and Rail Traffic Management System (ETCS/ERTMS).	(ECORAIL 2006)
ERSAT	ERTMS on SATELLITE	The main ERSAT EAV objective is to verify the suitability of EGNSS as the enabler of cost-efficient and economically sustainable ERTMS signalling solutions for safety railway applications.	(ERSAT EAV 2015)
GADEROS	Galileo Demonstrator for Railway Operation System	Study sponsored by the European Commission. The purpose is to make use of the Galileo Global Navigation Satellite System (GNSS) when it becomes functional. Current terrestrial railroad tracking systems require huge distances as safety margins. This leads to lower freight and passenger throughput.	(GADEROS 2004)
GALOROI	Galileo Localisation for Railway	GaLoROI enables an autonomous on-board safe localisation of trains. The liable position information will be safe according to legal requirements and railway standardisation with a SIL equal or higher	(Becker 2014)

	Operation Innovation	than 3, precise and track selective. GaLoROI will enable a more cost-efficient localisation of trains and will therefore be the base for more cost-effective railway operations life cycle in order to supply an emerging mass market of railway train control.	
GIRASOLE	Galileo Integrated Receiver for Advanced Safety of Live Equipment	The GIRASOLE project aims at developing a safety-of-life combined GPS/Galileo receiver product to be used in rail, aviation and maritime applications.	(GIRASOLE 2005), (Marradi et al. 2007)
GRAIL	GNSS introduction in the RAIL Sector	GRAIL will introduce GNSS technology in the railway domain for different applications in Europe. Technology developments following different paths has prevented the use of a common approach, which would allow interoperability of the technical solutions at different system levels in similar applications, and the reusability of products for different applications. The project proposes a strategy, consistent with the current deployment process of ERTMS/ETCS in Europe, for a smooth integration of GNSS into control and command applications and particularly in signalling.	(GRAIL 2005), (Jenkins, Urech, and Prieto 2007)
GRAIL-2	GNSS-based enhanced odometry for Rail	The objective of GRAIL-2 is to define, develop and validate an advanced, GNSS-based railway application (enhanced odometry) in the High Speed Railway Lines environment. Starting from the work done in the GRAIL Project, GRAIL-2 goes further in the implementation and testing of this application, thus achieving a system closer to a final product.	(González et al. 2012), (Marradi et al. 2012)
INTEGRAIL		The aim of INTEGRAIL is to open the way for profitable use of the EGNOS signal in safety-critical railway traffic management and control. The system aims at achieving significant improvements for the rail traffic operator with respect to cost, redundancy and reliability of the present train speed measurement systems, which are based on odometers, by adding satellite navigation information and the integrity information offered by EGNOS.	(INTEGRAIL 2004a), (INTEGRAIL 2004b)
IRISS	Intelligent Railways via Integrated Satellite Services	IRISS will develop and demonstrate a pre-commercial service with a British train operator involving a number of applications including tracking and tracing of rail stock on routes across the UK. Satellite communications will be used to provide connectivity in rural areas where there is a lack of terrestrial communications infrastructure.	[Dumville, 2011], [Kruijff et al., 2011]
LOCASYS		The purpose is to systematically analyse the dependability of the performance of GNSS enabled positioning systems and test their feasibility for use in position and speed determination.	(Thomas et al. 2008)
LOCOPROL/LOCOLOC	Low Cost satellite based train location system for signalling and train Protection	LOCOPROL provides an ideal solution filling the gap between the very low cost traditional solutions characterised by a very poor level of functionality and safety, and the very expensive ETCS based solution adapted for the main lines.	(LOCOPROL 2005), (LOCOLOC 2004)

	for Low density traffic railway lines		
M-TRADE	Multimodal Transportation supported by EGNOS	M-TRADE is the European platform to promote EGNOS and Galileo in the freight transport community. The project identified applications reflecting the user needs and maximising EGNOS/Galileo differentiators. It also analysed and validated the use of EGNOS commercial services for remote assets and the tracking and tracing of goods	(M-TRADE 2007)
NGTC	Next Generation of Train Control Systems	The main scope of the NGTC project is to analyse the similarities / differences of the required functionality of ETCS and CBTC systems, and to determine the achievable commonality level of architecture, hardware platforms and system design.	(Gurnik 2016a), (Gurnik 2016b)
P. Brocard PhD	Integrity Monitoring for Mobile Users in Urban Environment		(Brocard 2016)
RHINOS	Railway High Integrity Navigation Overlay System	Use of EGNOS to support safety-critical train localization for train control in emerging markets. Includes development of double-difference multipath monitor.	(Neri, Rispoli, and Salvatori 2015), (Neri et al. 2016), (RHINOS 2017), (Ales 2017) (Capua et al. 2017) (Grosch, Martini, and Garcia Crespillo 2017) (Roberts 2017), (Neri 2017)
RUNE	Railway User Navigation Equipment	The RUNE project (Railway User Navigation Equipment) is aimed at demonstrating the use of GNSS Integrity and Safety of Life service characteristics for defining a satellite-based system to perform train location for safe railway applications.	[Albanese et al., 2005], (Marradi, Albanese, and Di Raimondo 2008)
SafeRail	Improving Safety at Railway Level Crossings	The study is part of ESA's Integrated Applications Promotion (IAP) programme to improve railway level crossing safety using an integrated system, which will explore ways to enhance safety by combining terrestrial technologies with various space assets, such as telecommunications, earth observation and navigation.	(SafeRAIL 2014)
SATLOC	Satellite Based Operation and Management of Local Low Traffic Lines	The project addresses the development and demonstration of innovative GNSS Safety concepts in live rail applications of low traffic lines (LTL). The application contributes to the adoption of EGNOS in rail primary safety and paves the way to the introduction of Galileo in the rail safety domain. SATLOC aims at introducing GNSS train positioning and speed determination with SoL characteristics in all critical operations of a railway line. The project	(Barbu and Marais 2014), (Gradinariu, Stadlmann, and Nodea 2016), (UIC 2017)

		includes the development of new rail integrated operational concept, software, hardware, services and datasets compatible with the current evolution of the rail signalling and rail standards.	
STARS	Satellite Technology for Advanced Railway Signalling	The aim of this project is to fill the gap between ERTMS needs for safety critical applications and EGNSS services, through a characterisation of the railway environment and of GNSS performances assessment in that environment.	(Stamm and Gurnik 2017), (Gurnik and Stamm 2017)
TR@IN-MD	Le TRAnsport INtelligent par fer des Marchandises Dangereuses	The TR@IN-MD project aims to develop and experiment in real conditions an innovation system able to better manage the hazardous goods traffic by providing tracing facilities with GPS/GSM/GPRS balises and remote real-time diagnosis with the help of innovative sensors embedded on wagons.	(Minary and Lozac'h 2008), (Minary 2008), (Minary 2006)

Table 18 – Review of previous studies

3.1.1 3inSat

The 3InSat demonstration project will develop, test and verify a new satellite-based subsystem, based on the ASTS ERTMS system, for allowing the SIL 4 train localization function at Signaling System Level by using GNSS data. The proposed solution would be based on the ERTMS standard requirements. The requirements will be driven by the market needs and by the accreditation and certification strategy.

The 3InSat project has the objective to introduce a train monitoring and control system, based on the state of the art European and international regulations, adopting satellite based navigation and telecommunications systems. In such a way, the investments required along the rail tracks and the related maintenance activities will be minimized. This investment reduction will enable efficient and safe operations where today this cannot be sustained.

More specifically the objectives are:

- On the positioning part, the 3InSat project is aimed at designing and developing Location Detection System (LDS) prototype using GNSS and ERTMS functions with the objective to guarantee the stringent safety requirements of SIL4 at the signalling system level.

- On the telecommunication part, 3InSat will select and implement an integrated solution based on the combination of SatCom, 2G/3G systems and TETRA to realize a link between the on board train control system (e.g. European Vital Computer EVC) and the ground based infrastructure (e.g. the Radio Block Centre RBC). A Mobile Access Router (MAR) prototype will be developed to manage the multiple wireless links on-board.

Furthermore, 3InSat has the objective to verify these solutions along a regional railways line in Sardinia on 1 test train, where an end-to-end signalling solution will be installed (the installation will not interfere with the existing signalling and will not have any impact on the railway safety).

3.1.1.1 Users and their needs

- The Italian railway infrastructure manager (RFI) and the German one (DB Netz) are reference users and partners of the project; they contribute to the user requirements definition, the tests and the demonstration activities.

- Other reference users is the Australian private mining company Roy Hill which is building a railway line to transport the minerals from the mines to the port and has already awarded a contract to Ansaldo STS. This project is the first in the world that has specified a satellite-based train control system with a SIL4 train localization function at System Level expected to become operational in 2015.

The worldwide potential market for satellite-based train control systems is quite large. The demand is driven by different indicators: the growth of the core signalling market (+6% year), the government directive in the USA and to some extent in Russia, the new private players (the mining sector) and the need to modernize the old and low traffic lines in Europe.

An important market force is the need to deploy new lines in critical areas where the cost of maintenance of the railways is prohibitive (South Africa, Russia, Australia, Brazil). These needs can be fulfilled with the adoption of satellite technologies in order to reduce track-side circuitry and equipment to the largest possible extent.

3.1.1.2 Current Status

System Deployment Acceptance (SDA) was successfully concluded for the Localization Determination System (LDS) and the terrestrial (Vodafone M2M) and the satellite (Inmarsat Broadband Global Area Network (BGAN)) telecommunications subsystems.

In 2014, the TLC Test Campaign (both terrestrial and satellite) was executed on the Cagliari-Olbia line in Sardinia. The EURORADIO over IP protocol was tested on both solutions. A TLC networks performance analysis was conducted showing the performances of the network are compliant with the requirements expressed for low traffic lines. The proprietary augmentation network and the installations on board of the train have been concluded.

Currently, a passenger train equipped with the On Board LDS (operating in shadow mode) is running along the railway line.

A demonstration campaign of the integrated solution is expected to take place in Sardinia in Q1 2015. In Q3 2015 a complete and certifiable signalling solution will be deployed and tested again in Sardinia making use of the GNSS based LDS and the Satcom+2G/3G+TETRA+MAR.

3.1.1.3 3inSat Project Architecture

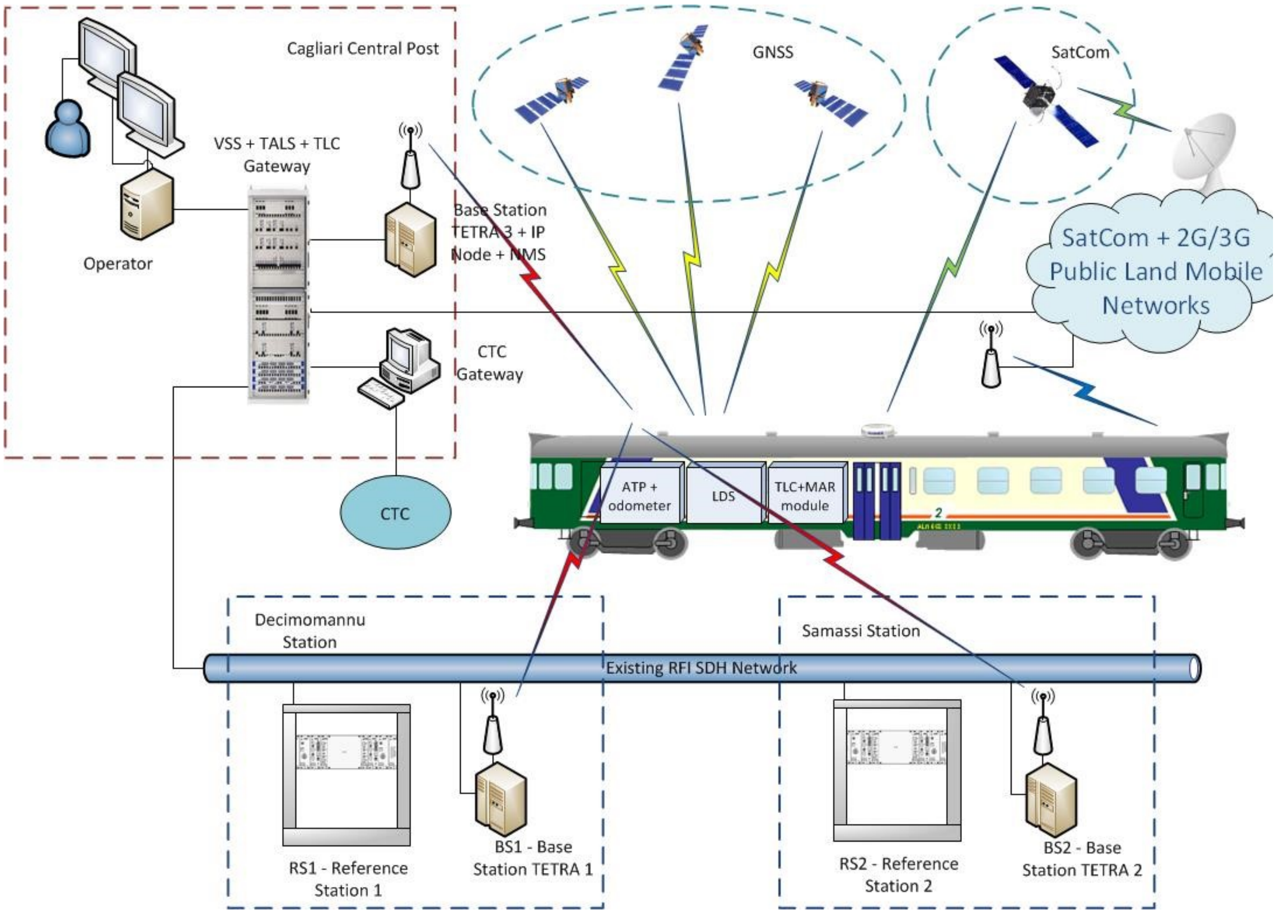

Figure 17 – 3inSat project architecture

3.1.2 APOLO

3.1.2.1 Background

The advantages of satellite-based systems over traditional systems of navigation and positioning in the railway environment are mainly attributable to having the required information in real-time. This makes it possible to manage traffic better, increase line capacity and raise safety levels. As the need for track-side signalling equipment is eliminated, costs of infrastructure and maintenance are reduced.

The EU is interested in a world-wide GNSS system and supports binding international standards. This project aims to improve interoperability on Western and Central European rail networks, which will lead to better transport services and more competitive suppliers. EU companies will be able to strengthen their presence in that market segment.

3.1.2.2 Approach

The APOLO technical solution is based on GNSS receivers. These receivers currently consist of GPS with differential EGNOS corrections, integrated with inertial sensors and on-board odometers, in an "intelligent" system of mutual calibration, error filtering and error correction. At the output of APOLO device, the location function improves overall performance and gives continuous coverage and achieves a high integrity even when, temporarily during train route, the SAT navigation signals are masked. Its application is made possible in a wide range of railway operational systems where autonomous position location is required with high levels of continuity, availability and integrity.

