D3.1 High-Level Design Document

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EXECUTIVE SUMMARY

This document is the deliverable **D3.1 High-Level Design Document** which describes the design of the high-level HELMET architecture with focus on the main general architecture solutions for the augmentation network subsystem as well as the general architecture solution for the onboard subsystem for each transportation segments. This deliverable starts by reviewing the user and system requirements as specified in deliverable D2.3. Then, it presents the HELMET high-level architecture solutions for augmentation, rail, automotive and UAV at general subsystem level. The general subsystem architecture is then used to convert the system and user requirements to the subsystem level including the traceability matrix at subsystem level. This document then tackles the identification of the technological gaps to satisfy such requirements. Finally, this document also covers the high-level design of the record and playback unit that will be used during HELMET project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DEFINITION AND ABBREVIATIONS

Acronym	Description
A	Availability
ABIA	Avionics Based Integrity Augmentation
ADS-B	Automatic Dependent Surveillance - Broadcast
AIMN	Augmentation and Integrity Monitoring Network
AL	Alert Limit (defined by user)
ARAIM	Advanced Receiver Autonomous Integrity Monitor
ASIL	Automotive Safety Integrity Level
ATP	Along Track Position / Positioning
ATPL	Along Track Protection Level
BTM	Balise Transmission Module
CAN	Controller Area Network
CC	Control Center
CCF	Common Cause Failure
CCS	Control Command and Signalling
CCS TSI	Control Command and Signalling Technical Specifications for Interoperability
CENELEC	Comité Européen de Normalisation Électrotechnique
CGS	Control Ground Station
CHK	Check
CMD	Cold Movement Detector / Detection
CNPC	Control and Non-Payload Communications
CONOPS	Concept of Operations
DaA	Detection and Avoidance
DB	Track Database
DCB	Differential Code Bias
DHD	Double Heading Differences
DTE	Driving Technical and control Error
E/E/PE	Electrical/Electronic/Programmable Electronic
EDAS	EGNOS Data Access Service
EGNOS	European Geostationary Navigation Overlay Service, i.e. European SBAS
EM	electro magnetic
ERSAT GGC	ERTMS on SATellite – Galileo Game Changer
ERSAT-EAV	ERTMS on SATellite – Enabling Application & Validation
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
EU	European Union
EUREF	IAG Reference Frame Sub-Commission for Europe
EVC	European Vital Computer
FDE	Fault Detection and Exclusion
FDIR	Fault Detection, Isolation and Recovery
FEE	Front End Electronics
FOG	Fibre Optic Gyroscope

FR	Failure Rate
FTA	Fault tree Analysis
Galileo	European GNSS
GBAS	Ground Based Augmentation System
GCS	Ground Control Station
GEO	Geostationary Earth Orbit satellite
GNSS	Global Navigation Satellite System
GNSS Rx(rx)	GNSS Receiver
GPS	Global Positioning System
GRSP	Galileo Reference Service Provider
GSA	European Global Navigation Satellite Systems Agency
HAS	High Accuracy Service
HELMET	High integrity EGNSS Layer for Multimodal Eco-friendly Transportation
HR	Hazard Rate
HPL/VPL	Horizontal/Vertical Protection Level
IMTM	Inspection, Monitoring and Traffic Management
IMTM UAS/RPAS-PI	Inspection, Monitoring and Traffic Management + Unmanned Aircraft System / Remotely Piloted Aircraft Systems. In this PIT station the UA/RPA can land and refuel batteries based for instance on a non contact equipment.
IMU	Inertial Measurement Unit
INDEP-CHK	Independent Check
INS	Inertial Navigation System
K_{fa}	Coefficient of False Alert
K_{md}	Coefficient of Missed Detection
KVH FOG	KVH (i.e. name of company) Fibre Optic Gyroscope
LDS	Location Determination System
LiDAR	Light Detection and Ranging
LNA	Low-Noise Amplifier
MA	Movement Authority
MDE	Minimum Detectable Error
MEMS	Micro Electro Mechanical Systems
METEO	Meteorological Conditions
MFMC	Multi frequency Multi-constellation
MI	Misleading Information
MOBU	Multi-sensor On-Board Unit platform
MTBF	Mean Time Between Failure
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
NAV	Navigation
NAVAIDS	Navigational Aids
NLOS	Non-line-of-sight reception
NMEA	National Marine Electronics Association
NP	No Power
NRTK	Network RTK
NTRIP	Networked Transport of RTCM via Internet Protocol

OBU	On-Board Unit
PF	Probability of Failure (average) per 1 hour
PHMI	Probability of Hazardously Misleading Information
PIT-Station	On ground Service Station
PL	Protection Level
Pmd	Probability of Missed Detection
PPK	Post-Processing Kinematics
PPP	Precise Point Positioning
PPP-AR	PPP Ambiguity Resolution
PPS	Pulse Per Second
PTP	Precision Time Protocol
PVT	Position, Velocity, Time
QoS	Quality of Service
RAIM	Receiver Autonomous Integrity Monitor
RBC	Radio Block Centre
RF	Radio Frequency
RHINOS	Railway High Integrity Navigation Overlay System – H2020 project
RIMS	Ranging Integrity Monitoring Stations
RIU	Receiver Interpolation Uncertainty
RNP	Required Navigation Performance
RPS	Remote Pilot Stations
RS	Reference Station network
RTCM	Radio Technical Commission for Maritime Services
RTK	Real Time Kinematics
RTM	Requirements Traceability Matrix
RXFE	Receive Front End
SBAS	Satellite Based Augmentation System: e.g.: EGNOS, WAAS, MSAT, SDCM, GAGAN
SDC	Self-Driving Car
SDR	Software-Defined Radio
SDT	Safe Down Time
SIL	Safety Integrity Level
SIS	Signal-In-Space
SNR	Signal to Noise Ratio
SoL	Safety of Life
SOM	Start of Mission
SR	Staff Responsible
SSR	State Space Representation
SW	Software
TDN	Time to failure Detection and Negation
TFFR	Tolerable Functional Failure Rate
THR	Tolerable Hazard Rate
TPL	Train Position Locator
TT&C	Telemetry, Tracking & Command
TTA	Time-To-Alert
U	Unavailability

UA/RPA	Unmanned Aircraft/ Remotely Piloted Aircraft
UART	Universal Asynchronous Receiver/Transmitter
UAS	Unmanned Aircraft System
UAS/RPAS	Unmanned Aircraft System / Remotely Piloted Aircraft Systems
UAV	Unmanned Aerial Vehicle
UNISIG	Union Industry of Signalling
UOBU	UAS On Board Unit
UTM	Unmanned Aircraft System Traffic Management; UAV Traffic Management
VB	Virtual Balise
VBN	Visual Based Navigation
VBR	Virtual Balise Reader
VTOL	Vertical Take-Off and Landing
WFOV	Wide Field of View
ZTD	Zenith Tropospheric Delay

1. INTRODUCTION

In deliverable D2.3 the user and system requirements are defined and specified. The architecture of the system from multiple levels is designed progressively based on the requirements, as shown by the dependency diagram in Figure 1.

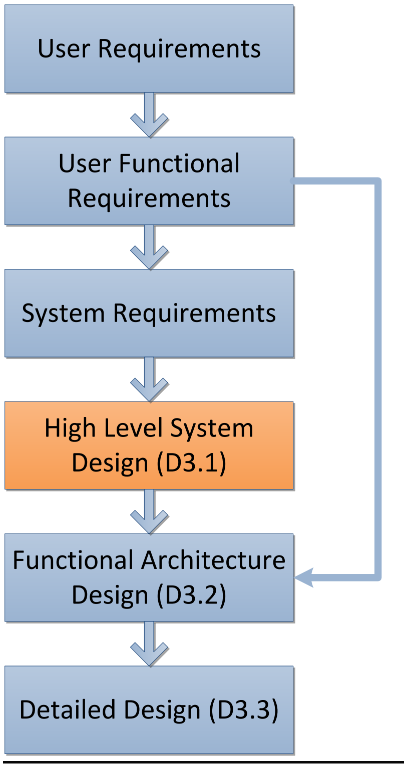

User Requirements
User Functional Requirements
System Requirements
High Level System Design (D3.1)
Functional Architecture Design (D3.2)
Detailed Design (D3.3)

Figure 1: General design flow

Based on the user and system requirements, the multimodal positioning and localization system architecture is proposed so that the requirements can be fulfilled. Figure 2 clarifies the division of different hierarchies used for the system design. The high level design implies the architecture on the system and subsystem level in the context.

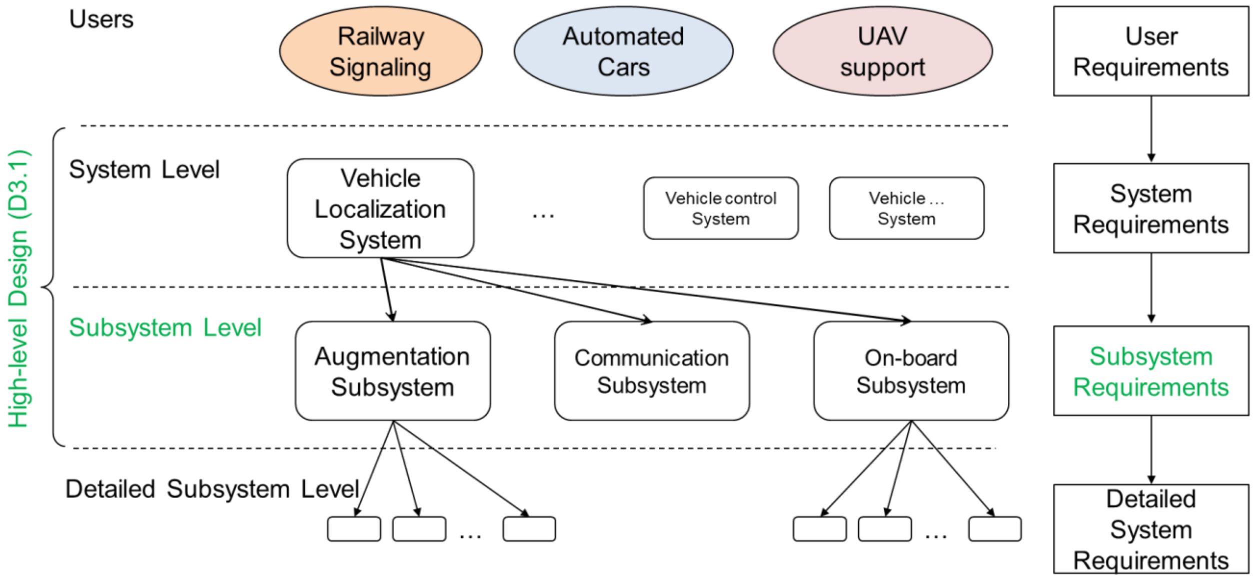


Figure 2: Overview of different design levels and their dependency

2. REVIEW OF SYSTEM REQUIREMENTS

This section reviews and summarizes the system level requirements from D2.3 [2] related to the vehicle localization system.

2.1 PROPOSED SYSTEM REQUIREMENTS REVIEW AND JUSTIFICATIONS

The System Requirements for the multi-modal HELMET solution have been derived from the HELMET high-level User Requirements, with the identification of constraints and limitations, specifying models and architectures of RAIL, AUTO and UAVs in order to perform an accurate safety analysis.

The requirements of railway applications are specified in section 5.1 of D2.3 [2]. Compared with the railway application, the road traffic has more diversity in the vehicles and environments, which also results in diverse requirements. The system requirements as functions of vehicle dimensions as well as the road and lane width are analysed in section 5.2 of D2.3 [2]. In this section, we calculate specific quantitative requirements for automotive with some typical values in order to better guild the following system design and development.

The most demanding requirement comes from the lateral dimension of the in-lane vehicle localization, which is defined by the following equation in D2.3 (and illustrated by Fig. 2) [2]:

$$AL_{lat} = \frac{W_{lane}}{2} - \frac{W_{veh}}{2} - DTE_{max}$$

where W_{lane} and W_{veh} are the width of the lane and the vehicle respectively, and DTE_{max} is the maximum driving technical and control error.

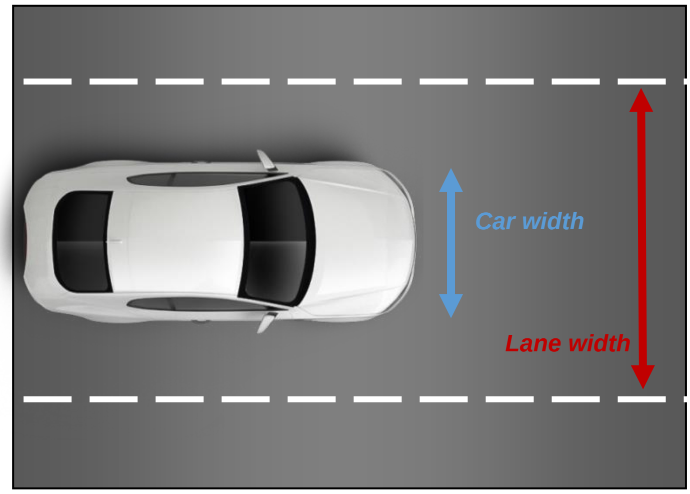


Figure 3: In-lane vehicle localization/positioning

In order to align the common requirements on the localization system in different traffic models, we investigate the specified requirements according to typical values of the parameters in Europe. Concerning the EU road definition, application, velocity, dimensions, presence of traffic lights / tolling stations have to be taken into account.

Although different road design principles are adopted in single countries, a typical width of 3,50 m to 3,75 m (https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/ersosynthesis2018-motorways.pdf) is considered in Europe. According to the following link about European lane widths (https://en.wikipedia.org/wiki/Lane), it could be assumed:

- V (highway/local/narrow) = 80-130 / 60-90 / 20-60 [km/h]
- Width lane (highway/local/narrow) = 3.75 / 3.25 / 2.75 [m]

The lane width is of particular interest mainly in the derivation of the lateral AL and correspondent accuracy.

About the car sizes, we have to try to adapt the needs to the European car market: from the following link (https://www.automobiledimension.com/car-search-engine.php), searching for cars with maximum width W, length L and height H, the maximum values obtained are (usually related to a VAN vehicle):

W / L / H = 1.986 / 5.4 / 1.977 [m] ≤ 2 / 5.4 / 2 [m]

For longitudinal dimension, the main constraint on longitudinal AL comes from the curves, where the vehicle must ensure to keep itself in the lane when passing these parts of the highway. More detailed analysis can be found in D2.3 [0], which results in the following equation and table:

$$AL_{long,curve} = \sqrt{\left(r + \frac{W_{lane}}{2}\right)^2 - \left(r - \frac{W_{lane}}{2} + 2AL_{lat} + W_{veh}\right)^2} - \frac{1}{2} l_{veh}$$

The curve radius of the road r depends on the road type and might differ from country to country. The minimum allowed radii are in relation to the designed speed requirement of the road has already been provided in Table 13 from D2.3 [2]. In addition, on local and narrow road, there is an additional requirement that the vehicle must stop at least one meter before any crossing or traffic light. Hence, the AL for longitudinal AL is set no smaller than one meter. For highways, there is no such constraint.

Exploiting the following typical values from our analysis and references as input data for the above reviewed equations from D2.3 [2]:

- W_{veh} / L_{veh} = 2 / 5.4 [m] (on the basis of the maximum dimensions currently available derived by the above link)
- Wlane (highway/local/narrow) = 3.75 / 3.25 / 2.75 [m]
- Minimum road radius (highway/local/narrow) = 240 / 120 / 10 [m]
- DTE_{max} = 0.2 [m]

we obtain the values listed in the Table 1 "*Summary of Localization System Requirements*".

It can be seen that with a narrow road width less than 3 m, the AL and positioning accuracy requirements might be challenging to achieve with high availability by considering the currently available technologies. We will further mention this point in the technology capability gap section (section 9).
The integrity risk for automated driving should not exceed 1e-6, according to the report from GSA [16]. From the integrity risk and the alert limit we can derive the corresponding 95% accuracy requirement. In HELMET we will investigate if it is possible to achieve even higher integrity to further ensure safety.

2.2 SUMMARY OF SYSTEM REQUIREMENTS

According to the review and justification in the last section, the system requirements for different models are summarized in Table 1.

Table 1: Summary of Localization system requirements

Application	Scenario User requirement / Use case	Integrity	Accuracy 95%	Alert Limit	Time-to-Alert	Availability	Continuity	Security
RAIL Localization system	Track Identification	<1e-9/h	0.7 m (SR-OBU-PER-006.a)	1.785 m (SR-OBU-SAF-005.a)	10s - 30 s (SR-OBU-FUN-007.a)	High	NA	Very high
	Odometry Calibration	<1e-9/h	0.7 m (SR-OBU-FUN-010.a)	1.7 m (SR-OBU-SAF-011.a)	< 1 s (SR-OBU-SAF-012.a)	High	NA	Very high
	Cold Movement Detection	<1e-9/h	2 m (SR-OBU-FUN-014.a)	5 m (SR-OBU-SAF-013.a)	< 10 s (SR-OBU-SAF-015.a)	High	NA	Very high
AUTO Localization system	Automated Driving on Highway	1e-6/h	27.6 cm lat (SR-OBU-PER-103.a) 4.58 m long (SR-OBU-PER-108.a)	67.5 cm lat (SR-OBU-SAF-102.a) 11.2 m long (SR-OBU-SAF-117.a)	1 s (SR-OBU-SAF-108.a)	> 99.5% (SR-OBU-SAF-110.a)	High (SR-COM-SAF-120.a)	Very high (SR-OBU-SEC-111.a)
	Automated Driving on Local Roads	1e-6/h	17.38 cm lat (SR-OBU-PER-105.a) 40.9 cm long (SR-OBU-SAF-118.a)	42.5 cm lat (SR-OBU-SAF-104.a) 1 m long	1 s	> 99.5%	High	Very high
	Automated Driving on Narrow and Curved Roads	1e-6h	7.16 cm lat (SR-OBU-PER-107.a) 11.86 cm long (SR-OBU-PER-112.a)	17.5 cm lat (SR-OBU-SAF-106.a) 29 cm long (SR-OBU-SAF-119.a)	1 s	> 99.5%	High	Very high
UAV* Localization System	Monitoring Mission	1x10-7/h to 2x10-7/h	1 m /10m hor & vert	~m	1 s	95%-99%	1x10-4/h to 1x10-8/h	Very high
	Inspection Mission	1x10-7/h to 2x10-7/h	1 m /10m hor & vert	~m	1 s	95%-99%	1x10-4/h to 1x10-8/h	Very high
	Traffic Management Mission	1x10-7/h to 2x10-7/h	10m / 30m hor & vert	~m	1 s	95%-99%	1x10-4/h to 1x10-8/h	Very high

*: Respective system requirement in section 5 of deliverable 2.3 “UAS-AUG-PER-REQ-19” refers to Accuracy/Integrity/Time-to-Alert/Continuity/Availability

3. HIGH-LEVEL MULTIMODAL SYSTEM DESIGN

A preliminary concept of the HELMET architecture has been introduced in D2.3 (as shown in Fig. 31 in [2]). If we extract the common essential part of the localization system for all three means of transportations, the multi-modal positioning and localization system high level architecture is illustrated in Figure 4. The system contains two main subsystems: Augmentation Integrity Monitoring Network (AIMN) and Multi-sensor OnBoard Unit (MOBU). The AIMN provides augmentation and GNSS integrity messages with different service levels based on a network of infrastructures. The MOBU subsystem is installed on the vehicles for multiple transportation modes, including railways, automobiles, and UAVs that supports the transportation tasks. A communication module is required to transmit the messages and services provided by AIMN and application-specific infrastructures to the MOBU. For different transportation modes, the localization system also exploits additional application-specific infrastructures, e.g., balise for railway applications and visual markers for road applications.

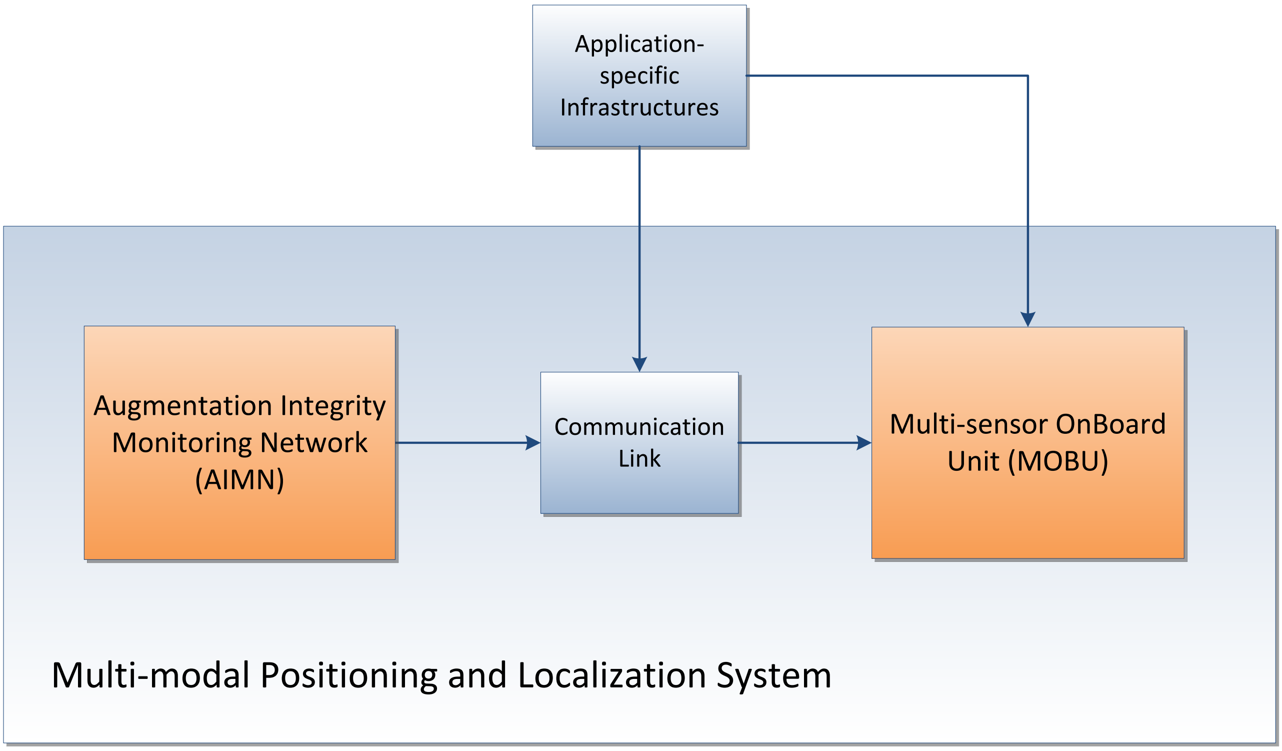

Application-specific Infrastructures
Augmentation Integrity Monitoring Network (AIMN)
Communication Link
Multi-sensor OnBoard Unit (MOBU)
Multi-modal Positioning and Localization System

Figure 4: Multi-modal positioning and localization system

The following chapter 4 describes the high level design of the AIMN with the definition of different service levels. Chapter 5, 6 & 7 describe the high-level architecture for Railway/Automotive & UAV applications.

4. MULTIMODAL AUGMENTATION INTEGRITY MONITORING HIGH LEVEL DESIGN

Starting from the high level functional analysis carried out within the D2.3, the Augmentation Network high level design is represented in Figure 5.