In order to eliminate the inconvenience of the canyon effect and to provide highest availability of location function, APOLO integrates the satellite position determination in a complex "intelligent" structure with inertial sensors and on-board odometer. On the basis of verified performances in terms of accuracy, availability and integrity of the location function (position + movement vector) the project will propose on-board architectures integrating APOLO locator in the various railway operational applications.

Such architectures will also aim at generically showing that APOLO technology would be capable of satisfying the currently agreed ERTMS RAMS requirements for the autonomous train location function as set for the ERTMS application level 3.

3.1.2.3 Achievements

A brief description has been produced of representative applications grouped into safety-related, mass commercial and infrastructural, scientific and civil engineering categories. Using that description, a comprehensive set of needs in terms of positioning accuracy, availability, and integrity have been established. For safety-related applications the APOLO location function has been assimilated with the on-board autonomous location currently achieved through euro-balise and odometer (ERTMS Level 3) and the requirements have been specified according to the ERTMS RAMS Requirements Specification for this function.

The APOLO prototype has been completed on the basis of the approach described, and the technical solution has been selected for integration of the SAT receiver, gyroscope and odometer signal into an "intelligent" errors' filtering device.

To provide cost-efficient coverage of a large set of applications, two classes of prototype have been selected for manufacturing and test purposes:

1. APOLO-SSA (Standard Service Accuracy) based on a Standard Service GPS receiver, intended for applications demanding medium accuracy (~50-100 m) but high coverage, availability and integrity of positioning.

2. APOLO-HA (High Accuracy), currently based on GPS + EGNOS receiver, for applications demanding high accuracy (5-10m) with the highest achievable coverage, availability and integrity of positioning function. The Test and verification plan identifies the relevant specific test scenarios, the verification procedures applicable in laboratory and field tests, the main instrumentation system and the requirements for documentation of tests and the acquisition and processing of test databases. The verification and test plan implement the principles and procedures set by the existing and on-going EU standards, including the ERTMS verification procedures for verification of hardware and software components usable in railway safety-related applications. Using this procedure is intended to make easier the future validation of APOLO technology in such applications.

3.1.2.4 Conclusions and plans for the future

Within the project, no direct application has been prescribed in a defined operational framework at specified railway administration. A direct validation of APOLO for an intended railway safety-related application is outside its objectives.

3.1.3 DITPOS RAIL

Train location systems have to satisfy high standards regarding reliability, safety, availability and integrity of position data, since erroneous position data might result in severe damage.

Existing location systems do often not only rely upon train based systems but also on track-side installations. In many rural areas, radio based communication systems also play a significant role.

The project DITPOS RAIL focuses on utilizing satellite based navigation technology for deriving an integrated positioning system (using GNSS, augmented by train-based sensors) which is independent from track-side installations. Focusing on the deployment and use in rural areas, the derived system will incorporate tailor-made integrity calculations that are suited for enabling subsequent certification processes.

The project aims to provide system design and safety concept elements as well as a demonstrator that are derived by strict adherence to processes applying formal certification requirements (TRL level 2 – 4). Regional train operators support the consortium during requirement analysis, system design and final validation of the demonstrator to be developed. Thus, a user driven development is ensured.

Results from this activity will enable the development of further products and/or services that increase the spectrum of train related technologies such as GNSS-based operation/activation of level crossings und thus facilitate benefits for the general public. Such systems will help to significantly reduce costs, as well as increase safety when activating level crossings and their safety equipment.

3.1.4 EATS

Currently European Train Control System (ETCS) rollout is a major concern for train manufacturers and railway infrastructure managers. Equipment for ETCS level 1 and 2 typically follows a long process before being put into service due to two main reasons. First, there are interpretation variations in the specification of the systems' behaviour. And second, available laboratory certification procedures do not completely address all the needs of the system and require long and expensive field-testing. On the other hand, migration from ETCS level 2 to level 3, which maximizes the railway efficiency, has not been yet foreseen due to the technical constraints that current GNSS solutions, based on GPS and EGNOS, cannot overcome.

In this context, EATS project has the objective to address the two previously described situations. On one hand, it will progress beyond the state of the art providing a model of the complete on-board ERTMS system behaviour to eliminate interpretation differences, and will include in the laboratory new tools to include the dynamic behaviour of the wireless interfaces and fault injection techniques in the external and internal interfaces for the safety assessment. This will lead to reduced laboratory and field-testing certification process time and cost. In the current economic situation, this is crucial in order to keep the ETCS deployment speed.

On the other hand, EATS will focus on the specific problem that is limiting the migration from ETCS level 2 to level 3. That is to say, EATS will propose a novel positioning system based on the combination of different techniques proved useful for other industrial sectors (multi-antenna assembly to reduce multi-path effects, combination of information sources such as GNSS, UMTS and GSM-R). Additionally, EATS will exploit unique features of the railway (1D problem) and the train (several receivers with known spatial separation to provide weighted positioning correction). Moreover, RAMS analysis to study the feasibility of the technical solution in the railway context and laboratory testing are foreseen to verify the proposed technical solution. This will be a step forward towards ETCS level 3 that minimizes trackside costs and maximizes track capacity.

The dissemination of the project outcomes is the ultimate objective. The consortium is clearly concerned about the return to the society of the funding obtained for this project. Therefore, in order to spread the knowledge acquired during the project, a set of concrete, quantitative and customized activities that involve all the actors in the society are planned. By means of the a web site with an open forum, the project will disseminate the information at worldwide level, 2 workshops will present the results to the railway industry and specific tasks assigned to contribute to industrial standards will help to harmonize the railway sector. In addition, with the double objective of disseminating the outcomes of the project and being exposed to different points of view, meetings with an Advisory Board will be held during the complete duration of the project. Regarding the scientific community, 8 contributions to technical journals/congresses are foreseen. Regarding the future labour force that will give competitiveness to Europe, it is worthwhile to mention that two courses for engineering students and professionals are planned.

3.1.5 ECORAIL

3.1.5.1 Introduction

Due to ongoing developments with the European Geostationary Overlay Service (EGNOS) and Galileo, satellite navigation is about to become an interesting innovation for all fields of transport.

One of these domains is the railways, which could profit considerably from the implementation of autonomous on-board positioning systems. Especially on local and regional railway lines there are various possible applications which could enable cost-effective modernisation and an increase in efficiency.

Train control poses high demands on positioning with respect to availability, reliability and integrity. These requirements can only be fulfilled by means of integrated positioning systems, which combine Global Navigation Satellite Systems (GNSS) with other sensors.

The EGNOS Controlled Railway Equipment (ECORAIL) project deals with the implementation of satellite navigation into the railway domain to demonstrate the feasibility and benefits of GNSS in combination with the European Train Control and Rail Traffic Management System (ETCS/ERTMS).

The ECORAIL project started in September 2001. The preliminary design was completed by June 2003 and a demonstration took place in June 2005. The project is expected to end by November 2005.

3.1.5.2 Objectives

The EGNOS Controlled Railway Equipment (ECORAIL) project is one of several GNSS-1 Rail User Navigation Equipment projects that deal with the implementation of satellite navigation in the railway domain to demonstrate the feasibility and benefits of GNSS in combination with the European Train Control and Rail Traffic Management System (ETCS/ERTMS).

The ECORAIL project is aimed at designing and testing a positioning system that is based on satellite navigation in a safety critical railway application.

To show the benefit of the innovation, the project focuses on the specific application of the control of automatic level crossings (ALX): Based on an on-board navigation unit employing a multi-sensor technique, it is possible to activate an ALX via a radio link. There is thus no need for cost-intensive track-side facilities, neither for positioning (e.g. track circuits, beacons) nor for signal transmission (cables).

3.1.5.3 Applications

The main applications of ECORAIL are going to be in the Rail domain with particular interest in Rail Traffic Management.

3.1.5.4 Technical Information

To demonstrate the efficiency of GNSS on trains, ECORAIL will perform an automatic level crossing control. Two trains of a local railway company in Upper Austria will be equipped with the proposed on-board system. To examine the quality of localization the activation of a level crossing will be simulated and compared with the data derived from the conventional equipment. In addition, a time-optimised activation based on the current speed of the train will be tested. Therefore, it is to demonstrate that the satellite navigation is not only an equivalent alternative to conventional track-side equipment but it has to be considered as a more efficient solution.

3.1.5.5 Schedule

The ECORAIL project started in September 2001. The preliminary design was completed by June 2003 and in August 2004 the demonstration campaign will take place. The project is expected to finish by the end of 2005.

3.1.6 ERSAT

3.1.6.1 Background

The ERSAT EAV proposal is relevant to the work program for the exploitation of the space infrastructure, in particular prioritizing the EGNSS uptake for the rail sector, fostering the competition and the innovation of the European space and rail industry and research community, and enhancing in parallel the strong coordination and synergy with the specific sector of European Railways and the main actors involved, building-up a system cantered to the ERTMS platform and able to bring to the ERTMS the “competitivity-dividend” of the satellite promises, linked with the enormous opportunity of the local and regional lines in Europe that represent about 50% of the total railways length.

3.1.6.2 Objectives

The main ERSAT EAV objective is to verify the suitability of EGNSS as the enabler of cost-efficient and economically sustainable ERTMS signalling solutions for safety railway applications.

The outcome of ERSAT-EAV is a priority for reusing the ERTMS standard architecture to satisfy the needs of the regional and local lines and for supporting the UNISIG Satellite Positioning Working Group that has been created (June 2012) to specify and standardize the application of the satellite positioning for the harmonization with the European ERTMS standard, by implementing and testing the solution on a pilot line as reference.

The objectives will be achieved, in a first phase by measuring and evaluating the gaps to be filled, in terms of technological criticalities and in relation to railway requirements. In particular, at first, by performing measurements under real operating conditions with the support of simulation tools and models. Then, by defining and developing a system solution, able to address and solve the critical issues, by implementing, testing and validating it on a pilot line, as reference for the future standardization and certification processes. The solution will fully exploit all the advantages of the multi-constellation approach and of EGNOS and Galileo services, providing an optimized augmentation service to the trains, in order to meet the railway requirements.

3.1.7 GADEROS

3.1.7.1 Key Results

The GADEROS project will demonstrate the use of GNSS for train location within ERTMS/ETCS. After developing the requirements base, from user needs to functional specification and test requirements, the specified tools will be implemented or adapted to set up the test bed. The project will perform tests on a number of prototypes on a low-traffic line – a real railway environment on the local line between Aranjuez and Valencia in Spain.

The data from the field trials will be used for an offline study and analysis of the performance, as well as input for the simulator to verify interoperability with ETCS. GADEROS will first define user requirements for low-density traffic lines, including inputs from related railway projects, in order to define a common ground for this type of application. It will then develop the architecture for the GNSS component in ERTMS/ETCS to reach the Safety Integrity Level required for the location function in railway operation systems. GADEROS will also develop standard test and evaluation procedures and tools for GNSS-based trials for railway safety applications. It will adapt simulation tools, based on an existing International Union of Railways (UIC) simulator, to provide compatibility and interoperability of train location by satellite with the ETCS kernel. Finally, it will develop a reference test site for railway safety-related GNSS applications.

3.1.7.2 Technical Implications

The expected technical achievements are:

1. Provide the Requirements Specifications for the software qualification tools used in the project, as well as for the data content, structures and qualification criteria of Digital Route Maps, including the update of software procedure specifications.
2. Contribute with the technological development for GNSS Locators and for Safety Qualifiers.
3. Requirements Specification for test, verification and evaluation procedures applicable to validations according to EU standards specification relevant to railway safety and under the frame of ERTMS/ETCS Interoperability Directive.
4. Trials and evaluation of at least one demonstrator produced by other projects, funded through EC or ESA projects.

3.1.8 GALOROI

GaLoROI will support the adoption of EGNOS by using it as an augmentation system, because it will lead to increased accuracy even before the usage of the Galileo Safety of Life Service is possible.

3.1.8.1 Background

This project acts as an appropriate base for the migration from conventional localisation equipment to the use of Galileo for transportation. As nearly 50% of all railway lines in Europe are secondary railway lines and this is even truer in other countries, this sector may be considered a niche that could become a mass market, based on the number of about 50,000 locomotives in Europe. The resulting localisation unit promises a short-term return on investment (ROI).

3.1.8.2 Objectives

A satellite based train localisation unit reduces high manufacturing, installation and maintenance costs because it only needs to be installed on trains and requires no track side equipment. The objective of GaLoROI is that the localisation unit delivers localisation information with high accuracy, integrity, availability and a Safety Integrity Level (SIL) which is sufficient for safety-relevant localisation within train control systems. The objective includes compatibility with other train control systems. The localisation through the satellite based localisation unit allows a continuous localisation which will increase capacity in comparison to discrete localisation of track side equipment.

In terms of practical usability in the railway system, a main objective of GaLoROI is the certification of the localisation unit according to European safety standards like the Common Safety Standards and Common Safety Targets of the European Railway Agency.

3.1.8.3 Description

In GaLoROI a certifiable safety relevant satellite-based on-board train localisation unit will be developed. After the certification, many operational options exist for commercial usage. The on-board train localisation unit can be part of an automatic train control system which no longer requires additional track side railway signalling technology. In this train control system, existing and new technologies will be integrated for efficient and safe operations in the railway network.

3.1.8.4 Results

This project will result in an on-board localisation unit that is ready for the market. This will lead to a significant reduction in costs, promoting train transport as a sustainable mode of transport ready for the future. As a result, GaLoROI will provide innovations in operations, safety and efficiency, as well as social and economic benefits.

3.1.8.5 GaLoROI System concept

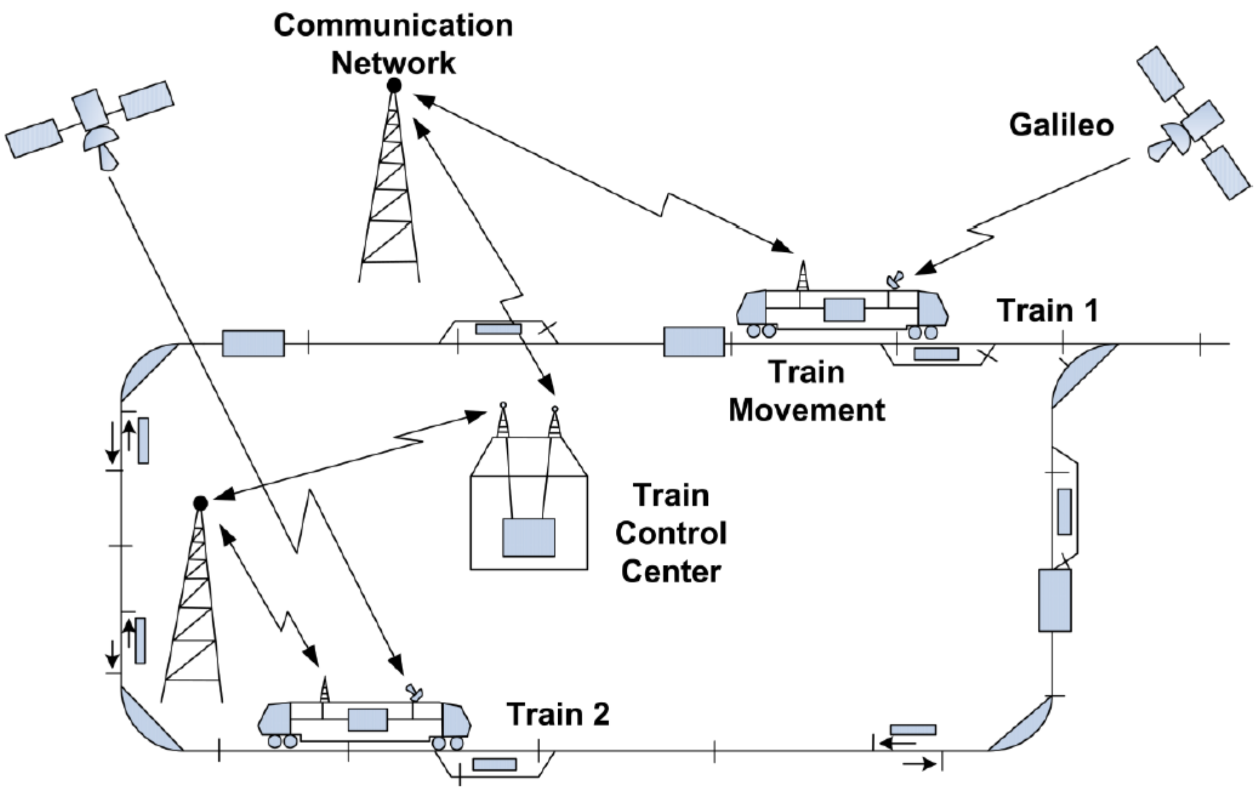

Figure 18 – GaLoROI System Concept

3.1.9 GIRASOLE

3.1.9.1 Background

One of the most appealing features of Galileo that GPS does not have is the signal-embedded integrity, which enables the system to inform users about the possible failure of the system. Thanks to this provision, the possibility of using GNSS in a safety-critical application (i.e. safety of life, SoL) can be envisaged for both EGNOS and Galileo. The receivers used for safety-critical application share some common specifications and are generally classified under the term ‘safety-of-life receivers’. The main characteristics of these types of receivers are their robustness and their capacity to identify failures coming from the constellations, from the signal in space, from the environment and from the receiver itself. Safety-of-life receivers are also subjected to a large quantity of specifications, resulting in a rigorous certification process.

3.1.9.2 Objectives

The activities within the project are aimed to reach four main objectives:

- Carry out thorough technological research oriented to identifying the technologies needed for SoL receivers;
- Develop common structures which can be shared among the different application-oriented receivers;
- Develop three basic SoL receivers prototypes for the three different application – aviation, maritime and rail;
- Develop tools to assist in the development phase.

Two Galileo signal simulators will be developed. The programme can be considered as a natural continuation of the GARDA programme. Core technology investigation and implementation will evolve, targeted at the SoL application of the GARDA core technologies.

3.1.9.3 Description

Inputs to the project

Several inputs are foreseen for the project, and those coming from the GARDA project have a particular importance. They include studies about the development activities of the Galileo receivers, identification and investigation on some core technologies, and development tools and preliminary development activities of a professional receiver. All these inputs will be taken into account and further developed within the current project.

Requirements and specifications

A first issue of the ‘requirement and specification’ document will be created based on the input to the project; this issue will then be considered the initial input to the subsequent task on the core technologies. A second issue of the requirement and specification document will be released covering the feedback coming from the core technology investigation task, and the third and final issue will be completed at the end of the project covering the feedback from the breadboard development task.

Core technologies task

Candidate core technologies are studied and criticised in order for them to be tailored to the specific needs of SoL applications. The result will be a set of technologies that act as a common base for all SoL applications, plus others which represent those specifically related to the targeted SoL applications. Once the technologies are identified, they will be analysed by means of the GRANADA tool in order to produce solutions and any other indications that will be used as a starting point in the breadboard development task.

Breadboard development

This activity derives from, and is conducted in parallel with the core technologies task, to which it provides feedback for a better identification, and which is aimed at the design and development of a receiver breadboard for each of the three identified applications: rail, maritime and aviation.

Common platform concept:

The common platform concept has been included as a logical attempt to reduce costs and development schedule, and to avoid spreading the efforts on similar designs of each receiver target application. The definition of a common receiver architecture is to be considered a good starting point. This means that the main characteristics of the 'ideal' receiver can be retained by a customised receiver for each application.

3.1.9.4 RESULTS

Currently the project is in the phase of testing the three receiver breadboards developed. The testing phase will be conducted using the developed simulation tools. One simulator has been developed by Space Engineering, which has evolved from the GARDA single-channel simulator (GMCS). A second simulator has been developed by NAVIS. The GRANADA software tool has been upgraded and now includes some features useful for investigating and analysing SoL technologies. The investigation on the core technologies has been completed and an assessment of the basic technologies for the SoL application done. Some basic technologies have been analysed with GRANADA. The investigation and analysis on the core technologies has highlighted some interesting topics that deserve further investigation. The first version of the GIRASOLE breadboard developed for rail application will be used on the test campaign on a train within the framework of the GRAIL project.

3.1.10 GRAIL

During the last few years, several projects funded both by ESA and the EC have been studying and demonstrating the use of GNSS for safety-related applications in railways, especially the ERTMS/ETCS application. In the framework of the GADEROS project a workshop was organised by the GJU to bring together representatives from these projects (GADEROS, INTEGRAIL, RUNE and LOCOLOC/LOCOPROL) with the EC, ESA, ERTMS users group and the GJU. During the review of the findings of those projects, it was detected that although they do not follow the same approach the conclusions reached were similar. These projects have proved the feasibility of introducing GNSS in railways and in particular ETCS by means of theoretical studies and demonstrations:

- Safety analysis on these concepts has already been performed (however, not yet as formal safety cases) and the results are positive
- Some system prototypes have already been developed by the industry
- Both railway signalling and GNSS industry have provided good co-operation towards a common interest.

Several different functional and technical concepts have been presented by these projects but they can be mainly summarised as follows:

1. GNSS system as odometry: GNSS-based location is used as a substitute or complement of the current odometry sensors (tachometers, INS, Doppler radar, etc.). Thus it can remain internal to the ETCS.
2. GNSS for the fixed balise marker: The GNSS system is used to provide the ETCS onboard system with a message equivalent to that provided to a fixed balise in the track for a position marker.

This project proposes a strategy, consistent with the current deployment process of ERTMS/ETCS in Europe, to provide a smooth integration of GNSS into control and command applications, particularly in ERTMS/ETCS. The GRAIL project will be based on three main objectives: 1. To specify, develop and test a GNSS prototype system for enhanced odometry, ready to be integrated in ETCS onboard systems; 2. To pave the way for the future introduction of more ambitious approaches at different levels of ERTMS/ETCS architecture; 3. To complete the perspective of safety-related applications with the study and demonstration of non-safety applications and the study of economic and legal issues.

3.1.11 GRAIL 2

The objective of GRAIL-2 is to develop and validate a GNSS based ETCS prototype/application in Rail Low Density Lines. Starting from the work of GRAIL, GRAIL-2 goes further in the implementation and testing of one of its applications so that a real validation of the application against user needs can be performed, thus achieving a system/application closer to a final product.

The proposed application is Absolute Positioning, combined with Train Integrity, in a context of Low Density Lines.

Absolute Positioning is considered to be a very promising application as it can achieve a full on-board localisation of the train, thus reducing or eliminating the trackside equipment for localisation (balises). Besides, combined with the Train Integrity application, we can achieve the “positive train detection” that allows a future implementation of “moving block” systems (future ETCS level 3). That is also compatible with other initiatives like Low Cost ETCS or Regional ETCS. Freight transport will also benefit by knowing the completeness of the train.

The framework of low density lines is considered to be more adequate for a short-term implementation of the GNSS applications:

- The operational requirements of the application are less demanding.
- There is no need for interoperability in short term, therefore, we can propose an application without the need of a formal adoption of the changes needed in the ETCS specification, but allowing for a future interoperable implementation when the ETCS specifications will be upgraded.
- Costs are kept low: The current ATP/ETCS means great investments in the LDL but this is not feasible because of the limited budget dedicated to the LDL in the railway community.

The ETCS environment is also preferred because ETCS is a standard system whose features are well defined and already proven. Besides, it should be noted that ETCS is suitable for all kind of lines and it is flexible and easily adaptable as demonstrated in GRAIL.

3.1.12 INTEGRAIL

The aim of INTEGRAIL is to open the way for profitable use of the EGNOS signal in safety-critical railway traffic management and control. The system aims at achieving significant improvements for the rail traffic operator with respect to cost, redundancy and reliability of the present train speed measurement systems, which are based on odometers, by adding satellite navigation information and the integrity information offered by EGNOS.

Moreover, the INTEGRAIL system is able to provide reliable position and integrity information under varying operational conditions. This was achieved by tailored requirements analysis, appropriate sensor selection, performance simulation and actual testing of the system "in-the-field". In the present project, train operations on secondary or rural lines were targeted for application testing purposes.

The INTEGRAIL project was initiated in September 2001 and completed in June 2004; successful field trials were carried out from February 2003 until December 2003 on tracks in Austria (LogServ/CargoServ, VoestAlpine: Linz – Steyrling) and in Belgium (SNCB).

3.1.13 IRISS

The IRISS feasibility project has identified the applications and requirements for an integrated information, communication and navigation gateway within the rail transport sector, designed and developed a solution and performed a proof of concept activity. The solution is based on the use of terrestrial and satellite communications in combination with traditional reporting systems and satellite navigation services. This new capability will allow Train Operating Companies (TOCs) to communicate with their assets irrespective of location and status, enabling data to be uploaded and offloaded in real time to support decision making processes and to improve the management of operations and incidents. The solution has been built with the objective of helping TOCs to achieve their key challenges of increasing capacity, reducing carbon (fuel consumption), lowering the cost of operations and improving customer satisfaction.

Specific objectives for IRISS in terms of improving TOC operations were:

- To generate better driving style
- To deliver better information to support decision making
- To improve the reliability of trains
  - Operations, performance
  - Engineering
- To provide up-to-date, accurate timetable information to the customer

The project therefore aimed to deliver the following:

- Development and trials of a single, seamless communications and navigation portal per train, including an on-train system, communication services and back-office utilities
- Provision of two-way communication services serving multiple on-train systems with different bandwidth requirements
- Provision of accurate train Position, Velocity, Time, Distance and Bearing to back-office and interfaces so that this data can be distributed to other on-train systems
- Service to multiple applications and services
  - On-train and back-office
  - Real-time and offline

In addition the project aimed to address the following questions:

- Which applications offer the best opportunity for a sustainable business case?
- What is the value added by integrating a satellite communications capability within the device?

- How may the device be best integrated within a train and which sensors can it successfully connect with?
- What is needed at a back-office in terms of server/data hub and analysis applications?

3.1.14 LOCASYS

GNSS technology forecasting within the rail industry of the UK has been initiated by the RSSB via a project awarded to Nottingham Scientific Limited (NSL). The purpose is to systematically analyse the dependability of the performance of GNSS enabled positioning systems and test their feasibility for use in position and speed determination. The project, LOCASYS, builds on previous research projects, such as APOLO, LOCO, GADEROS, RUNE, ECORAIL and LOCOPROL, which have all investigated various aspects of the application of GNSS technology, such as GPS, to the railway domain.

The LOCASYS project started in February 2006 and will run for 36 months. At the time of writing (January, 2008), the first measurement system has been designed, constructed, certified and installed on an operational train. The installation of a second system is imminent. Data collection from the first train has commenced and preliminary data analyses have been performed. It the intention of this paper to describe the project to date, together with the reasoning behind the project and present results of the preliminary data analyses.

3.1.15 LOCOPROL/LOCOLOC

3.1.15.1 Abstract

The project has developed an innovative cost-effective satellite based fail-safe train location system as the core of a train protection, control and command system, thereby achieving a significant cost reduction by concentrating more intelligence on-board. The proposed innovations have achieved a significant reduction of the cost aiming to short term applications for low density traffic railway lines. The developed system enhances and extends the ERTMS/ETCS system, currently covering high density lines, to low density lines.

3.1.15.2 Objectives

The four main objectives of the project are strongly interconnected:

- To define a new multi-technology location system based on satellite positioning combined with fail-safe on-board track mapping and interlocking;
- To study and prove its application to ERTMS/ETCS;
- To study and prove its short term applicability in Low Density Traffic Lines;
- To study its applicability in order to increase track side workers protection.

3.1.15.3 Description of work

The development process for the LOCOPROL project was slightly different from a pure top down approach. The reasons to do so were the following:

- The main objective of the project focused on the development of new sub-systems with reference to a complete signalling system
- The aim of the project was to validate the system principle as well as the application engineering guidelines from a safety point of view but not to validate the sub-systems or components.

- The project reused existing sub systems or modules already developed e.g. ERTMS components
- This procedure shortens the duration of the whole process.

It takes into account three types of processes:

- The already existing processes, performed in the frame of former projects. It is applicable to the component that do already exist and that has been used in our “new” system.
- The parallel process, performed in the frame of the project. It is applicable to sub systems for which the development work may start at an earlier time of the project with minimum risks, without waiting for the time were it should start according to a pure top down approach. The main aim for having this kind of process is to shorten the duration of the project. It is usually possible to do it with a minimum of risk on the basis of the company experience in the domain of application or on the basis of preliminary (not formal) studies already performed.
- The third process, also performed in the frame of the project, is the “well known” formal top down process that has to be performed in any case to be compliant with CENELEC standards. During this last process, all the work performed using one of the two other processes has to be validated based on the results of the top-down system formal approach. Discrepancies that are detected during this check point process are fed through to all lower level design phases that have already been performed. When there are such divergences, corrective actions have to be performed to put in conformity all the outputs of the two “early” processes.

3.1.15.4 Project results

The main results of the project are as follows:

1. A new multi-technology satellite based train location system based on satellite positioning combined with fail-safe, on-board track mapping & interlocking.

The principles used for the new train location system are:

- Safe digital mapping of possible trajectories;
- Fail-safe positioning on a given trajectory (line-based mode), using redundant and independent satellite pairs;
- Step by step determination of the pertinent trajectory via a dialogue with the points and/or the interlocking system (topologic mode).