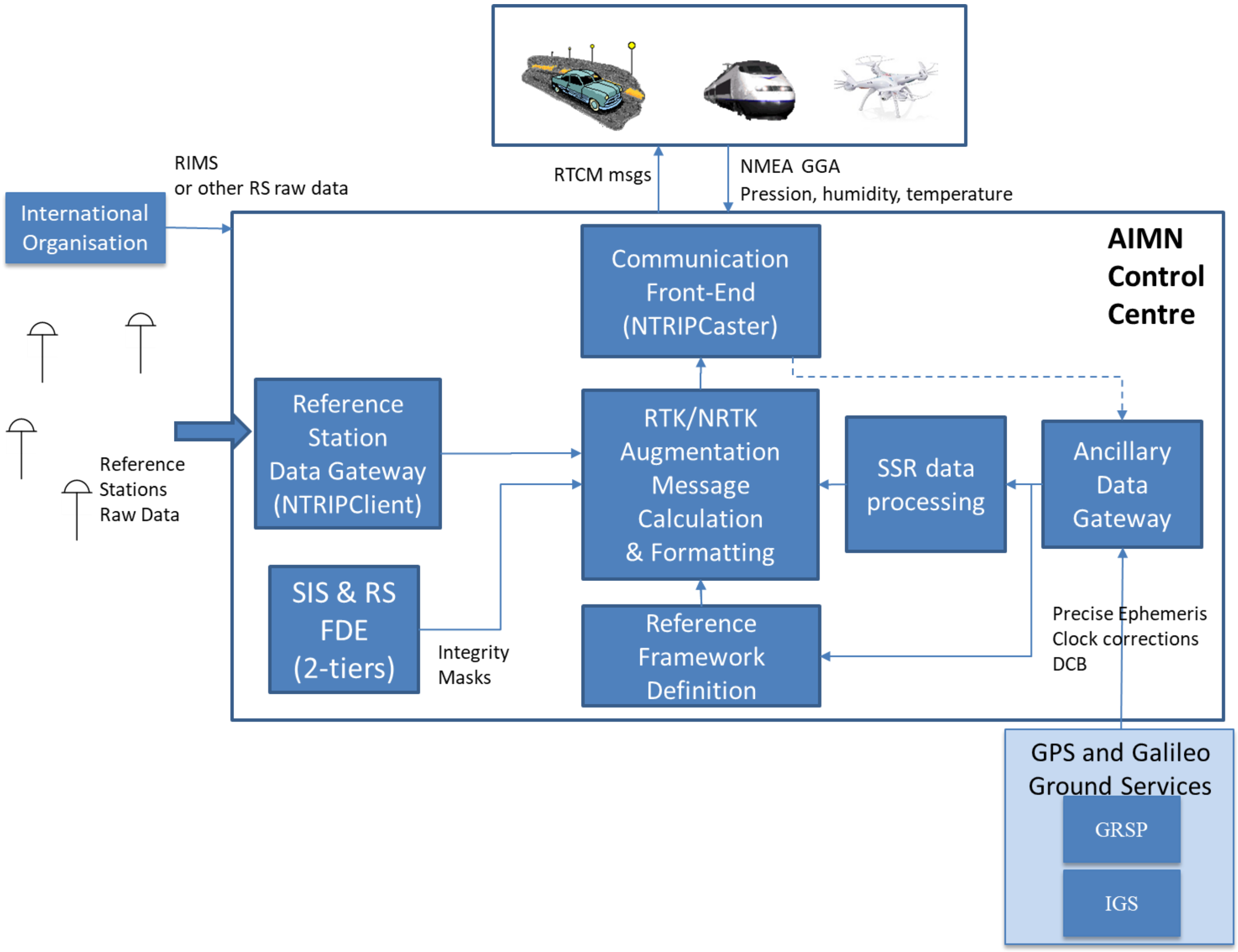

RIMS
or other RS raw data
RTCM msgs
NMEA GGA
Pression, humidity, temperature
International Organisation
AIMN Control Centre
Communication Front-End (NTRIPCaster)
Reference Station Data Gateway (NTRIPClient)
RTK/NRTK Augmentation Message Calculation & Formatting
SSR data processing
Ancillary Data Gateway
Reference Stations Raw Data
SIS & RS FDE (2-tiers)
Integrity Masks
Reference Framework Definition
Precise Ephemeris
Clock corrections
DCB
GPS and Galileo Ground Services
GRSP
IGS

Figure 5: Augmentation Network High Level Design

The AIMN Control Centre take as input the following data:

- **International Organisations**: International Organisation Reference Stations Raw data can be used (e.g. EUREF of EDAS RIMS)are used as reference for the implementation of the first tier of the 2-tiers FDE algorithm
- **Reference Stations Raw Data**: they are gathered through an NTRIP Client access from local Augmentation Service providers and are used for the implementation of the second tier of the 2-tiers algorithm and for the calculation and formatting of the augmentation messages
- **GNSS Ground Services**: they provide precise ephemeris, clock corrections and differential code biases needed for the AIMN Reference Framework determination. IGS and the Galileo Reference Service Provider system are used for GPS and Galileo

Users can connect to the AIMN through the single domain Physical Communication system. Standard NTRIP protocol and RTCM SC-104 formats are used, being it the most implemented standard for Augmentation data processing into GNSS receivers.

Main subsystems of the Augmentation network and relevant tasks are the following:

- **Reference Stations Data Gateway**: it implements NTRIP Client access to single Local Augmentation providers for gathering relevant raw measurements
- **Communication Front-End**: is an NTRIPCaster publishing mountpoints for the access to the generated RTCM augmentation messages and the 2-Tiers Integrity masks. It receives user position for Augmentation Messages calculation
- **SIS & RS FDE**: the 2-tiers algorithm ([5]), that has been proven to meet SIL-4 THR levels, is implemented and relevant integrity masks generated for satellites, constellations and Reference Stations and transmitted to the Augmentation Messages calculation and formatting for faulted sources exclusion by the user and the network
- **RTK/NRTK Augmentation Messages Calculation & Formatting**: a quality check on raw measurements is carried out and RTK messages calculated or Network RTK processing performed for Reference Stations data generation in the neighbour of the User Receiver Position. User position id received from the front-end and user for nearest station selection of NRTK messages generation
- **Ancillary Data Gateway**: Precise Ephemeris and Clock corrections, Differential Code Biases and other needed ancillary data are downloaded and used for the Reference Framework Calculation, errors estimations and SSR parameters gathering from relevant providers. Tropospheric (e.g. Pressure, Humidity and Temperature) from on the field sensors (e.g. OBU or Reference Station sensors, if available during the Pilots) can be gathered and processed for deriving a first level ZTD estimation to be used as a priori information for receivers estimations. The accuracy of the estimation depends on the quality of the provided data. Such processing is analysed at functional level, paving the way for a future implementation. Furthermore, precise Waypoints coordinates (easy detectable by an on board camera, e.g. Cadastral Fiducial point DB) can be broadcast to the OBU in a suitable format. Such points can be in a future implementation used by the OBU and merged with angular measurements for implementing sensor fusion PVT estimations
- **SSR Data Processing**: basic SR messages (Precise Ephemeris and Clock corrections) are gathered from external service providers for relevant processing or rebroadcasting. Galileo HAS corrections messages can be gathered in the same way when transmitted by the Galileo satellites

Reference Framework Definition: a network adjustment is performed through scientific software for calculating and updating Reference Stations Coordinates into the ETRF2000 Reference Framework

AUGMENTATION TO EXTERNAL DOMAIN COMMUNICATION INTERFACES DEFINITION

The Augmentation System Front-End makes available the augmentation messages to the single domain Communication Front-End (in charge of broadcasting them to the final user) or the OBU in a widely adopted standard protocol and data format. RTCM is currently the standard format adopted by the great part of the GNSS receiver manufacturers for the implementation of High Accuracy Services.

Conversion of such Standard to domain specific protocols or formats is in charge of single domain Communication subsystems or OBU.

5. HIGH LEVEL ARCHITECTURE FOR RAILWAY APPLICATION

This section deals with the preliminary design of HELMET high-safety integrity LDS architectures for ERTMS. The preliminary safety design is focused on such LDS solutions to meet user and system requirements for following functionalities: 1) Track Identification, 2) Odometry calibration, and 3) Cold Movement Detection. The presented preliminary architectures are designed according to Rail User Requirement specified in HELMET D2.1 (§4) [1] and Rail System Requirements summarised in HELMET D2.3 (§5.1 and §7.1) [2].

The first proposed LDS architecture is based on reactive fail-safety with independent diagnosis of GNSS. The independent GNSS diagnosis utilises ETCS odometry compliant with SIL 4. It is assumed that LDS initialization including Track Identification has been already performed before ETCS full supervision started. The main goal of safety analyses performed by Markov modelling is to demonstrate that the reactive LDS is able to meet THR for the along track position determination function during nominal train operation (full supervision). Design of key parameters (T_{DN}, P_{md}, K_{md}, K_{fa}, MDE, etc.) of safety monitor/ diagnosis of LDS is outlined. Calculations show that the currently guaranteed GNSS Integrity Risk for airplane final approach combined with the LDS safety monitor is able to meet high safety integrity and availability requirements for the ERTMS Virtual balise concept.

Second, a high-level LDS architecture for Track Identification based on composite safety is introduced. The composite architecture is intended for LDS initial position determination including Track Identification during train motion. It is shown that safe LDS initialization can profit not only from additional on-board sensors for rail infrastructure perception, but also from other external technical or operational provisions based on track-side data, such as characteristic features of a set train route (position of switch points) and Movement Authority granted to the train by the Train Control Centre.

The integral part of the external data is a so called meta data, which characterise the quality of external LDS data and there are critical for run-time safety evaluation performed by LDS. Fault Tree Analysis (FTA) demonstrates how significantly can the on-board sensing of infrastructure features (mainly positions of switches) and external trackside (technical & operational) data contribute to the reduction of safety requirement for GNSS. Excepting this, efficient experimentally proven on-board techniques for train routing detection on switches based on gyro-odometry and detection of switch points elements by a laser sensor developed at Czech Railways in the past have been reminded.

Third, it is briefly analysed what would happen if the above described composite LDS architecture would be also used for Start of Mission with the LDS status UNKNOWN in stand-still. FTA shows that unavailability of the rail infrastructure sensing function (composed of several techniques) and external technical and operational provisions (because they can be only applied during train motion) significantly increases safety integrity demands on GNSS. It is shown how the above findings could affect the architecture of Cold Movement Detector (CMD), which is the mandatory constituent of the ERTMS baseline 3.

Finally, based on the proposed high-level safety architectures (ARCHITECTURE_1 and ARCHITECTURE_2) and performed related safety analyses, the RAIL user and system requirements were converted to the subsystem level.

5.1 RAILWAY PRINCIPLES USED FOR SAFE ARCHITECTURE DESIGN

Railway safety related systems to be compliant with SIL 3 or SIL 4 must ensure that they will remain safe in the event of any kind of single random HW fault. This principle is known as fail-safety and can be achieved by means of the following techniques [3]:

- inherent fail-safety,
- composite fail-safety, or
- reactive fail-safety.

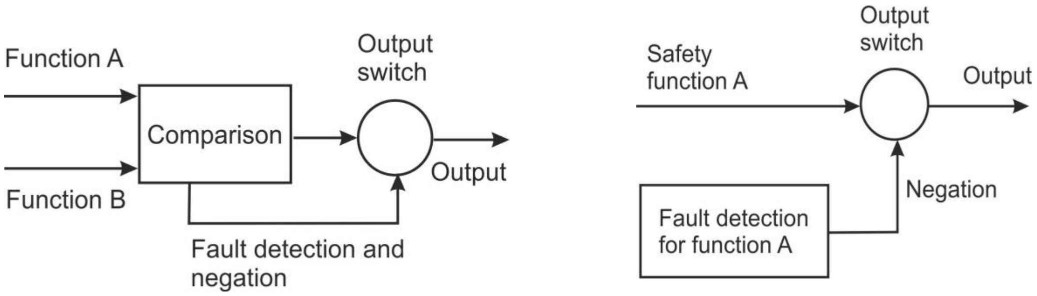


Figure 6. Fail-safe techniques according to CENELEC: (a) composite fail-safety, and (b) reactive fail-safety.