This approach is drastically different from the recently emerged train-aided satellite location systems where the safety is expected to be based on the concurrent use of satellite signals and information from additional sensors, combined with Kalman filtering techniques.

In LOCOPROL, the safe location is directly based on satellite signals GPS, EGNOS and future GALILEO, on which no specific integrity requirements are imposed. According to the hazard identification performed and the proposed mitigation measures to reduce failure risks, the preliminary safety case gives good hope the satellite measurement process for train positioning developed in LOCOPROL will achieve the 6.10-11/h objective and the SIL 4 requirements.

2. <u>A new control & command system</u> including a token-based simplified interlocking system and positive train detection.

The solution is a global control/command solution and performs all the functions required for an efficient railway operation. I.e. traffic supervision and command (ATS), automatic train command and control (ATC), automatic control of objects in the tracks (point machines and level crossing protection) and all necessary functions for a follow-up of the maintenance of the rolling stock.

Different ways of transmitting data between the moving trains, the trackside objects and the central radio block centre (RBC) have been studied. The main objective here was to reduce the cost as well for the equipment as for the operation cost (communication cost). Therefore different solutions have been tested essentially based on publicly available and existing infrastructures such as public GSM and packet based solutions like GPRS. Off course GSM-R can also be used. However typical LDTL lines are not equipped with GSM-R. We have shown that for these lines an important investment in GSM-R infrastructure is not necessary.

3. <u>Interoperability with ERTMS</u> – Integration of satellite based odometry in ERTMS/ETCS onboard architecture.

The project has proven that it is possible to integrate the LOCOPROL satellite based location and speed calculation module into the ERTMS/ETCS on board. This paves the way to use the LOCOPROL odometry not only for applications on low density lines, but also to substitute the high-cost classical (mostly radar based) odometry by the much cheaper LOCOPROL satellite based module even on high density lines.

4. End user interface.

The ATS module developed for the Nice – Digne demonstration includes also the necessary interface allowing the end user (the hauler or addressee of the transported goods) to follow the progress of the transport over an internet connection.

5. A fail safe worker terminal (specification).

The project has given much consideration to the problem of the worker's safety along the track. A hand held device has been studied and fully described in a specific deliverable.

6. A tool for geographical database creation for railway lines.

The track data base generation is absolutely necessary to have an accurate geographical description of the track in order to be able to deliver data used by the 1D algorithm in connection with the information delivered in real time by the satellite sensors.

The track data based is obtained on the basis of amongst others GPS measures during a specific test campaign, and a better accuracy is obtained by a specific post processing.

Globally, the tests done on site 1 showed that the process of the track date base was better always than 5 meters and better than 2 meters in most cases. It was also demonstrated than a 1 meter accuracy was possible by improving the post processing algorithms and/or by using DGPS/RTK.

3.1.15.5 System concept and architecture

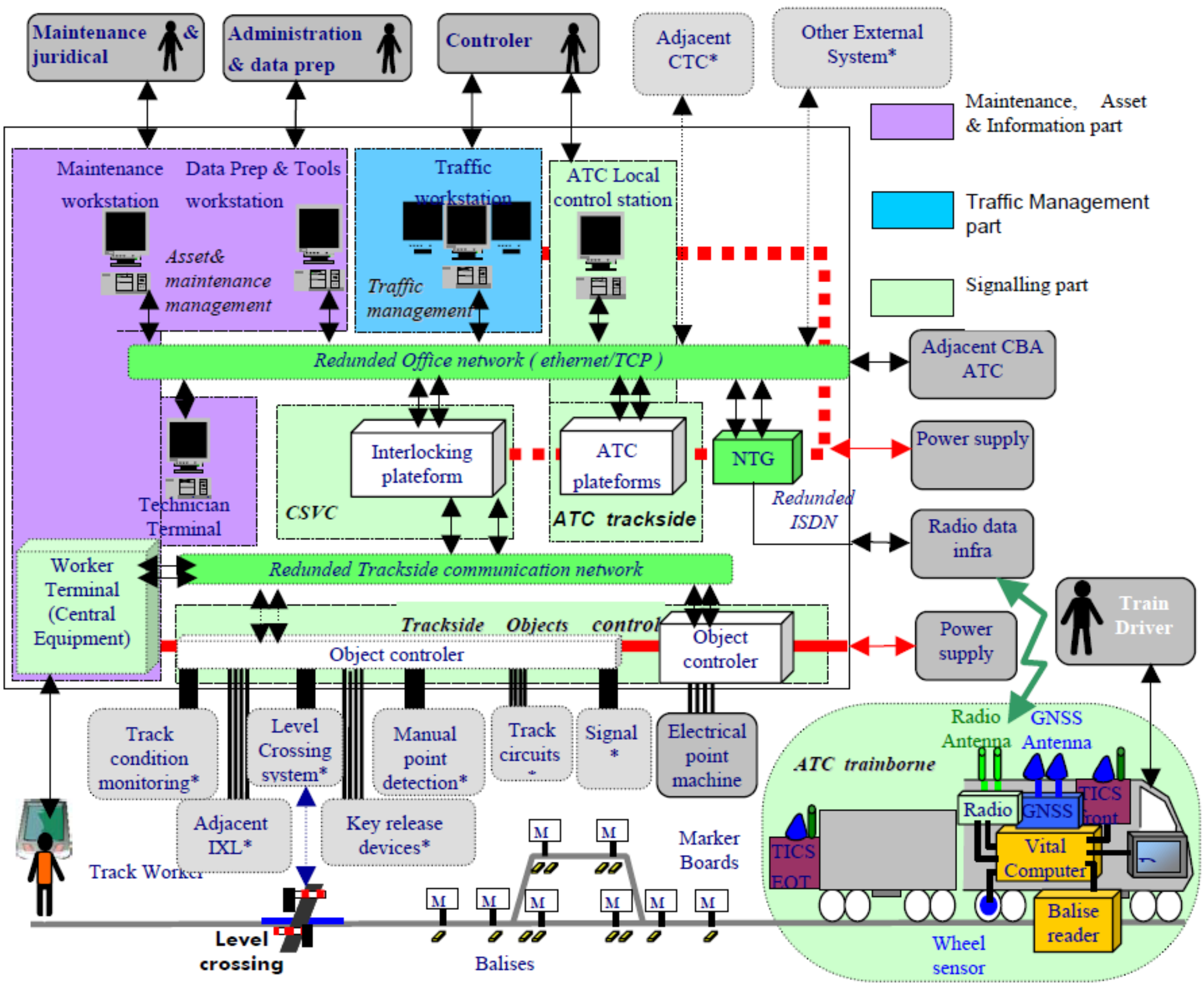

Figure 19 – LOCOPROL System Concept and Architecture

3.1.16 M-TRADE

3.1.16.1 Background

Europe's transport policy has been characterized by liberalization and harmonization over the years, which has shaped the current transport system. Globalization and the concept of a wider Europe create further challenges. Rapidly increasing freight transport contributes to growth and employment but also causes congestion, accidents, noise and pollution. M-TRADE targets European policies in support of transport's sustainable development and short-sea-shipping promotion. In the '2001 White Paper on Transport' mid-term review, the European objective was to shift to more environmentally friendly modes, especially on long distance journeys and on congested corridors, in favour of co-modality (i.e. the efficient use of different modes on their own and or in multimodal integration in the European transport system). The 'Program for the Promotion of Short Sea Shipping' recommends measures aimed at enhancing the quality of transport, by increasing the reliability throughout the whole transport chain and facilitating administrative procedures. A common vision is that intelligent transport systems (ITS) can play a key role. Advanced solutions based on GNSS, coupled with other technologies such as RFID, can contribute towards reaching an optimal and sustainable use of resources. Services for remote localization of cargo in all modes allow a reliable tracking of both journey and goods, thus decreasing the need for individual controls, and contributing to an efficient and safe management of supply chains.

3.1.16.2 Objectives

The M-TRADE objective is to analyses the use of EGNOS/Galileo in freight transport applications.

3.1.16.3 Results

M-TRADE validated the use of EGNOS Commercial Services for remote asset and the tracking and tracing of goods. M-TRADE developed an end-to-end solution, demonstrated it in real-life operative scenarios and evaluated its introduction in customs and border control applications. Two different on-board units were developed, using GPS/EGNOS assisted via GPRS and integrating RFID technologies. M-TRADE tracking and tracing services are conceived to cope with safety and efficiency operative needs, in line with standards and regulations, and to exploit 'market' value for EGNOS/Galileo differentiators, i.e. dangerous goods, perishables and remote assets. M-TRADE performed four pilots over European freight chains, combining maritime, road, rail and river. Gathered user feedbacks showed friendly service access and benefits in operations, and provided recommendations for enhancements. M-TRADE also studied the case of EGNOS/Galileo introduction in the customs domain. The analysis evaluated user interests and identified opportunities for GNSS to provide benefits in customs operations, supporting anti-fraud enforcement and trade flows control. M-TRADE is the first step towards the operative use of GNSS in multimodal freight applications and shows the way for future progress in the regulated applications domains.

3.1.17 NGTC

The main scope of the Next Generation Train Control (NGTC) project was to analyse the commonality and differences of required functionality of two major train control systems ETCS (European Train Control System) and CBTC (Communications-based train control), and determining the level of commonality of architecture, hardware platforms and system design that can be achieved. The proposed NGTC solutions are based on the experience of ETCS and its standardised train protection kernel and by using experiences suppliers have gained by having developed very sophisticated and innovative CBTC systems around the world.

Nevertheless, the goal of the project was not to develop a system of 'one size fits all', but to make progress for all railway domains in terms of increasing the commonality in system design and hardware, with various benefits like increasing economies of scale for suppliers, and amongst other things customers having the benefit of being able to choose the most competitive supplier, based on standardised functions and interfaces.

NGTC has also delivered general moving block principles for rail applications, in-depth study on future generations of IP-based radio communications and significantly progressed in research on satellite-based train positioning suitable for ETCS.

The wide and successful deployment of ETCS technology across the EU network and worldwide is providing new opportunities for safety and capacity improvements, and cross-border operations on the mainline network. Likewise, numerous new innovative CBTC based control and command signalling systems are being introduced in the urban rail area, equally providing capacity and reliability improvements.

On the one hand ETCS defines a standard train protection system which is based on a set of defined functions and track-to-train messages (airgap) providing full interoperability between the infrastructure and the trains. On the other hand, the various control and command systems in the urban world (CBTC) have proven to be successful performers, yet are not "interoperable'' between themselves. The same European industry is the world leader for both of these types of systems.

With the continuous growth of large cities, the market is more and more looking to signalling solutions to provide a smooth connection between dense urban network and the surrounding suburban/mainline network. The next generations of rail systems will have to address the following different markets:

- Urban systems (metro) operated on fully independent infrastructure; many with very high performance requirements;
- Mainline systems connecting cities;
- Regional systems (sometimes suburban) which are fully part of the mainline domain;
- Suburban systems (like the Paris RER or the London Crossrail and Thameslink) which are neither “fully mainline” nor “fully urban”.

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Finally, achieving these objectives will help the European Industry maintain a competitive advantage worldwide.

NGTC paved the way for standardized train control systems for mainline and urban domains which provide ATP, ATO, and ATS functionality and support train operation from Grade of Automation GOA0 to GOA4, whilst reducing TCO/Life cycle costs, and achieving an overall improvement in performance at lower cost. In addition, it must be possible to offer scalability for different customer requirements (ranging from low density lines to high performance lines).

A major condition for the project was to preserve the backward compatibility with the current Baseline 3 ETCS in order to protect the already large investments made by the Customers and Suppliers in this field.

More specifically, NGTC has followed four main objectives with the number of research activities, described below:

1. Further development of CBTC (Communication Based Train Control) based control systems including the on-board and wayside equipment and associated standard interfaces: NGTC work has been based on CBTC Standardisation such as, MODURBAN deliverables, existing standard IEC62290- 1 and 2, and the IEEE 1474 series of standards with the overall objective to overcome the past constraints of proprietary CBTC solutions.
2. Introduction of new technologies in the ERTMS (European Rail Train Management System) standard architecture to fit further requirements from railway undertakings: Based on worldwide market driven requirements, NGTC has undertaken research work on Satellite positioning and IP based radio communication, as potential future add-ons to the existing Baseline 3 ETCS. Also, a further study of the Moving Block concept from a system point of view has been addressed.

3. Investigation of the next generation of ERTMS technical specifications and their associated standard interfaces: The new ERTMS message structures have been proposed to make the system a more scalable solution, while maintaining, the backward compatibility with the Baseline 3 ETCS message specifications.

4. Investigation of various possible industrial synergies between the control systems of the two domains, in terms of specifications for on-board and wayside equipment, certification processes, as well as the facilitation of trans-border operations between the mainline and suburban systems: Functional requirements common to the mainline and urban domains have been identified and common functional allocation for mainline and urban applications has been developed. This provided the opportunity for common hardware and software platforms for suppliers and making the obsolescence management challenges less problematic for operators.

3.1.18 P. Brocard PhD thesis

3.1.18.1 Motivations of the work

Due to the modernization of current Global Positioning System (GPS) and GLObal Navigation Satellite System (GLONASS), the development of Galileo and Beidou, and the developments of augmentation systems, the fields of application that could benefit from Global Navigation Satellite Systems (GNSS) is constantly expanding.

GPS together with augmentations has been a proven technology for safety-critical applications such as civil aviation for which the GNSS use is performed in a fair environment (mostly open sky reception, controlled frequency bands, etc…). With the advent of multiple GNSS systems and the availability of signals located in different frequency bands, better performance can be expected from GNSS even in more challenging conditions. As a consequence, there is a trend to investigate the use GNSS for other critical applications taking place in locations where GNSS signal reception can be difficult (forest, light urban, urban). These applications are not necessarily safety-critical, but can be liability-critical and thus still require a certain quality of service to be maintained. This is for instance the case for terrestrial rail and road position monitoring systems, which currently requires costly ground infrastructures.

- In the rail domain, the European Train Control System (ETCS) is the automatic signaling, control and train protection system that is currently being deployed for an improved interoperability in Europe. In ETCS level 2 and 3, the vehicles have to self-monitor their position and speed based on a combination of radiobeacons (Eurobalises) installed along the railway to provide reference positions - and odometry. The density of these radiobeacons should be at least one per 2.5 km. The possible introduction of GNSS in ETCS could thus allow a significant reduction in the number of radiobeacons resulting in an important cost saving and a reduced exposition to degradations and robbery.

- In the road domain, GNSS could be used as a technology for Electronic Toll Collection (ETC) in order to replace or limit the amount of costly tolling gates necessary for other technologies. GNSS is already used for tolling of heavy good transportation in Germany (Toll Collect) and Slovakia (MYTO).

The main objective of this PhD thesis is to investigate the feasibility of using GNSS-based positioning for these two above-mentioned applications, which means understanding of its specificities, construction of a position solution and insurance of the matching of the positioning quality provided with the application requirements.

The first challenge that slows down the introduction of satellite navigation in these critical terrestrial applications is the lack of standardized requirements for the GNSS-based positioning system. This process took long years in civil aviation and is a work in process in rail and road. The first objective of the thesis is thus to investigate the foreseen operational requirements for train control and ETC.

As mentioned earlier, unlike aircrafts and ships that operate in open sky conditions, terrestrial vehicles are likely to operate in constrained environments such as forests, urban canyons and tunnels. The performances of GNSS in terms of accuracy are highly dependent on the environment in which the receiver is located. The thesis focuses on the most challenging environments which are suburban and urban environment. In urban environment, the obstacles such as buildings and vehicles usually mask several satellites and thus degrade the geometry of the constellation from the receiver point of view. In deep urban canyons and tunnels, even less than 4 satellites may be in view which leads to GNSS unavailability (depending on the dimension of positioning, e.g. 2D, 3D, 4D). As standalone GNSS can have poor availability in constrained environment, it requires the use of complementary sensors. For instance, inertial navigation provides a positioning solution by integrating angular rates and specific forces from Inertial Measurement Units (IMU). Therefore, unlike GNSS, the resulting solution is independent from the propagation environment of the vehicle. However this technology cannot be used on its own for navigation as the position error is unbounded due to integration of biases. By coupling GNSS with a 6 axis IMU, it is possible to get a solution that is more accurate than each system taken separately because of the complementarity of their error models. Other sensors or information can be available on terrestrial vehicles such as wheel speed sensors and track database for rail applications. The integration of these measurements can be used to improve the accuracy and the robustness of the whole navigation algorithm. A second objective of this PhD thesis is to propose concrete system architectures that integrate the different sensors available on board for both rail and road applications.

In order to design the sensor fusion algorithm (as well as to design an efficient integrity monitoring algorithm), it is necessary to characterize and model the measurement error associated to each sensor integrated in the solution. These errors, classified into nominal and faults (from an integrity point-of-view) and their different sources are investigated in this thesis. In particular, the distribution and magnitude of the GNSS measurement errors specific to an urban environment are of interest. In suburban and urban environments, the GNSS measurements can frequently be affected by large errors due to strong multipath. If the satellite is not in view which is likely to happen when the satellite is masked by a building, the receiver may track a diffracted or reflected ray. This phenomenon is referred to as Non Line-Of-Sight (NLOS) reception. The range measurements that result from NLOS signals are positively biased compared to the true geometric ranges due to the non-direct trajectory of the signal. They can thus lead to erroneous positioning. Such error sources and their distributions should be investigated and modelled in order to derive realistic models. This is another objective of this thesis.

Then, another objective of this thesis is to design the data fusion algorithms and assess their performance in order to check that they are coherent with the anticipated performance requirements. This study can be conducted by simple simulations, by feeding the algorithm with measurements generated by a measurement generator that integrates the realistic sensors measurement error models developed in this thesis. Another objective of this study is to implement the proposed fusion algorithms on real data campaigns. Quantizing the benefit of integrating as much measurement and sensors as possible is of particular interest.

Then the possibility to improve the reliability of the solutions by pre-selecting the GNSS measurement according to the values of different criterion is investigated. The objective is to assist the integrity monitoring algorithm by excluding from the solution the faulty-prone measurements (due to the effects of the environment). In particular, one of the motivations of this thesis is to detect abnormal measurements at the signal processing level. Moreover, the use of additional sensors appears to be a promising technique to protect against outliers among the GNSS measurement.

Finally, the positioning systems have to be augmented to fulfill the integrity requirements of the critical applications of interest. Current augmentations systems were designed to monitoring integrity of GNSS positioning in the context of civil aviation. Algorithms inspired from ABAS are deemed to be the best candidates because they are able to detect failures of the receiver. The last objective of this PhD thesis is thus to adapt integrity monitoring algorithms to the proposed GNSS/Sensors architecture and assess their true performances in real urban/sub-urban environments.

3.1.18.2 Contributions

The major contributions of this thesis are:

- A state of the art of the existing operational requirements for train control and ETC has been done.
- A realistic way to fulfill the very low integrity risk requirement for train control is proposed based on using redundant subsystems based on independent constellations
- A characterization of pseudorange error measurements due to multipath have been conducted by connecting a realistic receiver simulator to the Land Mobile Satellite channel developed by the DLR. After overbounding of the error distribution, an error model has been proposed for urban environment. The results have been published in (Brocard, Salos, et al. 2014).
- New results have been found for the detection of abnormally large multipath interference by monitoring the correlation function. It includes rigorous threshold expressions to design the tests, and a theoretical way to assess the performance of such tests in terms of sensitivity. The behavior of such metric was investigated on the tracking simulator connected to the DLR model. The results have been published in (Brocard, Thevenon, et al. 2014).
- The measurement model of GNSS, IMU, Wheel Speed Sensors (WSS) and track database have been proposed. The models are added to the ideal sensor measurements that are generated by simulations. It is used as the reference for the validation of the system in the nominal case. Failure sources and models for each sensor are proposed in this work.
- An Extended Kalman Filter (EKF) that couples GNSS and a 6 axis IMU has been proposed, and implemented. The IMU measurements are processed by a quaternion based mechanization that has been implemented. A method for the validation of the GNSS/IMU hybridized filter is proposed. Two architectures for ETC and train control have been developed. In particular, a method to integrate the measurement from the track database is given in this thesis. Early results obtained by simulations and real signals have been published in (Brocard, Julien, and Mabilleau 2015b)
- A statistic NLOS error model in urban environment is proposed in the Thesis. The distribution of NLOS error is also assessed thanks to a real measurement campaign. It will be used to characterize this source of failure in urban environment. A test based on the predicted pseudorange (innovation) is used to detect the abnormally large jumps and exclude or down weight the dangerous measurements due to NLOS and residual multipath.
- A method to calculate the biases that are critical in the sense that they can make the error exceed the HAL is given. The output of this calculation is used as the input of the multipath detection algorithm and the innovation monitoring test.
- An integrity monitoring algorithm designed for GPS/INS architectures in civil aviation is adapted to our case of study. It aims at providing protection levels and detecting the residual faulty measurements. The results obtained with such an algorithm have been published (Brocard, Julien, and Mabilleau 2015a). A reliability checking algorithm for the IMU is also proposed.
- Finally, accuracy and integrity performances of the proposed solutions are assessed in real urban environment in downtown Toulouse.

3.1.18.3 Proposed Architectures

For train control and ETC it has been proposed to augment the GNSS with other sensors that are available on board. The hybridization scheme proposed is tight coupling as it is the most adapted to the navigation in harsh conditions. Both solutions integrate a 6 axis MEMS IMU, however different additional sensors were used for each application:

- The architecture proposed for train control integrates the data from a map of the rail tracks

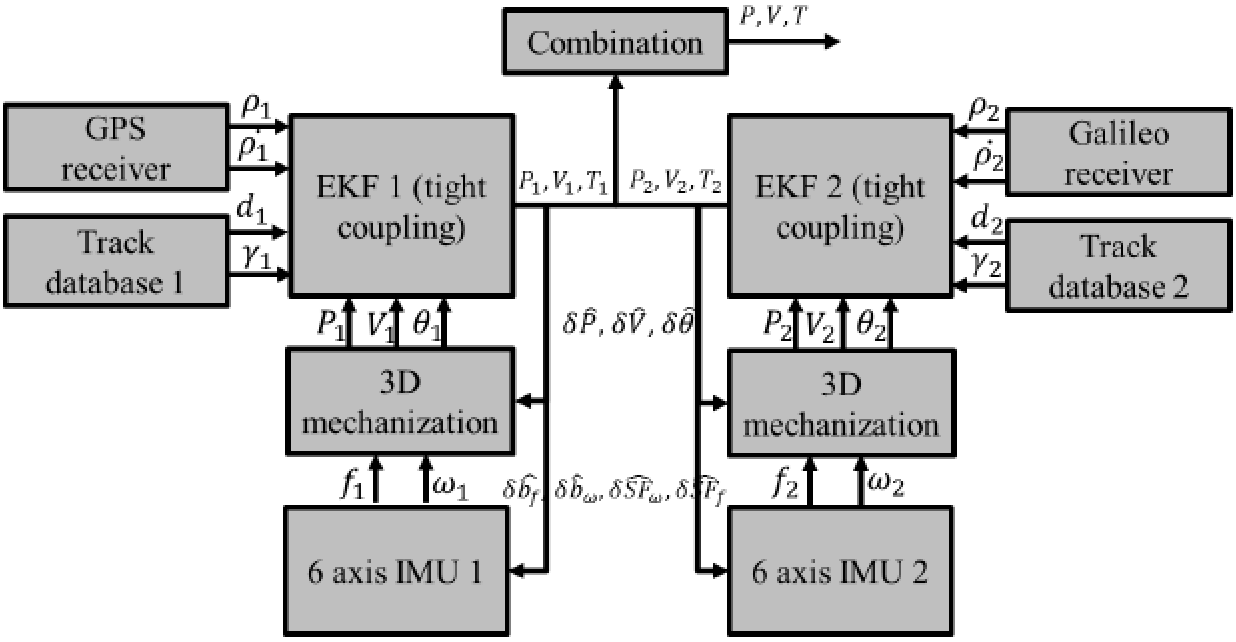

Figure 20 – Basic architecture of the solution proposed for train position determination in train control

- The architecture proposed for ETC integrates WSS measurements

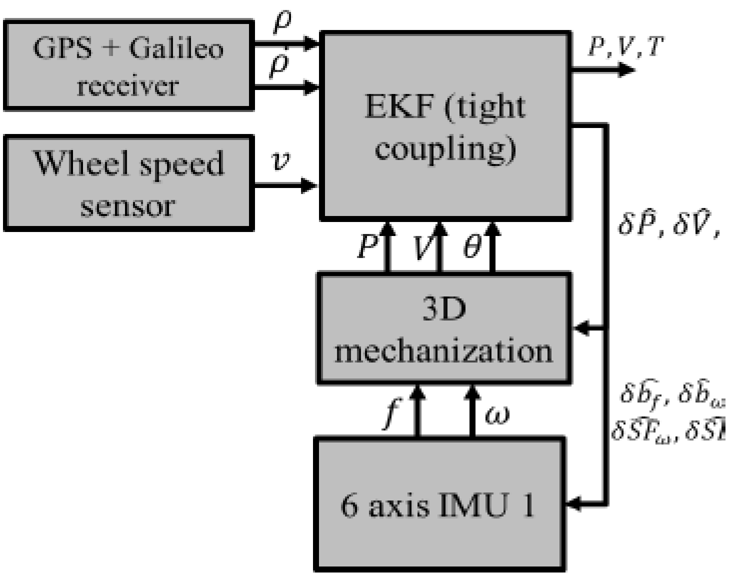

Figure 21 – Basic architecture of the solution proposed for ETC

For train control, the solution proposed is based on two redundant EKF that each integrates measurements from different GNSS, track databases and IMUs in a tightly coupled architecture. As medium cost IMU are used, the inertial sensors are calibrated in real time prior to the inertial mechanization. It is assumed that actual beacons are kept at crossing in order to determine on which track the train is located.

The solution developed for ETC is an EKF that integrates measurements from a dual constellation receiver, an IMU and wheel speed sensors which are already available on board. As for train control, a tightly coupled architecture operating in a closed loop scheme is preferred.

The error models of the different sensors of reference have been studied. They have been divided into nominal measurements and sensor faults. The nominal error models of the inertial sensors have been derived from the datasheet of the IMU. For the GNSS measurements, the civil aviation error models can be applied for both applications, except for multipath and NLOS-induced errors. For these 2 types of errors, models based on simulations conducted on an urban channel model coupled with a realistic tracking simulator were proposed. However, statistical modelling and tests based on real measurements showed that abnormally large pseudorange errors can result from multipath or NLOS. It was thus proposed to integrate these large errors either as nominal errors (as they are frequent in urban environments) or as failure (which means that they must be detected in an efficient way).

The data fusion algorithm, based on an Extended Kalman filtering has been fully described. The way to improve the accuracy of the solution by incorporating additional measurements (motion constraints) to the solution has been discussed. The way to integrate the aiding such as a track database (for train control) or WSS (for ETC) has also been presented. After a thorough validation, their performance were assessed based on simulations using a realistic error models and on a real data collection conducted in Toulouse and surroundings. As Galileo is not currently operational, GLONASS has been used as a second constellation instead. It has been observed that the solutions tested for train control and ETC are able to fulfill the most stringent accuracy requirements in suburban environments. However, it was not the case in dense urban environments. It has also been observed that the motion constraints only slightly improve the accuracy of the solutions. On the other hand the addition of the GNSS Doppler measurements have been shown to improve the accuracy of the proposed solutions.

3.1.19 RHINOS

3.1.19.1 Background

RHINOS aims at increasing the use of EGNSS to support the safety-critical train localization function for train control in emerging regional and global markets. RHINOS adds value to EGNSS by leveraging the results from prior or existing projects, and develops a Railway High Integrity Navigation Overlay System to be used by the rail community.

RHINOS pillar is the GNSS infrastructure realized for the aviation application with additional layers that meet the rail requirements in the difficult railway environments.

RHINOS will feature an international cooperation with the Stanford University that has been involved in the aviation application since the birth of the GPS, gaining an undeniable knowledge of the GNSS performance and high-integrity applications.

3.1.19.2 Objectives

The aim of the RHINOS project is to develop a Railway High Integrity Navigation Overlay System to be used by the rail community. RHINOS's pillar is the GNSS infrastructure realized for the aviation application with additional layers that meet the rail requirements in the difficult railway environments.

The main objectives of the project are:

Objective 1: To define the architecture of a train Location Detection System (LDS) and of the supporting infrastructure, with the following properties:

- Joint use of GPS and GALILEO and wide area integration monitoring and augmentation networks like WAAS in North America and EGNOS in Europe;
- Standard interface (SBAS-R) for providing Safety of Life services for railways through SBASs, regional augmentations or hybrid SBAS/GBAS systems;
- Compliance with European as well as US railway requirements and regulations;
- Sharing as much as possible of the supporting (i.e., augmentation) infrastructure and on board processing, including new developments such as Advanced Receiver Autonomous Integrity Monitoring (ARAIM), with the avionics field;
- Provisioning at the same time, of a set of functionalities tailored to the specific needs of the rail sector.