It is evident that implementation of these techniques not only determines which level of safety can be achieved in the Virtual Balise Reader (VBR) based on GNSS SoL service, but also how efficiently the GNSS service may be used. The applicability of the individual fail-safety techniques within the GNSS -based VBR is analysed below.

The inherent fail-safety technique allows a safety-related function to be performed by a single channel, provided that all the credible failure modes of the channel are not hazardous. It would be very difficult or impossible to make such evidence in the case of the complex GNSS + VBR, and therefore inherent fail-safety is not further considered.

The composite fail-safety (Figure 6(a)) allows a safety-related function to be performed by at least two independent channels. A hazardous fault in one channel shall be detected and negated in sufficient time to meet the required THR. The fault is detected by the comparison of the output values of these two or more channels, or also by means of an additional independent diagnosis. This technique can be applied if two fully equivalent and diverse safety functions exist. Application of this technique is investigated in case of Track Identification function below.

Finally, the reactive fail-safety (Figure 6(b)) allows a safety-related function to be performed by a single channel, provided its safe operation is assured by fast detection and negation of any dangerous fault. For example, legacy SBAS (Satellite Based Augmentation System) or GBAS (Ground Based Augmentation System) itself can be considered as a system with reactive fail-safety, because the safety function (i.e. position determination) is performed by the GNSS constellation(s) and its correctness is checked by the SBAS/ GBAS infrastructure.

5.2 ARCHITECTURE_1: REACTIVE FAIL-SAFETY FOR ALONG TRACK TRAIN POSITION DETERMINATION

This section deals with the preliminary reactive Location Determination System (LDS) architecture intended for Virtual Balise (VB) detection, Cold Movement Detection (CMD) and Odometry Calibration.

Position determination along track is a position estimation problem. In this case, it is possible to define a FAIL-SAFE STATE when a hazardous failure arises – i.e. train can stop, slow-down, etc. Therefore, the reduction of Time to Fault Detection and Negation (T_{DN}), which correspond to Safe Down Time (SDT) according to EN 50129 [3], can enable a significant reduction of safety requirements (i.e. THR increasing) for subsystems such as GNSS and independent diagnosis – see Figure 6.

In composite solution (Figure 6(a)) the independent diagnosis can be performed by comparing two full-value diverse safety functions (A and B). In this case it is considered that both Function A and Function B provide absolutes independent position determination.

Reactive fail-safety in Figure 6(b) is in fact a modification of the composite solution, because an independent diagnosis (i.e. fault detection) of Function A must be performed. In case of reactive safety there is only required that the independent diagnosis must detect and negate promptly enough all failures, which could bring the system into a hazardous state.

The reactive LDS architecture was selected to implement the along track GNSS-based safe positioning function. The reduction of railway safety requirements for GNSS SoL service, i.e. exploitation of existing aviation EGNOS SoL service, and use of already available ETCS odometry (SIL 4 compliant) are the main reasons why the reactive solution is proposed for along track train position determination. It means that reactive fail-safety is achieved by combination of absolute position determination (GNSS) and relative positioning (odometry). It is the major difference with respect to composite fail-safety applied for along track positioning (ATP), which is considered to be realised by two diverse absolute position determination functions. Since excepting GNSS no other efficient absolute positioning technology is available, therefore the reactive LDS architecture with a fail-safe state based on GNSS and odometry was proposed in sections below.

5.2.1 Markov model of reactive LDS

A possible high-level reactive LDS architecture solution (Architecture_1) based on GNSS + AIMN + ETCS odometry including its Markov model is outlined in Figure 7 [4]. Reactive fail-safety is based on the principle that the first single failure which could be hazardous, i.e. an excessive along-track position (ATP) error, either alone or if combined with a second failure, shall be detected and a safe state of the system enforced (i.e. failure negated) to meet the specified quantified safety target (THR_{H7} of 3.3e-10/h – Virtual Balise insertion along track [2]). Note that THR_{H7} is in fact a hazard related to virtual balise detection, not specifically the output of the LDS for which the hazard is that the ATPL (Along Track Protection Level) does not bound the ATP error. For simplification, however, THR_{H7} is referred to as the safety target in this section.

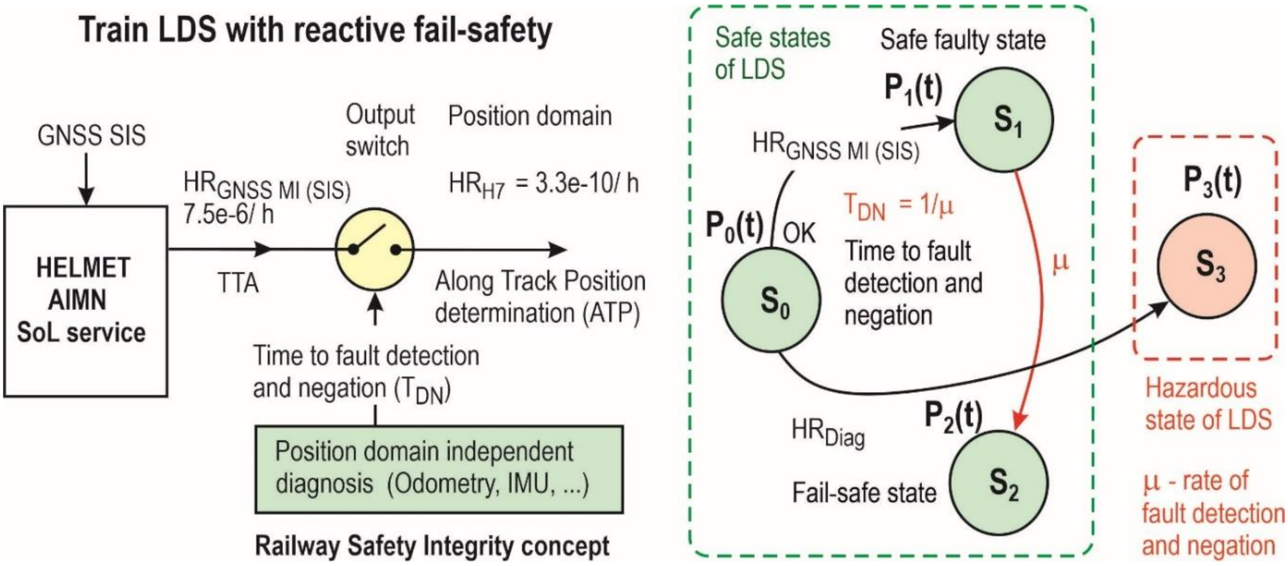

Train LDS with reactive fail-safety
GNSS SIS
HELMET AIMN SoL service
HRGNSS MI (SIS) 7.5e-6/ h
TTA
Output switch
Position domain
HRH7 = 3.3e-10/ h
Along Track Position determination (ATP)
Time to fault detection and negation (TDN)
Position domain independent diagnosis (Odometry, IMU, ...)
Railway Safety Integrity concept
Safe states of LDS
Safe faulty state
P1(t)
S1
HRGNSS MI (SIS)
P0(t)
OK
S0
TDN = 1/μ
Time to fault detection and negation
μ
HRDiag
P2(t)
Fail-safe state
S2
P3(t)
S3
Hazardous state of LDS
μ - rate of fault detection and negation

Figure 7: Reactive LDS safety structure based on HELMET AIMN and independent diagnosis, including Markov model

Time to failure detection and negation (T_{DN}), which is a critical parameter of the reactive architecture, can be derived using the above Markov model – see Figure 7 on the right. T_{DN} is also called Safe Down Time (SDT) according to EN 50129.

The following four system states are defined for the model:

- S_0: Fully functional LDS state: both ATP (Along Track Positioning) and independent diagnosis work well according to the specifications. The corresponding probability P_0(t) represents probability of correct LDS functioning;
- S_1: Safe faulty LDS state: ATP is faulty (out if specifications) and rapid diagnosis is functional. This represents the state of the system prior to T_{DN} elapsing. The state is characterised by the tolerated LDS faulty state probability P_1(t) that directly depends on T_{DN}. Note: If the faulty sate probability is tolerated, then it means safe (faulty) state;
- S_2: Fail-safe state of the LDS: ATP fault was detected and negated within T_{DN}. The corresponding probability P_2(t) represents LDS failure probability in the absorbing state;
- S_3: Hazardous LDS state, i.e. dangerous undetected failure mode: Independent diagnosis of ATP did not detect the fault. Note: although LDS can function properly according to the specifications, the LDS is in a dangerous state. The corresponding probability P_3(t) represents probability of dangerous undetected LDS failure in the absorbing state.

A set of first-order differential equations with constant coefficients describing the Markov model in Figure 7 is following:

$$\frac{dP_0(t)}{dt} = - \left(HR_{GNSS\ MI} + HR_{Diag}\right) \times P_0(t)$$

$$\frac{dP_1(t)}{dt} = HR_{GNSS\,MI} \times P_0(t) - \mu \times P_1(t) \qquad (1)$$
$$\frac{dP_2(t)}{dt} = \mu \times P_1(t)$$
$$\frac{dP_3(t)}{dt} = HR_{Diag} \times P_1(t)$$

Boundary conditions are following: $P_0(0)=1$, $P_1(0)=0$, $P_2(0)=0$, $P_3(0)=0$.

5.2.2 Derivation of Time to Fault Detection and Negation

The corresponding time-dependent LDS state probabilities derived from the set of differential equations (1) are followings:

$$P_0(t) = e^{-\left(HR_{GNSS\,MI}+HR_{Diag}\right)\cdot t} \qquad (2)$$

$$P_1(t) = -\frac{HR_{GNSS\,MI}[e^{-(HR_{GNSS\,MI}+\,\mathrm{HR}_{\mathrm{Diag}})\cdot t} - e^{-\mu\cdot t}]}{HR_{GNSS\,MI} + \mathrm{HR}_{\mathrm{Diag}} - \mu} \qquad (3)$$

$$P_2(t) = \frac{HR_{GNSS\,MI}}{(HR_{GNSS\,MI}+HR_{Diag})(HR_{GNSS\,MI}+HR_{Diag}-\mu)} \times$$
$$\times \left[HR_{GNSS\,MI} + HR_{Diag} - \mu + \mu \cdot e^{-\left(HR_{GNSS\,MI}+HR_{Diag}\right)\cdot t} - HR_{GNSS\,MI} \cdot e^{-\mu\cdot t} - HR_{Diag} \cdot e^{-\mu\cdot t}\right] \qquad (4)$$

$$P_3(t) = \frac{HR_{Diag}}{(HR_{GNSS\,MI}+HR_{Diag})}\left[1 - e^{-\left(HR_{GNSS\,MI}+HR_{Diag}\right)\cdot t}\right] \qquad (5)$$

Where, $HR_{GNSS\ MI}$ is hazard rate per 1 hour of GNSS+AIMN-based ATP determination, HR_{Diag} is hazard rate of independent GNSS diagnosis, μ is rate of fault detection and negation, i.e. $\mu = 1/T_{DN} = 1/SDT$.

$P_0(t)$ represents LDS reliability, i.e. when both GNSS and independent diagnosis are functioning correctly. It includes only one successful LDS state – S_0. The other system states (S_1, S_2, S_3) are faulty states – safe states (S_1, S_2) or dangerous state (S_3). State S_3 is the most feared sate, i.e. dangerous undetected fault.

States S_2 and S_3 are absorbing states. An absorbing state means that model ends in this state. Since in this reactive LDS architecture we assume that T_{DN} is very short (with respect to Mean Time to Failure (MTTF) of the other channel, i.e. 1/ $HR_{GNSS\ MI}$), then we can say that S_1 is practically also an absorbing state, because the $P_3(t)$ is very low (negligible).

Hazard rate of the system (λ_{system}) is generally calculated using failure probability density f(t) and reliability R(t) as follows:

$$\lambda_{system}(t) = \frac{f(t)}{R(t)} = \frac{-dR(t)/dt}{R(t)} \tag{6}$$

However, R(t) is calculated using state probabilities for non-absorbing states. It means that we cannot calculate R(t) which would also include probabilities for absorbing states S_1 and S_2. Therefore, we had to find another solution.

P_1(t) is the safe faulty state probability of LDS in case of GNSS+AIMN-based ATP fault. Then the tolerated (expected) probability P_1(t) for a given value of T_{DN} over next interval of 1 hour characterizes integrity of the safe faulty state S_1. The expected LDS failure probability P_1(t) during next 1 hour interval for T_{DN} can be used instead of HR.

Since ($HR_{GNSS\ MI}$ + HR_{Diag}) is much smaller than µ, then equation (3) can be simplified as follows:

$$P_1(t) \approx -\frac{HR_{GNSS\ MI} \cdot [1-0]}{-\mu} = HR_{GNSS\ MI} \cdot T_{DN} \tag{7}$$

It is evident from equation (7) that P_1 (t) depends on T_{DN} (i.e. on 1/ µ) and is no longer dependent on the time t – see Figure 8. The required THR for LDS during one hour long mission can be expressed as THR_{req} = P1 per 1 hour = $HR_{GNSS\ MI}$ × T_{DN} × 1 $hour^{-1}$. Then the T_{DN} can be calculated as:

$$\mathrm{T_{DN}} = \frac{\mathrm{THR_{req}}}{\mathrm{HR_{GNSS\ MI}}} \times 1\ \mathrm{hour}$$

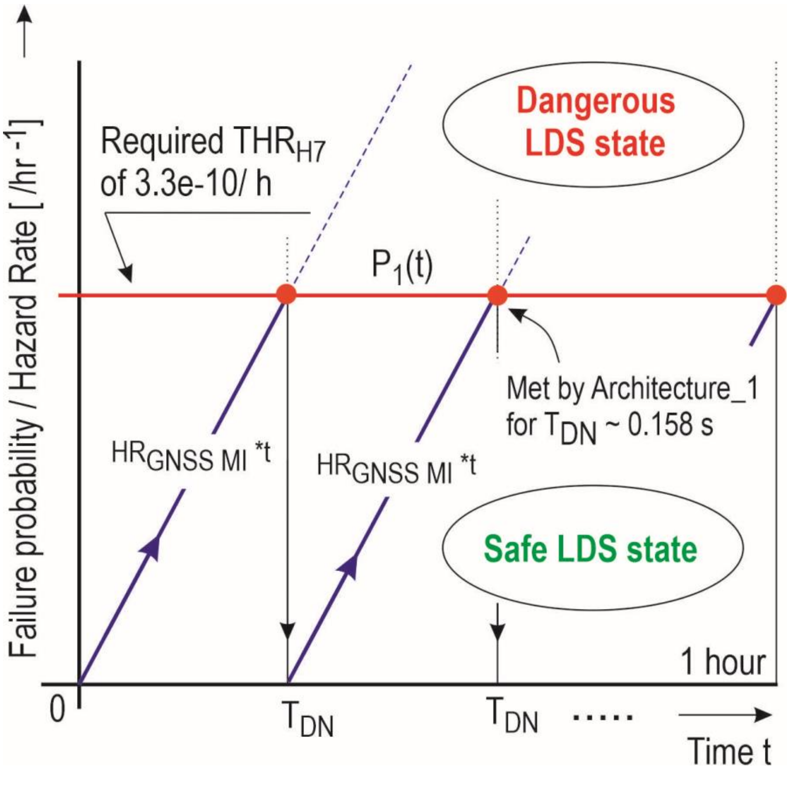


Figure 8: Probability of failure as a function of $HR_{Non\text{-}Train(SIS)}$ and T_{DN}

Failure of ATP determination (by GNSS) at the LDS system level must not bring the system into a dangerous state. The safe faulty state (P_1) of the LDS system in case of ATP failure when the independent diagnosis is functional has a duration of T_{DN} at most because the value of T_{DN} is designed in such a way that the LDS meets the required THR_{req} – i.e. THR_{H7} of 3.3e-10/h. In other words, the reactive LDS will be in a safe state although ATP has failed. If ATP failure has not been detected and negated within T_{DN} , then the LDS state is considered as hazardous. An ATP failure due to GNSS MI cannot be considered as the TPL hazard. It can be only considered as cause of TPL hazard because the independent diagnostic channel (i.e. Safety Monitor) exists.

The parameters of the diagnostic channel, also called safety monitor, are derived below.

5.2.3 Numerical verification of meaning of LDS state probabilities

Example_1:

Let's assume $HR_{GNSS\ MI}$ = 7.5e-06/ hour (see §4.1.5 in [2]), HR_{Diag} = 1e-10/ hour (example taken for ETCS odometry), **T_{DN}= 4.4e-05 h (0.158 s), t=1 hr**

Results:
P0 = 0.999992499928126
P1 = 3.2999752508518 21e-10 …. i.e. THR_{H7} of 3.3e-10/h is met
P2 = 7.499641877184870e-06
P3 = 9.999962499759281e-11

Example_2

Let's assume $HR_{GNSS\ MI}$ = 7.5e-06/ hour, HR_{Diag} = 1e-10/ hour, T_{DN}= 4.4e-05 h (0.158 s), **t=100 hrs**

Results:
P0 = 0.999250271187198
P1 = 3.297525896005952e-10 …. i.e. THR_{H7} of 3.3e-10/h is met
P2 = 7.497184867985195e-04
P3 = 9.996250887349615e-09

Example_3

Let's assume $HR_{GNSS\ MI}$ = 7.5e-06/ hour, HR_{Diag} = 1e-10/ hour, **T_{DN}= 2.77e-3 hour (10 s)**, **t=1 hr**

Results:
P0 = 0.999992499928126
P1 = 2.083317751586627e-08 …. i.e. THR_{H7} is not met for T_{DN}= 10 s
P2 = 7.479138697198274e-06
P3 = 9.999962499759281e-11

Conclusions from Examples_1 to 3:

- Probability P0 corresponds to reliability. It is evident it is time dependent.
- Probability P1 doesn't depend on time t. It depends on T_{DN} . It is evident that required THR_{H7} of 3.3e-10/ h can be met for T_{DN}= 4.4e-05 h = 0.158 s (Example_2). If T_{DN} is longer, e.g. 10 s (i.e. 2.77e-3 hour), then P1 = 2.083317751586627e-08 over 1 hour interval doesn't meet the required THR_{H7} of 3.3e-10/ h (Example_3).
- Probabilities P2 and P3 depend on time t (Example_1 and Example_2). It is natural that. But it doesn't have a practical relevance. It is because P2 represents a fault probability after fault was negated – no hazard can happen in the state S_2 . P3 represents dangerous undetected fault probability of independent diagnosis, which is latent in any case.

5.2.4 Interpretation of T_{DN} as P_{md}

The above described time dependency having impact on resulting THR cannot be directly modelled by means of an FTA diagram. Therefore, the above reactive technique depicted in Figure 7 can be redrawn using Fig. 38 in HELMET D2.3 [2] as it is outlined in Figure 9:

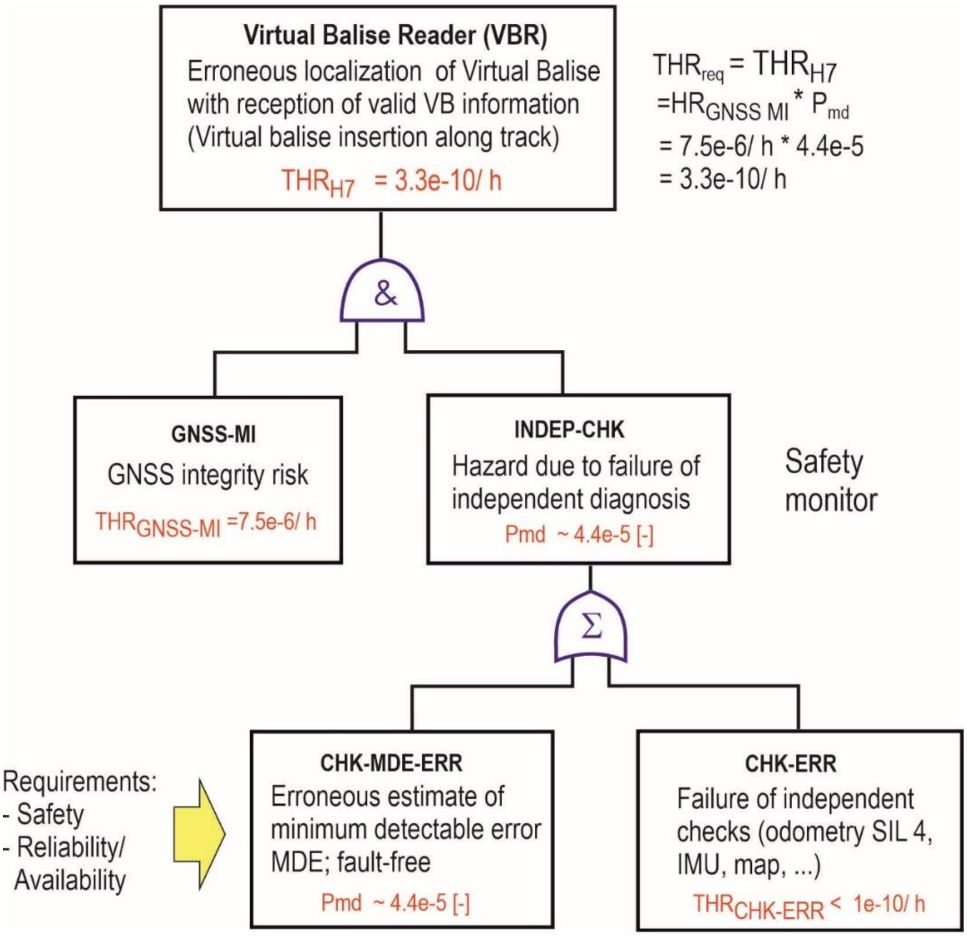

Virtual Balise Reader (VBR)
Erroneous localization of Virtual Balise with reception of valid VB information (Virtual balise insertion along track)
THRH7 = 3.3e-10/ h
THRreq = THRH7
=HRGNSS MI * Pmd
= 7.5e-6/ h * 4.4e-5
= 3.3e-10/ h
&
GNSS-MI
GNSS integrity risk
THRGNSS-MI =7.5e-6/ h
INDEP-CHK
Hazard due to failure of independent diagnosis
Pmd ~ 4.4e-5 [-]
Safety monitor
Σ
Requirements:
- Safety
- Reliability/ Availability
CHK-MDE-ERR
Erroneous estimate of minimum detectable error MDE; fault-free
Pmd ~ 4.4e-5 [-]
CHK-ERR
Failure of independent checks (odometry SIL 4, IMU, map, ...)
THRCHK-ERR < 1e-10/ h

Figure 9: Safety monitor in FTA diagram.

The derived Time to Failure Detection and Negation T_{DN} can be interpreted in the FTA in Figure 9 via the Probability of Missed Detection (P_{md}). Interpretation of T_{DN} as P_{md} is explained below in § 5.2.8 .