Objective 2: To assess the performance of the defined architecture by means of:

- A proof-of-concept integrating, in a virtualized test bed, rich sets of data collected in a real railway environment, historical time series related to rare GPS SIS fault events concerning both satellite malfunctions and atmosphere anomalous behaviors (e.g. ionospheric storms), including simulated faults for the new-coming GALILEO constellation;
- Appropriate analytical methods for the verification and safety evidence of defined architecture according to relevant railway safety standards (e.g. CENELEC EN 50129, etc.)

Objective 3: To contribute to the missing standard in the railway sector about the way of integration of GNSS-based LDS, into current Train Control System (TCS) standards (e.g. ERTMS) by publishing a comprehensive guide on how to employ, in a cost-effective manner, GNSS, SBAS and other local infrastructures in safety related rail applications worldwide, and by defining a strategic roadmap for the adoption of an international standard based on the same guide.

The RHINOS work program includes the investigation of candidate concepts for the provision of the high integrity needed to protect the detected position of the train, as required by the train control system application. The EGNSS (GPS and GALILEO) plus the SBAS constitute the reference infrastructure that is available worldwide. In addition to that, local augmentation elements, ARAIM techniques and other sensors on the train are the add-on specific assets for mitigating the hazards due to the environmental effects which dominates the rail application. A further objective of RHINOS is to contribute to the definition of a standard for the Railway High Integrity Navigation Overlay System. The standard is a key success factor for spreading the GNSS application into the rail.

RHINOS will be developed through an international cooperation with the Stanford University researchers that have been involved in the aviation application since the birth of the GPS. They have indisputable knowledge of the GNSS performance and high-integrity applications. The ambition is a positive step beyond the proliferation of GNSS platforms, mainly tailored for regional applications, in favor of a global solution. RHINOS would release the potential benefits of the EGNSS in the fast growing train signaling market. The European Union and United States Cooperation Agreement on ARAIM is a reference model to be taken into consideration for the development of RHINOS. This well-established EU-US cooperation in the aviation sector is expected to be extended to include rail applications. We hope to apply the new understanding of high integrity applications and enhance the emerging role that Europe and USA are having on promoting the rail sector.

The certifiability is the key to operational usage of RHINOS solution. The RHINOS GNSS railway interface is intended for high-safety integrity signaling systems where safety evidence, safety case and system certification are mandatory. The safety concept of RHINOS solution intends to meet the highest railway safety requirements – i.e. Safety Integrity Level 4 (Tolerable Hazard Rate - THR < 10-9 per hour per train) and also fulfil all requirements specified in specific railway safety standards, such as EN 50126, EN 50128, EN 50129, etc. Tasks regarding RHINOS solution life cycle, verification, validation, safety case, and its certification have to be solved by manufactures and notified bodies in successive activities.

The RHINOS solution aims to be a candidate for the global SBAS-R standard. The international standardization of the SBAS-R interface will help to fill the existing gap between the aviation SBAS and railway ETCS standards. This new worldwide standard will significantly support interoperability in railway signaling based on the Virtual Balise concept, especially on long routes within individual regions, like Europe, Africa, Asia, Australia, or between regions such as East Asia-Europe.

3.1.20 RUNE

3.1.20.1 Introduction

In the Railway User Navigation Equipment (RUNE) project, a team led by Laben (Italy) is using European Geostationary Overlay Service (EGNOS) as part of an integrated solution to improve the train driver's situational awareness.

Today, the driver does not receive advanced warnings of the status of signals or speed restrictions and, as a result, it is harder to deploy drivers on new lines. RUNE integrates EGNOS/GPS with other on-board positioning sensors, and signalling and speed restriction information from a central control centre. This will significantly improve safety as a result of improved situational awareness, and should also speed up the deployment of drivers on new routes.

3.1.20.2 Objectives

The primary objective is to demonstrate the improvement of the train self-capability in determining its own position and velocity, with a limited or no support from the track side, and to show that the equipment can comply with the European Railway Train Management System (ERTMS) requirements. The achievement of such objective would lead to the reduction of the frequency of balises distributed along the track line and typically needed to reset the train odometer error. This implies a significant reduction of the infrastructure costs by replacing physical balises with virtual balises, still maintaining the level of safety currently provided. The RUNE project involves both a HW-In-the-Loop laboratory set-up as well as a 3 months field-testing on-board an experimental train of the Italian operator Trenitalia.

3.1.20.3 Applications

The main applications of RUNE are going to be in the Rail domain with particular interest in ERTMS compatible railway operations.

3.1.20.4 Consortium

RUNE has been developed by the European Space Agency in partnership with the Italian company Laben.

3.1.20.5 RUNE Architecture Overview

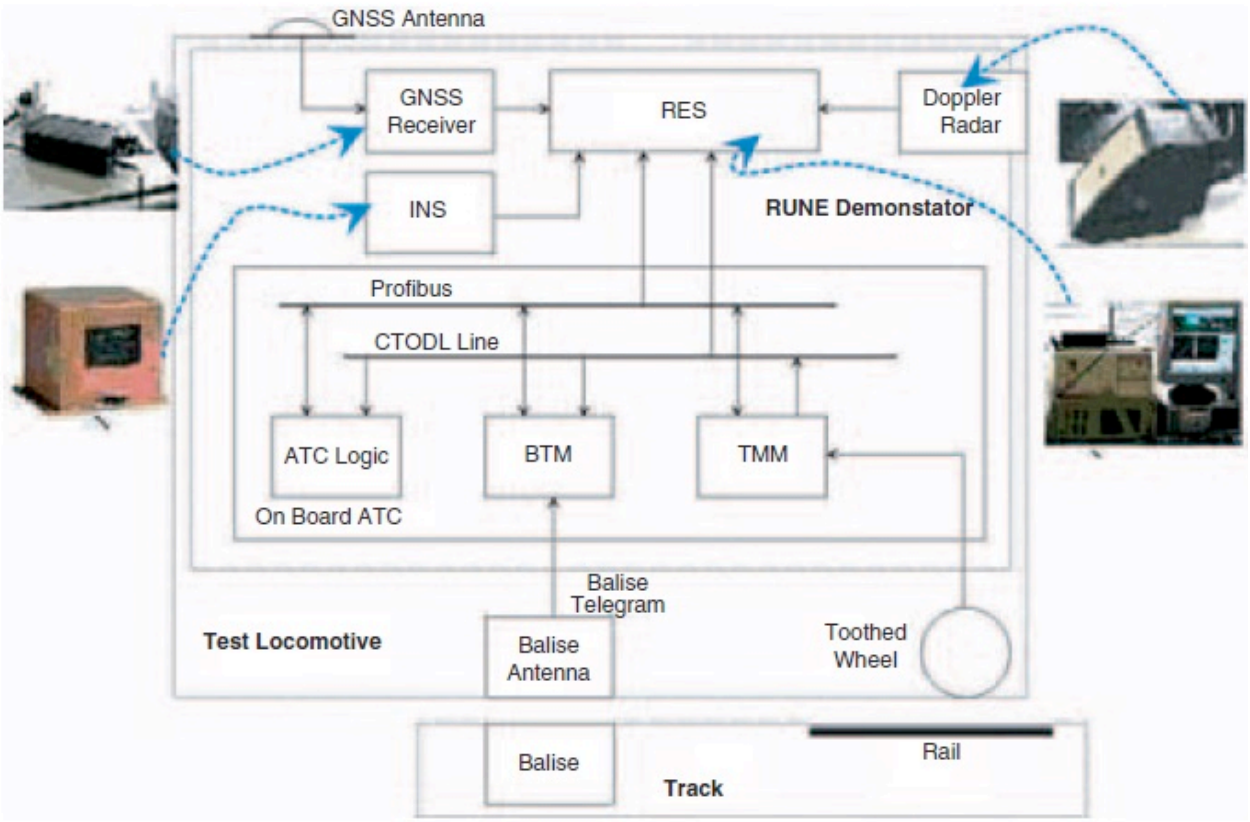

Figure 22 – RUNE Architecture Overview

3.1.21 SafeRail

In order to improve safety at rail level crossings, nowadays passive crossings are either removed or upgraded. Upgrades are expensive, which limits the number of crossings that can be upgraded. Additional costs have to be made for communication and signaling infrastructure in case of remote areas. SafeRail provides a low cost solution using Satellite Navigation and Satellite Communication technology, allowing railway operators to accelerate their level crossing upgrade program.

Based on evaluation of the present situation at level crossings and interviews with stakeholders across Europe who are relevant for the deployment of level crossing solutions (e.g. ÖBB Infrastructure (AT), JHMD (CZ), SZDC (CZ), train operators Stern & Hafferl (AT), Graz Köflach Bahn (AT), and ADAC (DE), Kuratorium für Verkehr (AT) and UIC (FR)), user key needs and opportunities for improvement were identified and translated into the SafeRail System. SafeRail is basically a satellite based train positioning system which enables continuous train detection and safe operation of level crossings.

An upgrade of passive level crossings to active ones is possible at remarkably reduced costs compared with standard upgrading approaches / conventional systems, because of:

- Strongly reduced initial installation costs: no track cabling required

- Future upgrading of additional level crossings requires only additional infrastructure at the respective level crossing, the central part of the system is shared by all level crossing

Even for trains running at different speed the system can now provide homogeneous closure periods to the road user.

SafeRail in its current state is targeted for Rail Operations, because the technical feasibility and business viability assessments have proven to be very promising. Future extensions of SafeRail may include services for Road Users and Rail Maintenance.

3.1.21.1 User and needs

The SafeRail study included a series of workshops and a few tens of expert interviews with users and other stakeholders in order to establish a description of the current situation (and challenges) at level crossings and to conclude on user needs and requirements.

Users considered in this study are:

- Road User
- Train Driver
- Train supervisor
- Rail Inspector

Stakeholders taken into account included:

- Rail Infrastructure Manager (IM)
- Railway Undertaking RU
- National Rail Safety Authority (NSA)
- Road Safety Authority
- Railway Signaling Manufacturer
- Telematics (Data) Provider
- Road Vehicle OEM

The main findings in terms of user requirements are:

- Railway companies want to increase the percentage of road users who respect the traffic rules at level crossings.
- Road users want to be supported with appropriate hazard warnings if there is a specific danger while approaching the level crossing. The road user would like to pursue his journey without being obstructed and without feeling a lack of safety by the operations of the level crossing.
- Traffic safety specialists want to support road users in perception and appropriate action of the situation at the approached level crossing.

- Road users want to have in advance information regarding the status of the level crossing in order to perform an optimal routing.
- Secondary line operators want low cost, yet safety-compliant active level crossing installations (legal conditions require upgrading many passive level crossings to active level crossings due to increased traffic density).
- Secondary line operators and safety authorities prefer short closure periods (yielding less impatient road users crossing early).
- Infrastructure Managers want to support the level crossing inspection with seamless data management and remote inspection.

SafeRail has no general geographical limitation and can be implemented world-wide. The first focus is on Central Europe.

3.1.21.2 Current status

The SafeRail team is currently preparing a demonstration project which will involve equipping at least two secondary rail lines in Central Europe with the proposed SafeRail solution. The aim of the demonstration project is the implementation of a pre-operational SafeRail solution which will be operated for at least 6 months in a "shadow" environment to gain further confidence in the sustainability of the solution. The demonstration project will benefit from a close collaboration with the potential customer and will show the benefits from the integrated use of Satellite Navigation and Communication. This pre-operational SafeRail will be transferred into regular operations after the demonstration phase. The consortium is currently in discussion with strongly interested Rail Infrastructure Managers about further details of the demonstration project.

3.1.22 SATLOC

3.1.22.1 Background

The SATLOC (Satellite based operation and management of local low traffic lines) project comes within the scope of this long-term work. Its objective is to develop and demonstrate an innovative concept of applying the

GNSS to railway safety and advanced operation on low traffic lines aiming at:

- Stimulate adoption of EGNOS in new innovative rail operation with important market impact and with important effects on socio-economic, mobility and environment;
- Prepare markets for Galileo introduction since EGNOS is the precursor of GALILEO and enablers will be created including the awareness and preparation of the railway to immediately apply the new system;
- Stimulate EU GNSS industry competitiveness in domains which are reputed (railway safety, railway integrated operations) for using mostly traditional ground-based technologies and conservative for global approach.

The overall objective provides life demonstration – to create impact and proof of evidence - validated and certified under the EU ruling and applied on the line Brasov – Zarnesti of the RCCF-TRANS (Romania).

3.1.22.2 Objectives of the project

The different objectives of the project are:

- The elaboration and demonstration of innovative conception of GNSS use in the low traffic lines signalling and train control (primary railway safety).
- Enlargement of the GNSS application field to railway safety, with potential of application until ~ 35 - 40% of the rail network in Europe and much higher in the world.
- Alignment of railway solutions for safety to the standards of EGNOS and GALILEO initially set to aviation.
- Creation and inclusion of fully innovative services of integrated rail traffic control and management, real-time information for passengers, increase of transport reliability and quality which are only enabled by the continuous trains' movement supervision with GNSS.

3.1.23 STARS

3.1.23.1 Background

The aim of STARS project is to develop a universal approach to predict the achievable GNSS performance in a railway environment, especially for safety critical applications within ERTMS (The European Railway Traffic Management System).

The result will allow the railway companies to guarantee the interoperability between the equipment provided by different GNSS suppliers.

This shall make it possible to include GNSS into ERTMS, while maintaining both the safety of the system and the interoperability to fill the technology gaps in order to reach a cost-efficient satellite-based ERTMS.

As a result of the project it shall be possible to predict performance of GNSS in the railway environment in regards to accuracy, availability and safety. This shall be possible for specific locations or sections along railway lines, and based on using a receiver compliant with the guidelines as defined in the NGTC project.

3.1.23.2 Objectives

The aim of the STARS project is to develop a universal approach to predict the achievable GNSS performance in a railway environment, especially for safety critical applications within ERTMS (The European Railway Traffic Management System).

3.1.24 TR@IN-MD

Hazardous goods traffic should rise up of 35 % until 2020. SNCF Freight Activity wants to enhance its presence in that sector, which represents more than 16 millions of tons in France / 5.9 billion ton-kilometers.

Due to increased regulation for such products and customer requirements for better service, logistic operators must improve the level of service by monitoring, in particular with tracking and tracing, innovative services for customers, security and safety.

The French TR@IN-MD project currently experimenting with an innovative system, which is able to better manage the hazardous goods traffic by precise tracing facilities: geolocalization and real-time diagnosis of goods or wagons with the help of on board innovative sensors.

These sensors / beacons will communicate with a new information system used by central and local railway operators, linked with customers systems for services such as positioning and fleet management.

The Tr@in-MD tests began in 2006, tracking 10 chemical carrying wagons with different GPS/GSM beacons. In 2008 & 2009, 20 to 30 wagons will be equipped with sensors for remote diagnosis.

TR@IN-MD project is supported by the French Land Transport Research program PREDIT, and includes a 9 partner consortium, led by SNCF.