5.2.5 Proposed Safety Monitor for run-time safety evaluation

The principle of the safety monitor to be developed for the reactive LDS architecture is outlined in Figure 10. It evaluates difference in travelled distance measured by GNSS-based LDS and safe ETCS odometry (SIL 4). If the position error exceeds the Maximum Threshold T_{max} (defined by user, $T_{max} \geq$ MDE), then the GNSS ATP failure is detected and negated.

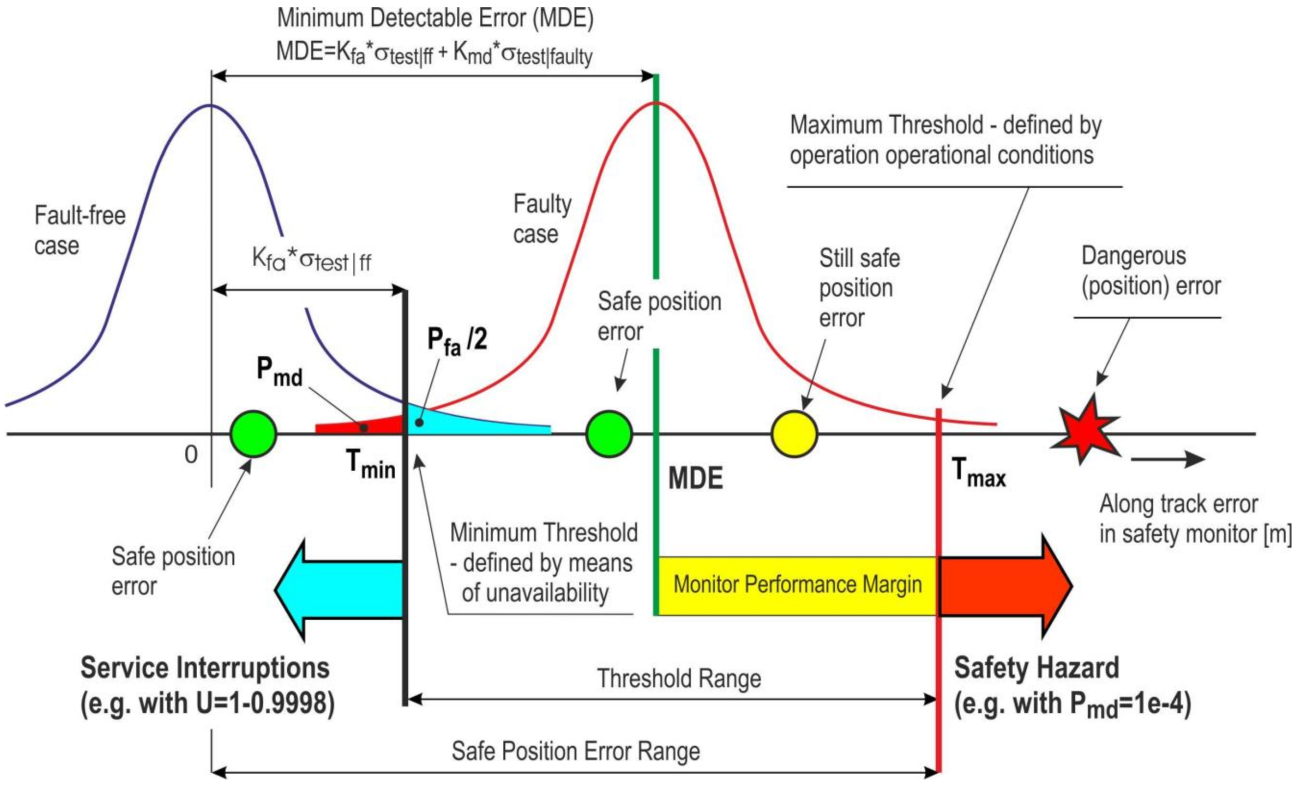

Minimum Detectable Error (MDE)
$MDE=K_{fa}*\sigma_{test|ff} + K_{md}*\sigma_{test|faulty}$
Maximum Threshold - defined by operation operational conditions
Fault-free case
Faulty case
$K_{fa}*\sigma_{test|ff}$
Safe position error
Still safe position error
Dangerous (position) error
$P_{fa}/2$
P_{md}
0
T_{min}
MDE
T_{max}
Along track error in safety monitor [m]
Safe position error
Minimum Threshold - defined by means of unavailability
Monitor Performance Margin
Service Interruptions (e.g. with U=1-0.9998)
Safety Hazard (e.g. with P_{md}=1e-4)
Threshold Range
Safe Position Error Range

Figure 10: Determination of Minimum Detectable Error (MDE) and maximal decision Threshold T_{max}

5.2.6 Steps in Safety Monitor design

Design of safety monitor of reactive LDS consists of following steps:

i. Determination of safe down time (T_{DN}) using THR_{req} and $HR_{GNSS\ MI}$

T_{DN}= T_D (Time to failure Detection) + T_N (Time to failure Negation);

ii. Determination of missed detection probability (P_{md}), which corresponds to the ratio of T_{DN}/ 1 hour;

iii. Derivation of probability of false alert P_{fa} from the required LDS availability;

iv. Derivation of scaling coefficients K_{md} and K_{fa} of the safety monitor;

v. Determination of Minimum Detectable Error (MDE) of safety monitor.

5.2.7 Example: Derivation of time to failure detection and negation (T_{DN})

Based on Figure 39 in HELMET D2.3 [2], the following assumptions may be made:

- $HR_{GNSS\ MI}$ = 7.5e-6 / hour, which includes Ground segment fault free system Integrity Risk (FAULT-FREE), Integrity Risk due to Signal-In-Space Misleading Information (SIS-MI) and Integrity Risk due to user MI (USER-MI);

- THR_{req} =THR_{H7} = 3.3e-10 / hour (Virtual Balise insertion along track);

Then time to failure detection and negation T_{DN} may be calculated according to:

$$T_{DN} = \frac{THR_{req}}{HR_{Non-Train(SIS)}} \times 1\ \text{hour}$$

This gives T_{DN} = 3.3e-10 / 7.5e-6 x 1 hour = 4.4e-5 x 1 hour = 0.158 s.

5.2.8 Example: Determination of P_{md} for GNSS+AIMN-based ATP failure

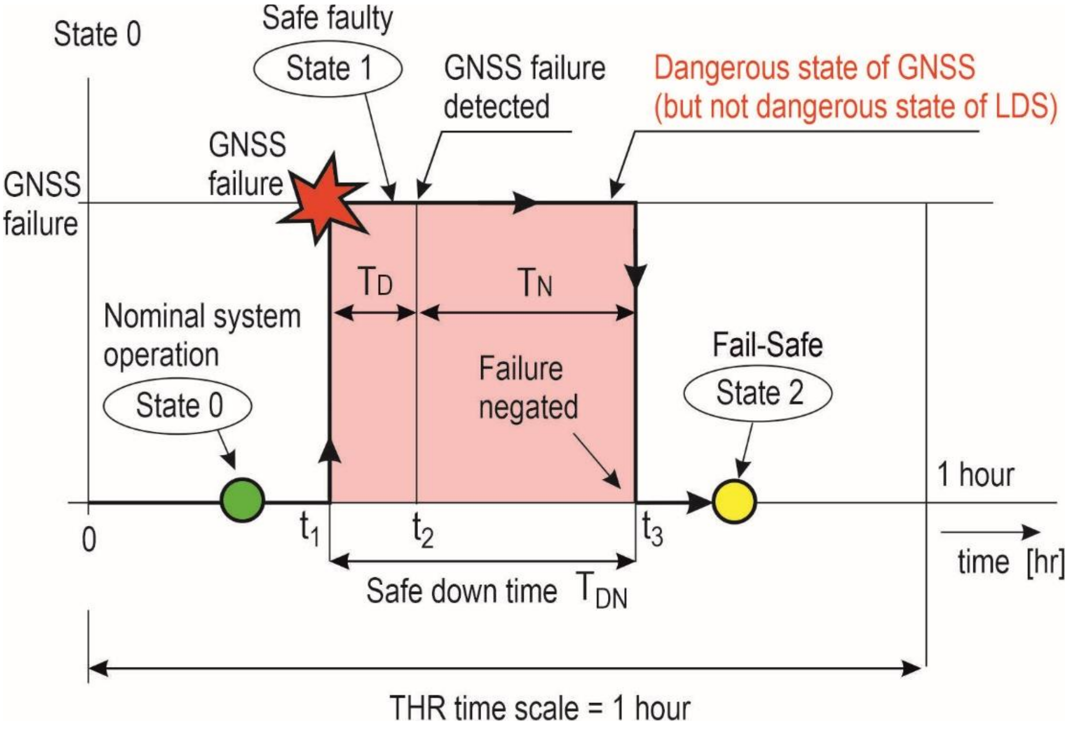


Figure 11: Determination of P_{md} from duration of GNSS+AIMN-based ATP failure T_{DN}

Safe down time T_{DN} represents the time interval during which the LDS (GNSS+AIMN + independent diagnosis) is in safe state and also remains safe after output switch was disconnected – see Figure 11 and Figure 7. Since it is assumed that the GNSS+AIMN-based ATP dangerous failure can appear during the next 1 hour time interval with a certain probability, then the T_{DN} [hr] relative to 1 hour represents acceptable Probability of missed detection P_{md}, for which the system still remains safe with regard to the required level THR_{req}. The probability $P_{md}= T_{DN}/$ 1 hour [-] represents one of the basic parameters of independent diagnosis, i.e. safety monitor.

P_{fa} - is derived from the required LDS availability A defined using unavailability (of ETCS on-board equipment) U= 1- A= P_{fa}. The Gaussian distribution is employed in the safety monitor – see Figure 10. The K_{md} and K_{fa} coefficients are determined as follows:

$$K_{md} = \left|\Phi_{Gauss}{}^{-1}(\,P_{md})\right|$$

$$K_{fa} = \left|\Phi_{Gauss}{}^{-1}\left(\frac{P_{fa}}{2}\right)\right|$$

5.2.9 Example: MDE determination

Let us assume as an example that LDS unavailability for ERTMS OBU should be U=1e-6, as it is defined in HELMET D2.3 [2]. Then availability is A= 1-U = 0.999999. If MTTR (Mean Time to Repair) =1 hour, MDT(Mean Down Time) for ETCS OBU is 1 hour, then MTBF (Mean Time Between Failures) is about 1e6 hours. Probability of false alert during 1 hour mission is P_{fa} = 1/MTBF * 1hour = 1.0e-6 [-]. Correlation in the monitored travelled distance error is omitted due to diversity between GNSS and odometry sensors. Further let us assume that P_{md}= 4.4e-5 [-] (derived above). Then

- K_{fa} (along track) = Norminv (1 - 1.0e-6/2, 0, 1) = 4.8916 ≈ 4.90
- K_{md} (along track) = Norminv (1 - 4.4e-5, 0, 1) = 3.9214 ≈3.92

Let's assume that 1-sigma of position accuracy along track (σ_{ATP}) is about 1.5 m for SBAS and odometry error is omitted for short travelled distance. Then MDE can be estimated as

$$MDE = K_{fa} \text{ x } \sigma_{test|ff} + K_{md} \text{ x } \sigma_{test|faulty}$$

$$MDE \approx (K_{fa} + K_{md}) \text{ x } \sigma_{ATP} = (4.90 + 3.92) \text{ x } 1.5 = 8.82 \text{ x } 1.5 = 13.23 \text{ m} \approx 14 \text{ m}$$

Let's assume that 1-sigma of position accuracy along track (σ_{ATP}) could be about 0.1 m for HELMET solution supported by AIMN, then

$$MDE \approx (K_{fa} + K_{md}) \text{ x } \sigma_{ATP} = (4.90 + 3.92) \text{ x } 0.1 = 8.82 \text{ x } 0.1 = 0.882 \text{ m} < 1 \text{ m}$$

In this case MDE would meet requirement for the location accuracy (of on-board ERTMS Balise Transmission Module – BTM), which shall be within ±1 m for each (physical) balise, when a balise has been passed [5]. In this case HELMET solution would meet the requirement for the Odometry calibration function.

Maximal decision threshold T_{max} can be set to e.g. 20 m due to operational reasons (to further improve LDS availability).

5.3 ARCHITECTURE_2: COMPOSITE SAFETY FOR TRACK IDENTIFICATION

Track discrimination required for ERTMS Start of Mission (SOM) with UNKNOWN status (train position is not a priory known) is a **decision problem**. In this case it is not possible to define a FAIL-SAFE STATE from the system design point of view, which could help to reduce (via fast diagnosis) safety requirements for subsystems (GNSS and independent diagnosis) and simultaneously meet required THR (FFR). We cannot say that the determined position of train on one track is safer than on the other one. A fast diagnosis used in the above Position Estimation Problem is not applicable for Track Identification / discrimination. It would be wrong to say that fast diagnosis reduces the system FFR (Functional Failure Rate) in this case. If we would (incorrectly) accept this possibility, then THR of 3.3e-10/ h required for track discrimination/ identification could be theoretically met (see HELMET D2.3, §4.1.4, eqn (1)) by low quality functions A and B (let’s say $FR_A = FR_B$=1e-2/ h) if SDT would be very short, i.e. 3.3e-6 hour = 0.01188 s - and it is a nonsense.

It is assumed that Track Identification function in LDS status UNKNOWN is performed in Staff Responsible (SR) mode with a defined low ceiling speed (e.g. v < 30 km/h). It means that safety of moving train during execution of Track Identification function is under responsibility of driver. If LDS failure is detected, it means that Track Identification was not successfully completed. Dangerous undetected failure of Track Identification function has no impact on railway safety in SR mode. However, this latent LDS failure can have hazardous consequences in subsequent normal train operation (full supervision of ETCS). Therefore, derivation of (hazardous) Functional Failure Rate (FFR) of Track Identification function is derived below.

Since fast LDS diagnosis during SR mode has no impact on railway safety, then LDS can be modelled in a simplified way as a system without failure detection mechanisms. Note: In reality, the LDS will obviously have a failure detection mechanism to notify that the Track Identification function has not been successfully completed. The corresponding Markov model of two-channel LDS (two-out-of-two) performing Track Identification function is shown in Figure 12.

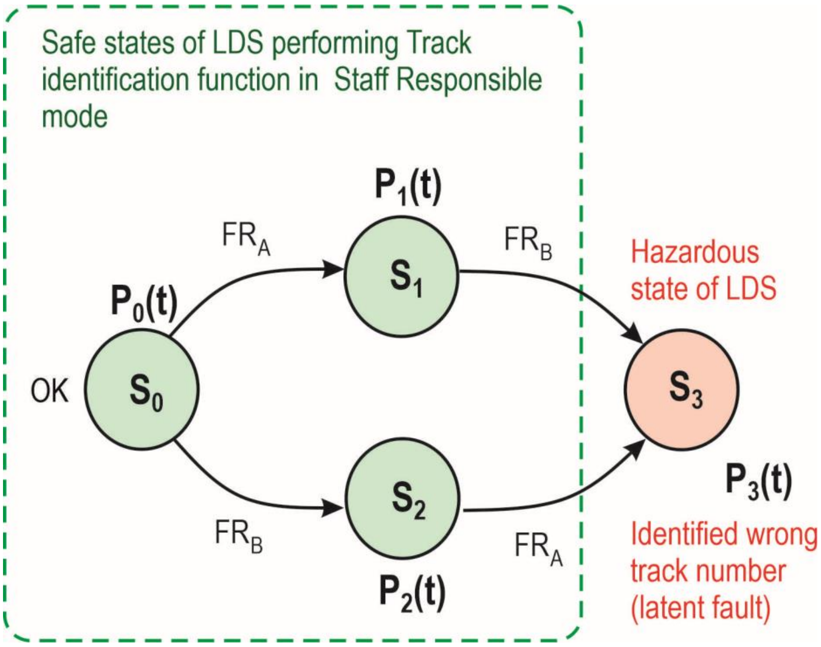

Safe states of LDS performing Track identification function in Staff Responsible mode
P1(t)
FRA
FRB
S1
Hazardous state of LDS
P0(t)
OK
S0
S3
S2
P3(t)
FRB
FRA
Identified wrong track number (latent fault)
P2(t)

Figure 12: Markov model of two- channel LDS (2oo2) without failure detection

The following four system states are defined for the model:

- S_0: Fully functional LDS state at time t=0;
- S_1: Element A has a failure - safe faulty state in SR mode;
- S_2: Element B has a failure - safe faulty state in SR mode;
- S_3: Both elements have failure Hazardous LDS state – it is dangerous undetected failure mode. The corresponding probability P_3(t) represents probability of hazardous latent failure. This latent failure can endanger railway safety in ETCS full supervision mode.

Solution of liner differential equations of Markov model gives probability P_3(t) as

$$P_3(t) = (1 - e^{-FR_A * t}) * (1 - e^{-FR_B * t}) \approx FR_A * FR_B * t^2$$

Since P_3(t) corresponds to FFR * t, then for next 1 hour interval one can write

$$FFR \approx FR_A \times FR_B \times 1\, hour$$

It is evident that realization of the Track Identification function using composite safety requires higher demands on subsystems (A, B) from viewpoint of safety integrity. For example, the THR requirement of 3.3e-10/ h for track discrimination function can be met by GNSS position determination as a Function A with FR_A of 1e-6/ h and independent diagnosis of GNSS as a Function B with FR_B of 1e-4/ h. In this case $FFR_{\text{Track discrimination}}$ equals to 1e-10/ h.

In case of Along Track Position (ATP) estimation, the THR requirement of 3.3e-10/ h can be met e.g. by GNSS as a Function A with FR_A of 1e-4/ h and independent diagnosis of GNSS as a Function

B (also absolute position determination) with FR_B of 5e-3/ h and SDT of 1 s. It can be calculated using

$$FFR \approx \frac{2 \times FR_A \times FR_B}{SDR} = 2 \times FR_A \times FR_B \times SDT$$

as stated in [3] and §4.1.4 of HELMET D2.3 [2]. Then $FFR_{\text{Position estimation}}$ equals to 2.7778e-10/ h.

Duration of track discrimination is limited by operational reasons – i.e. by the average duration of Start of Mission in Staff Responsible, which is 3% of mission duration (1 hour) according to the SUBSET-088 [6], i.e. 108 seconds. However, this operational parameter has no impact on safety integrity of the proposed system architecture.

ETCS onboard subsystem shall take no more than 60 s to go from No Power (NP) to being ready to accept data entry in Standby (SB) [11]. Therefore, values of 10s < TTA < 30 s proposed by the HELMET User Requirement UR_001 [1] is appropriate.

5.3.1 Rules for realization of safety related functions with TFFR < 1e-9/ hour (EN 50129, IEC 61508)

The quantitative safety requirement for Track Identification is expressed through THR_{H9} of 3.3e-10/ hour which is related to erroneous reporting of Virtual Balise in a different track – see HELMET D2.3, Figure 34 [2]. In this development stage, this requirement can be also considered as THR requirement for across track train position determination function.
According to EN 50129, a safety-related function having quantitative requirements more demanding (lower) than 1e-9/h shall be treated in one of the following ways:

- if it is possible to divide the function into functionally independent sub-functions, the TFFR can be apportioned between those sub-functions (allocating TFFR to these functions) and a SIL allocated to each of them;
- if the function cannot be divided, the measures and methods required for SIL 4 shall, at least, be fulfilled and the function shall be used in combination with other technical or operational measures in order to achieve the necessary TFFR.

Similarly, IEC 61508-1 sets a lower limit on the target failure measures for a safety function carried out by a single E/E/PE safety-related system. For E/E/PE safety-related systems operating in a high demand or a continuous mode of operation, the lower limit is set at an average frequency of a dangerous failure of 1e-9/ hour.

Conclusion: Track Identification function for ERTMS with based on GNSS must not be realised as a single function.

5.3.2 AND-combination logic

Railway functional safety is strictly based on logical AND-combination approach, i.e. failure of functions shall be independent with respect to systematic and random faults. Independence among functions, from common random causes (CCF) and common systematic causes is required.

When a hazard results from the failure of two or more independent functions (i.e. logical AND combinations), the following rules shall be applied (EN 50129 [3]):

- Freedom from common random and systematic causes shall be demonstrated by CCF analysis;
- Each function shall be able to prevent the hazard. Therefore, a failure of one of the independent functions shall not lead to the hazard (i.e. fail-safe approach must be implemented);
- The functions shall be diverse (i.e. use different functional approaches or technology) so as to avoid common causes leading to the hazard;
- Safety integrity of each independent function shall not rely on the results (e.g. outputs) of the other independent function(s).
- A fault in any function shall be detected and a safe state enforced within a time compatible with the THR/TFFR of higher level hazard or function. This detection should be provided by a means independent of the function under consideration.

Note: In case of Track Identification function (LDS status UNKNOWN), time to failure detection and negation T_{DN} doesn't impact safety integrity of LDS. Track Identification is a decision problem without a priory defined a fail-safe state (track number). Track Identification (LDS status UNKNOWN) is being performed in Staff Responsible (SR) mode with low ceiling speed (v< 30 km/hr), so railway safety in this mode is under train driver's responsibility.

5.3.3 High-level composite LDS architecture for Track Identification based on track-side data

In this section there is proposed LDS architecture with composite safety (ARCHITECTURE_2) that profits from competitive technical and operational data (including relevant meta data) provided by the railway track-side infrastructure and Traffic Control Centre. The safety-related track-side data and relevant meta-data are aggregated for a pre-set train route before Movement Authority is granted to the train driver. The on-board LDS sensor data are then AND-combined with the diverse track-side data (and meta-data) in order to improve LDS safety integrity. In addition to Track Identification, this architecture is also intended for along track position determination. The proposed composite LDS architecture is outlined in Figure 13.

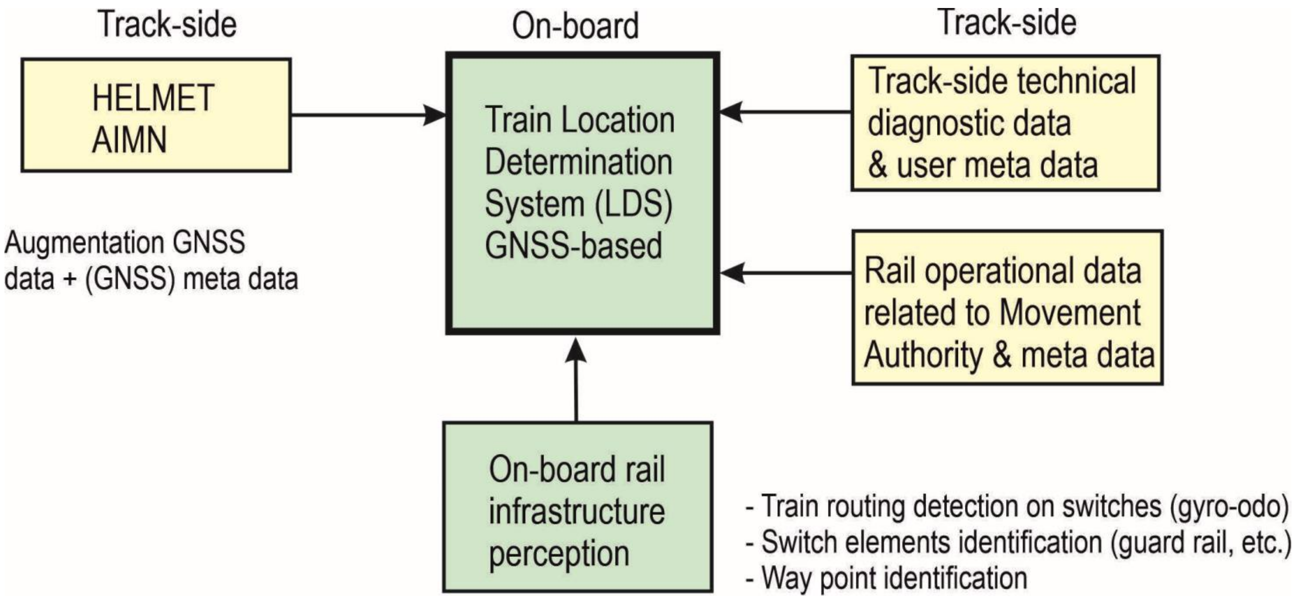


Figure 13: Principal composite safety LDS architecture intended for Track Identification function

In contrast to road transport, railway vehicles cannot arbitrarily move on the railway infrastructure. A Movement Authority must be granted to a specific train / driver. Before the MA is sent to the train, it must be known where the train has to go (track number, location) and which route the train will run on. It is evident that the operational information rated to MA and technical information regarding train route setting could be utilized for LDS safety improvement. It means that in addition to functional safety principles (used for GNSS-based LDS) also other safety provisions such as Technical measures or Operational measures can significantly improve safety integrity of train position determination function, if they could be logically combined via AND operator – see Figure 14.