3.2 Baseline Architectures (T1.2)

The GNSS based architectures summarised in 3.1 are both widespread and wide-ranging. Proposed implementations for the rail sector vary as a result of the extent to which they take account of existing positioning architecture to meet legacy demands and to the extent they utilise additional sensors, typically inertial but potentially odometers, video, LIDAR. Section 3.2.1 shows the ECTS positioning architecture based on the eurobalise and odometry before 3.2.2 presents the notion of the virtual balise concept and

3.2.1 ECTS Architecture

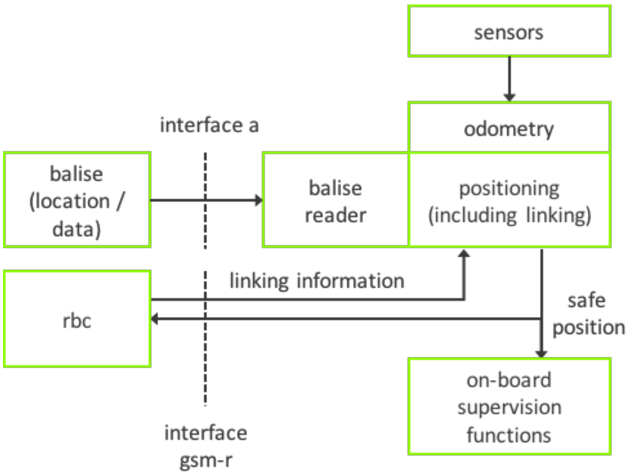

Figure 23 – Current ETCS Positioning Architecture

Sensors typically included wheel tachometers and Doppler radar but may also include standalone accelerators or within inertial platforms. The odometry function generates speed and distance with given accuracy and safety requirements. It outputs a confidence interval. The balise reader detects balises on the track and delivers an absolute reference position and balise data. The positioning function determines the position of the train based on the last balise, train orientation and odometry information. This information is then provided to on-board functions and to the trackside control (RBC).

3.2.2 Virtual Balise 1

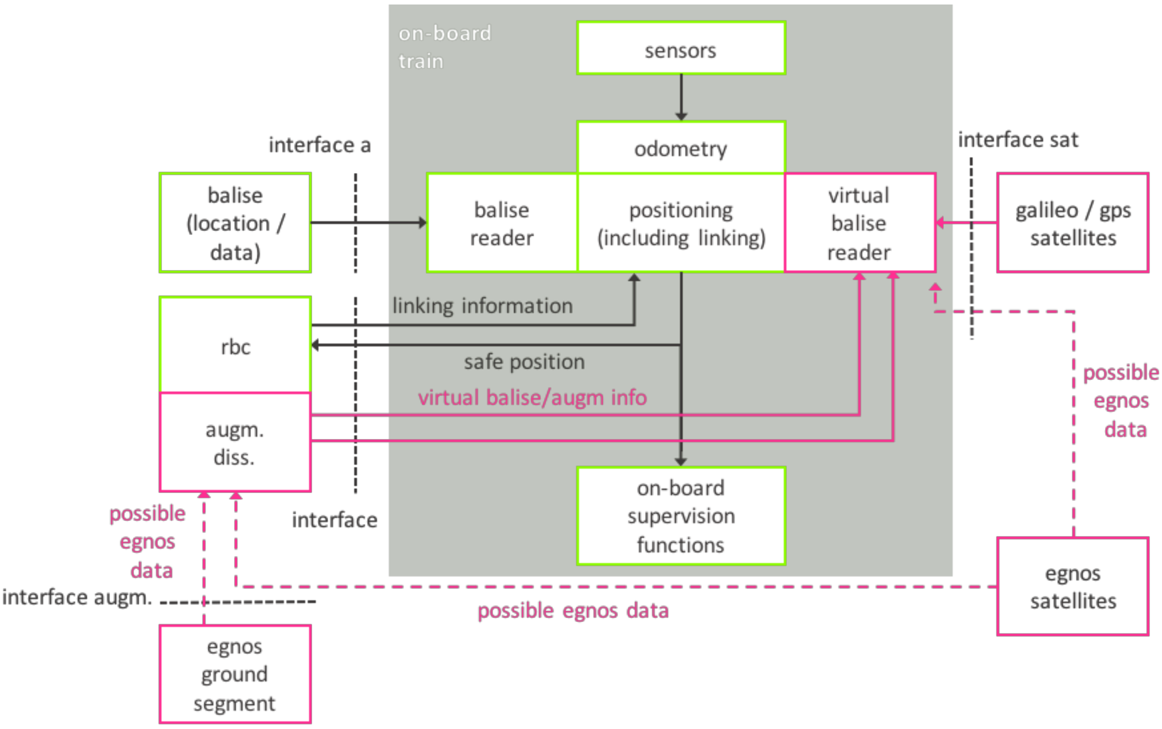

Figure 24 – Proposed Virtual Balise Based Architecture

The architecture presented in Figure 24 is intended to match and mimic the functionality of the classic ECTS architecture given in Figure 23. In addition to the existing legacy functions, some balises would be replaced by *virtual balises* that are *detected* by passing a location as determined by the GNSS capability, contained within the *virtual balise reader*. Augmentation system information may be provided either directly to the train using an SBAS receiver or from a trackside dissemination that obtains the data either directly from the ground segment or through reception from EGNOS satellites (or other source).

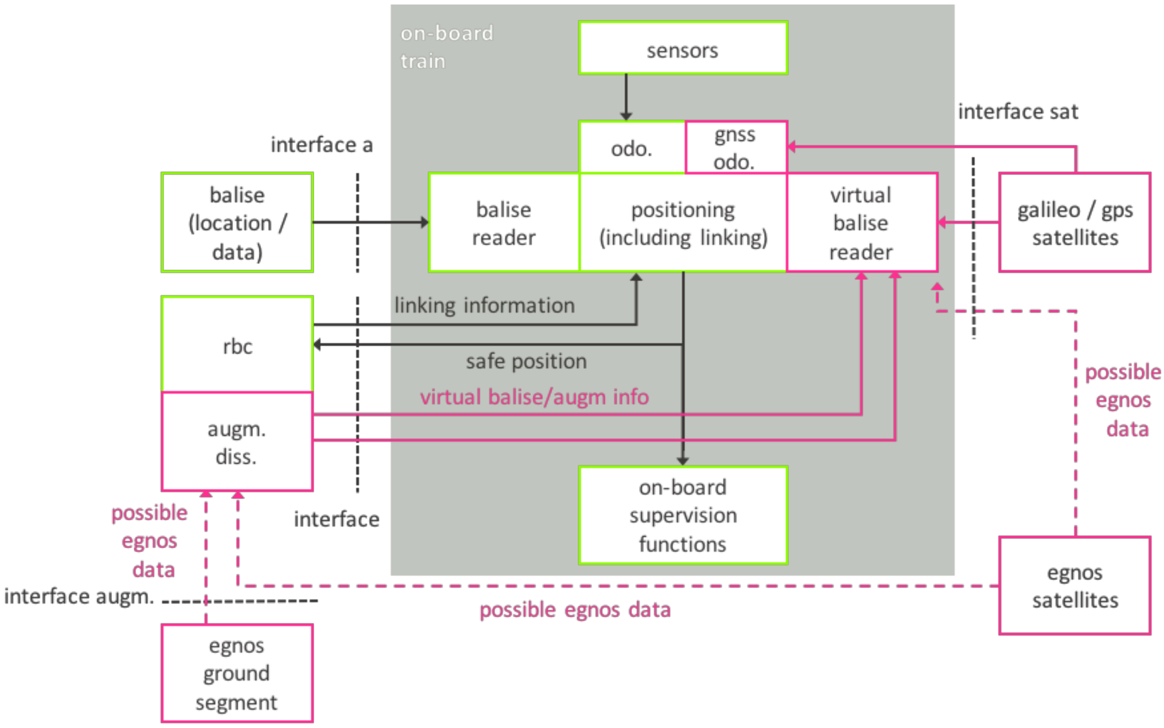

Figure 25 – Proposed Virtual Balise + GNSS Odometry Architecture

3.2.1 Baseline Architecture 1 – RHINOS

Within the ASTRail project WP1, two baseline architectures have been selected for study. The first is based on the RHINOS project expressed in 3.1.19.

RHINOS architecture has been selected as reference for ASTRAIL study because it is considered to be close to the core concept of ASTRAIL. In particular, it deals with the Virtual Balise Concept, involves SBAS augmentations and couple GNSS and odometer data. RHINOS study provided a reliable solution for designing a GNSS based architecture in the framework of the ASTRAIL project.

The RHINOS architecture has been interpreted in Figure 25. Recall that it is based on a code-based solution employing SBAS and Local Area Differential GNSS (LADGNSS) corrections within a snapshot Weighted Least Squares (WLSE) estimation. This allows an easier integrity development. Furthermore, carrier phase measurements are used for smoothing only, prior to incorporation of the pseudoranges into the positioning algorithm. Single frequency observables processing is used in order to limit the impact of multipath. The RHINOS project architecture is only therefore able to ensure the along track position without the ability to discriminate tracks.

Techniques that could potentially augment the performance of RHINOS are:

- Divergence-free processing could be used to limit the impact of ionospheric divergence transients not common to the LADGNSS network (McGraw and Young 2005).
- Relative RAIM function to perform carrier phase coasting of the protection level through regions of high signal blockage, shadowing and multipath.

Possible weaknesses of the RHINOS model are:

- The use of a probabilistic model for extreme multipath must be further understood and justified. Potentially not in line with a specific risk approach
- Optimistic view of the SBAS/LADGNSS satellite failure monitoring down to 1e-9 for full failure magnitude range.
- Potentially costly LADGNSS service if GBAS is the model for multipath.

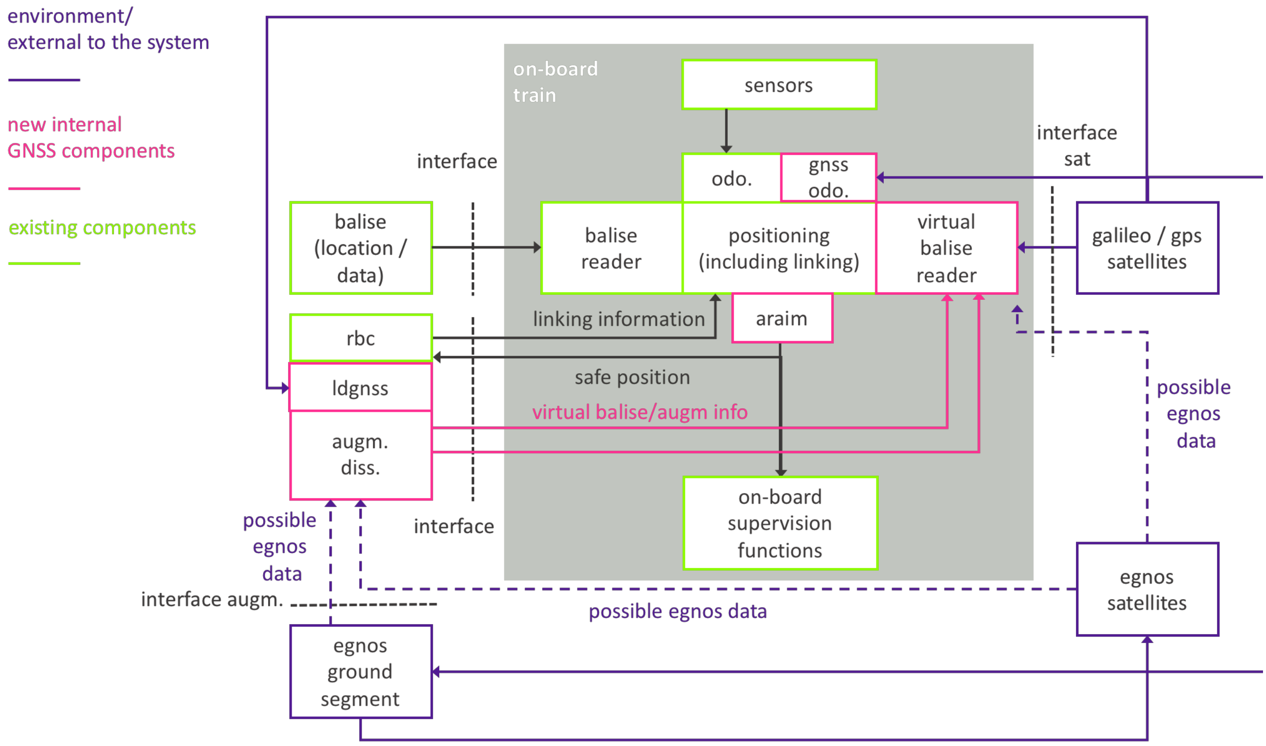

Figure 26 – RHINOS architecture

3.2.2 Baseline Architecture 2 - BROCARD

In Figure 27 an alternative architecture is given based on the project given in 3.1.18.

Philippe Brocard PhD represents a serious alternative to RHINOS project. That solution did not focused on the Virtual Balise concept but proposed a detailed algorithmic solution integrating GNSS and odometer or track database. The study performed in the framework of its PhD received a full technical revision from navigation experts through revision of the PhD thesis and presentations of several papers in international conferences.

This methodology follows a similar approach to the 1D algorithm given in 3.1.15 but instead uses solutions based on separate constellations hybridized with independent six-state Inertial Measurement Units (IMUs). Since the inertial and GNSS sensors are hybridized using a tightly coupled architecture, the integrity concept will be complex, far more so than that of the RHINOS architecture. The advantage of this approach is the lack of a ground infrastructure to support the provision of corrections. Instead the solution is aided by the independent sets of three gyrometers and three accelerometers. This adds additional cost to the train implementation but reduces the cost of the trackside systems.

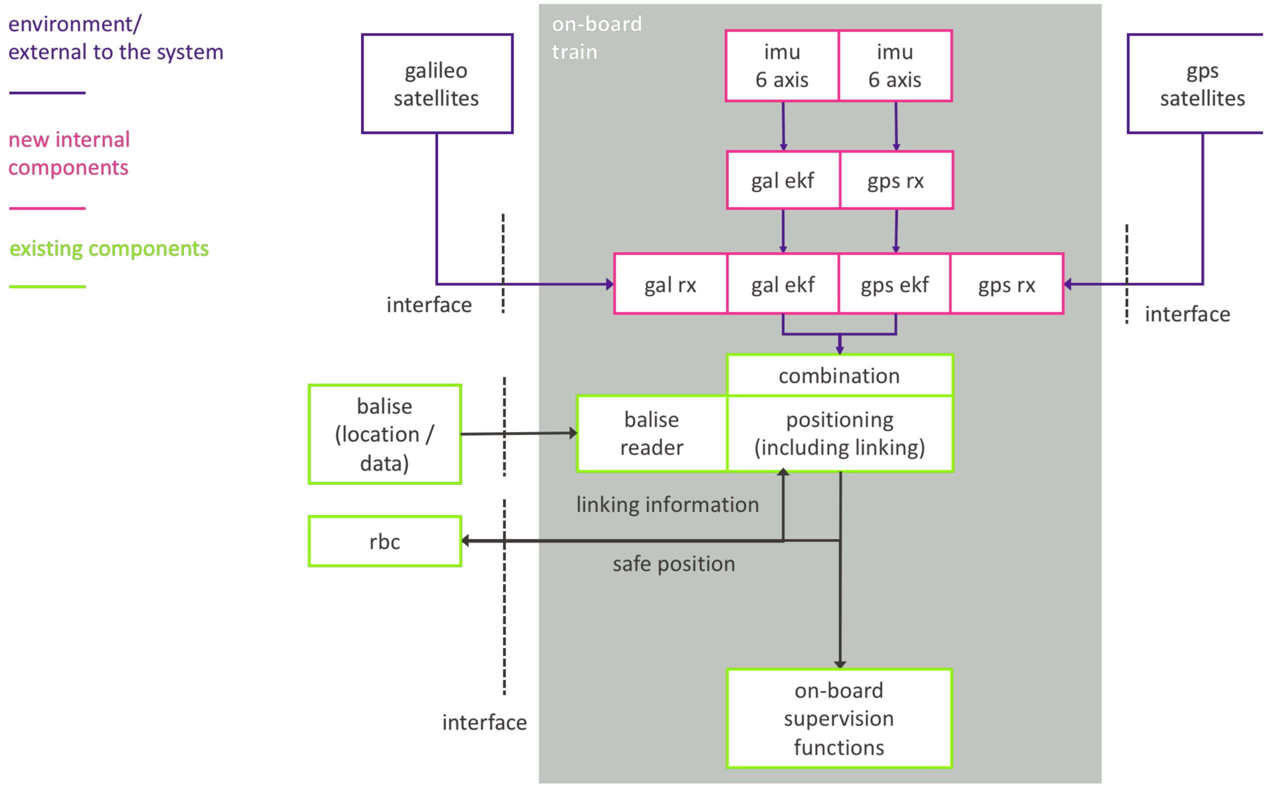

Figure 27 – Brocard

4 Aviation to Rail Transfer

4.1 Key Assumptions (T1.1)

ASTRail contributors have discussed the key points relating to the transfer of GNSS to rail, in particular the mapping of RAMS requirements. The group agreed that given the architectural constraints, the project should concentrate on the solution which provides along track positioning only, without the ability to perform track discrimination. The justification for this decision is that whilst track discrimination would be the ultimate success for GNSS use, it is infinitely more feasible to enable determination of the along track position. The previous works presented in 3.1 have considered both along track position and track discrimination but the proposed architectures focus on achieving only the along track integrity level. Attaining a protection level at a level of 2-2.5m is likely to require carrier phase-based positioning techniques which whilst precise are not currently sufficiently robust for safety of life applications, notably they are not under consideration for airport surface operations for aircraft arriving at the gate. Instead for track discrimination it may be more fruitful to utilise other sensors as addressed in WP3.

In order to define an architecture for positioning and integrity in rail, the following key assumptions are taken from civil aviation. Note that in some cases, further decisions are needed on the values.

KA.1 Along track positioning to be addressed in ASTRail. Proposed approach to first generation of GNSS for rail.

Given the time constraints of the project and the technological constraints at the current state-of-the-art it, such a restriction is sensible.

KA.2 Virtual Balise concept to be the basis for architectural integration.

Given the emphasis of the proposal and the recent project outputs at the time of writing, the Virtual Balise concept was preferred.

KA.3 The prior probability of a single satellite failure (e.g. no greater than 10^{-4} per hour per satellite for GPS)

Such an assumption will be needed for Augmentation System (i.e. EGNOS) assessment.

KA.4 The prior probability of a wide failure (constellation) (e.g. no greater than 10^{-4} per hour for Galileo)

Such an assumption will be needed for Augmentation System (i.e. EGNOS) assessment.

KA.5 The prior probability of a constellation outage is zero

Such an assumption does not impact safety integrity, only the predicted availability of the system. Given the low risk behind this assumption a practical value based on previous aeronautical decisions is chosen.

KA.6 The probability of common constellation failure is zero

Such an assumption has been studied in detail within aeronautical Working Group C. The analysis is of very high standard by the most recognized international experts.

KA.7 The nominal distribution of ranging errors may be over-bounded by a non-zero mean Gaussian model with known nominal bias and standard deviation

Such an assumption has been used extensively in aeronautical applications. By Gaussian model, temporal correlation effects are not excluded, nor are variations of the model with time (non-stationarity). The relevant parameters remain to be determined.

KA.8 The ranging errors of each pair of satellites may be considered to be mutually independent when using zero-differenced measurements

Such an assumption has been used extensively in aeronautical applications.

KA.9 The temporal correlation of GNSS ranging errors may be modelled by a first order Gauss Markov process with correlation time for clock and ephemeris of 30 minutes (GPS), for the troposphere of 15 minutes (all), for the multipath and noise based on specific antenna and application, TBD.

Such models are standard approaches in GNSS although in the local environment it is important to consider the stationarity of the employed model.

KA.10 The constellation slot (healthy) probabilities may be taken from the service commitments

Such probabilities impact the availability outcomes and are not a safety issue. The service commitments may be taken as reasonable.

KA.11 The time for the control segment to flag an unhealthy satellite (e.g. average of 1 hour and no greater than 6 hours for GPS)

When not employing a differential system, the control segment response assumption is needed.

KA.12 GPS Satellite ephemeris sets are uploaded typically every 12 hours and each is broadcast every 2 hours

When not employing a differential system, the upload rate is needed. Also in differential mode such assumptions are required for IODE management.

KA.13 The discontinuation of a GNSS satellite service by a provider will be preceded by a minimum six year notification period

Such an assumption has been used extensively in aeronautical applications to justify trust in the availability of the navigation system.

KA.14 The assumed specification of the RF environment will be consistent with the real environment

The modelling of the RF environment must be sufficient to place confidence in this assumption.

KA.15 In order to minimise the impacts of multipath on positioning solution, single frequency observables are proposed to be used

A reasonable approach to mitigate ionospheric errors using differential corrections

KA.16 Ionospheric errors will be mitigated through corrections

A reasonable approach to mitigate ionospheric errors using differential corrections

KA.17 For the purposes of GNSS signal-in-space performance specifications the receiver is assumed to be fault-free. It is a receiver with nominal accuracy and time-to-alert performance and has no failures which impact SIS integrity, continuity and availability

Such an assumption has been used extensively in aeronautical applications.

KA.18 A Failure Mode and Effects Analysis captures the key failures which must be mitigated through monitoring

Whilst an FMEA process has been followed by the RTCA and WG-C for aeronautical applications due to the variation in environment.

KA.19 Multiple failures may occur at the same time with a determinable and trusted probability of occurrence (ARAIM).

Such an assumption has been used in aeronautical applications

KA.20 The integrity risk may be assigned to different parts of the system. For example a fault free risk might be computed on board, whilst satellite failure is handled by ground (trackside) infrastructure.

Such an approach has been used extensively in aeronautical applications

KA.21 Fault detection will be based on hypothesis testing, be it performed trackside within a DGNSS based architecture or on-board within an Autonomous Integrity Monitoring (AIM) architecture.

Such a statistical approach is necessary to meet the probabilistic requirements.

KA.22 When the prior probabilities of known fault modes (or derived models) are known, the probability of hazardously misleading information (integrity risk) may be determined using a multiple hypothesis approach

For an autonomous integrity monitoring solution this approach is optimal over a worst case approach

KA.23 Errors may be characterized as either nominal, narrow faults affecting a single satellite or wide faults affecting multiple satellites simultaneously.

This classification is logical and has been employed in aeronautical applications.

KA.24 Errors and faults which may impact the system include, satellite clock errors, satellite orbit errors, code-carrier incoherence, inter-frequency bias, satellite antenna bias, ionospheric delay, tropospheric delay, receiver noise and multipath.

This fault list has been employed in aeronautical applications following previous FMEA studies.

KA.25 Ionosphere-free smoothing with the same smoothing constant as used in single frequency carrier smoothing is subject to larger multipath and noise errors in a statistical average sense.

Such a relation has been well established during aeronautical developments.

KA.26 Divergence-free smoothing with the same smoothing constant as used in single frequency carrier smoothing is subject to equivalent multipath and noise errors in a statistical average sense.

Such a relation has been well established during aeronautical developments.

KA.27 For an integrity risk specified over an operation, operational interval or arbitrary interval (e.g. 1hour), this refers to the probability of an out of tolerance condition at any point within the interval and thus must be allocated to each cycle of the integrity monitoring algorithm.

This mapping is a necessary one to ensure requirements are met in the long term.

KA.28 Specific risk approach is appropriate for rail requirements setting.

This safety focused philosophy is applicable to the highly stringent rail domain.

4.2 Initial Rail Requirements (T1.2)

Many of the final requirements to be defined in T1.8 will depend upon the decisions taken regarding the architecture and algorithmic development. Here some key initial requirements are given.

KR.1 Receivers shall be tested under controlled environmental conditions (pressure, temperature, humidity etc.) within a lab to ascertain aeronautical suitability

As employed in aeronautical standards this is critical to ensuring the quality, reliability and safety of the solution.

KR.2 The receiver shall monitor for undetected cycle slips

A standard requirement for an operational receiver.

KR.3 The receiver shall meet the tracking constraints shown in Figure 4 or Figure 5 depending upon the relevant implementation.

Standardisation of tracking constraints is important for limiting differential biases and reducing performance assessment loads.

KR.4 Any reference receivers shall fail with a probability less than a prescribed value (e.g 10^{-5} per hour)

Reference receivers must be reliable to allow a reasonable allocation of risk and monitoring.

KR.5 Ground corrections accuracy shall meet a designated levels TBD in the standards

In order to meet a global system requirement, correction will be required to meet a level of accuracy TBD

KR.6 Safety integrity is not assured in the event that the receiving unit fails to receive three consecutive corrections messages (MT1)

A requirement regarding missed communications is necessary to protect against unindicated faults.

KR.7 Any reference receivers shall provide data for corrections processing at a minimum rate of 1Hz

Corrections must be provided at a reasonable rate to facilitate frequent movement authorities.

KR.8 Fault Detection algorithms must meet an allocated missed detection probability

Allocation of global tolerable hazard rates (THR) must be further passed to the monitoring functions taking into account prior probabilities of such states.

KR.9 Fault Detection algorithms must meet on allocated false detection probability on average in a manner that allows the total Availability and Reliability requirements to be met.

Thresholds must be set for detection and to ensure global requirements on the reliability of the system are met, they should be fed down to false detection rates.

KR.10 Receiver manufacturers must verify performance with respect to predefined test procedures and where necessary demonstrate performance with additional tests.

Test procedures are required to verify the performance of any autonomous fault detection functions.

5 Conclusions

This deliverable, D1.1 of ASTRail has presented too key areas of work. Firstly, a review of civil aviation requirements and their relation to railway RAMS requirements has been made (section 2). Secondly a thorough review of previous studies of GNSS use in rail has been presented (section 3). Based on the review of previous projects, two architectures have been taken forward, a primary baseline, based on the RHINOS project and a secondary hybridised solution (Brocard). It is clear that the assessment of the performance of the chosen architecture will depend upon the assumptions taken. These include the prior probability of failures, the error model assumptions, including the correlation properties and the allocation of integrity risk between subsystems and monitors.

Section 2 presented the work of ASTrail WP1 tasks 1.1 and 1.2 on the transfer of assumptions and requirements for the application of Global Navigation Satellite Systems (GNSS) from the civil aviation domain to the rail domain. The philosophy taken has not been to apply the civil aviation requirements, specified in terms of the four Signal-In-Space parameters of accuracy, integrity, continuity and availability. Rather, the approach is to use the railway formulation of requirements in terms of Reliability, Availability, Maintainability and Safety with guidance from the experience of civil aviation.

It is noted that in comparison to the reliability and safety of existing railway components, GNSS safety integrity, meaning the trust that the positioning and localisation solution is not subject to dangerous undetected errors, is a function of time. This is as a result of the non-stationary error distributions due to satellite motion. Furthermore, the Safety Integrity Level (SIL) must be achieved under all stated conditions as per the rail industry standards, this is interpreted to account for the worst-case conditions regarding the impact of a failure and other driving parameters relating to the measurement error model. In fact, what is known as *specific risk* in the aviation world, should be applied when safety is at stake. If a parameter's distribution is not well-known (overbounded correctly), or is predictable in some same, then the specific risk (worse case value) should be used.

The SIL in rail is referenced to a Tolerable Hazard Rate (THR) for a particular function, notably 10^{-9} per hour for SIL4 the most demanding level. This THR is the total risk during any hour of function. Since the probability distributions for the components are with conventional systems stationary, the designer only has to compare a computed hourly risk to the requirement to check compliance. With GNSS, since the real time risk varies, compliance must be verified in real time, unless it can be guaranteed that the requirement is met whatever the state of the system.

ASTRail accepts that the virtual balise concept is well established as a means to integrate a GNSS based positioning component to the rail localisation unit (LU) without a complete overhaul of the train architecture. This concept will then form the backbone of the architectures addressed in ASTRail. However, GNSS may also be used to provide a more frequent position update than provided by physical balises and thus relax requirements on the odometry function.

The approach setup in this document which will be followed throughout WP1 is to map RAMs requirements directly to the needs of the GNSS receiver requirements and not through the Signal-In-Space (SIS) requirements framework of civil aviation. This no doubt requires GNSS expertise, and it is critical when assessing the hazard of an incorrect GNSS location determination, that the correlation of errors be accounted for in order to model the duration of a fault condition. Similar with regards to the availability and reliability, it is shown herein that continuity is not the most appropriate means to quantify the performance at some SIS level since it is a measure of unpredictable events. Instead, system outages, or (non-hazardous) failures may be predictable due to the changing geometry of the constellation. It is therefore advised that a finer analysis of the up and down time with respect to all possible causes be performed for the use of GNSS in rail and that through this, the RAM requirements may be both set and validated. This will not obviate the need for a certain failure risk to be assigned to real-time monitors for threats in the same manner that the continuity budget is employed to compute the required probability of false alarm.

Studies of the current advances in civil aviation augmentation systems, which is being continued in T1.4, show that certain techniques may be applicable to the rail application. Namely, the multiple hypothesis approach of Advanced RAIM offers improved local integrity monitoring for the train’s on-board function. Dual frequency positioning and monitoring techniques developed within the next generation GBAS work may help to inhibit some effects of ionosphere whilst reducing through smoothing the multipath. Such elements will be studied in greater detail in T1.6 and T1.7.

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