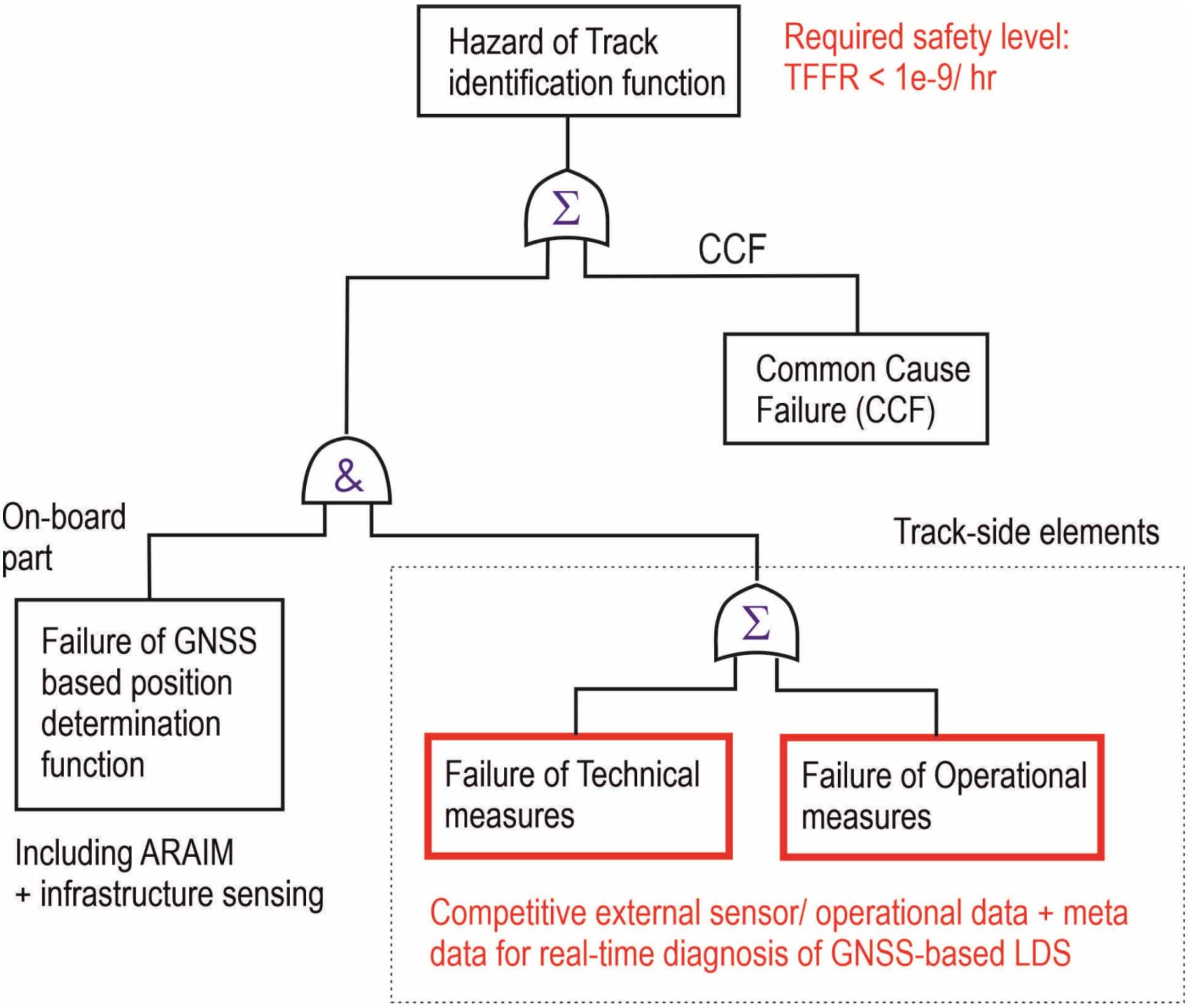

Hazard of Track identification function
Required safety level:
TFFR < 1e-9/ hr
Σ
CCF
Common Cause Failure (CCF)
&
On-board part
Track-side elements
Failure of GNSS based position determination function
Including ARAIM
+ infrastructure sensing
Σ
Failure of Technical measures
Failure of Operational measures
Competitive external sensor/ operational data + meta data for real-time diagnosis of GNSS-based LDS

Figure 14: FTA of the LDS with composite safety: technical and operational safety measures have been introduced to meet the required THR < 1e-9/ hr for main LDS hazard.

In addition of train position determination using GNSS + ARAIM, movement of train on the railway infrastructure could be determined via on-board environment sensing techniques such as gyro-odometry, computer vision, detection of rail switch elements (e.g. guard-rail), etc.

Further, diagnostic data coming from railway infrastructure (e.g. switch position monitored via switch position sensor device) supporting LDS integrity enhancement can be used as Technical safety measures. And finally the information regarding MA provided by a Traffic Control Centre could be utilized as Operational safety measures – see Figure 15.

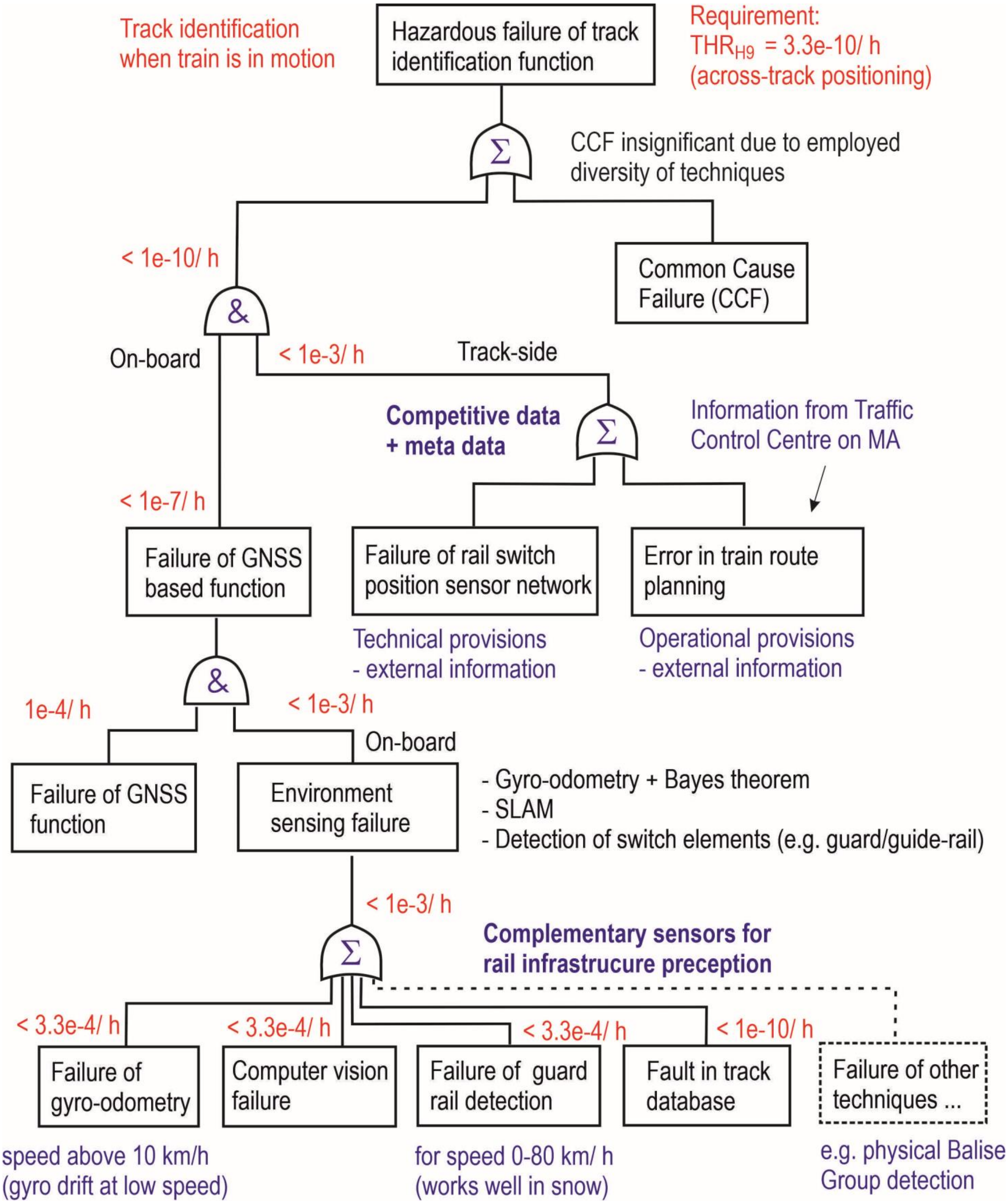

Track identification
when train is in motion
Hazardous failure of track identification function
Requirement:
THR$_{H9}$ = 3.3e-10/ h
(across-track positioning)
Σ
CCF insignificant due to employed diversity of techniques
< 1e-10/ h
Common Cause Failure (CCF)
&
On-board
< 1e-3/ h
Track-side
Competitive data
+ meta data
Σ
Information from Traffic Control Centre on MA
< 1e-7/ h
Failure of GNSS based function
Failure of rail switch position sensor network
Error in train route planning
Technical provisions
- external information
Operational provisions
- external information
&
1e-4/ h
< 1e-3/ h
On-board
Failure of GNSS function
Environment sensing failure
- Gyro-odometry + Bayes theorem
- SLAM
- Detection of switch elements (e.g. guard/guide-rail)
< 1e-3/ h
Σ
Complementary sensors for
rail infrastrucure preception
< 3.3e-4/ h
< 3.3e-4/ h
< 3.3e-4/ h
< 1e-10/ h
Failure of gyro-odometry
Computer vision failure
Failure of guard rail detection
Fault in track database
Failure of other techniques ...
speed above 10 km/h
(gyro drift at low speed)
for speed 0-80 km/ h
(works well in snow)
e.g. physical Balise
Group detection

Figure 15: FTA of LDS with applied specific technical and operational safety measures. Examples of minimum THR/TFFR requirements for individual functions in the composite solution are marked in red)

5.3.4 Rail track-side infrastructure sensing

Train routing detection on rail switch points can be efficiently based on measurement of train movement direction by gyroscopes. Problem is that gyros suffers by drift and therefore this technique can be usually used for speeds above about 10 km/ hr. For speeds less than 10 km/ h another technique should be used.

In sections below there are remembered two (rail environment) sensing techniques, which were developed and successfully tested at Czech Railways around year 2000. These techniques are:

- Train routing detection on switch point based on gyro-odometry and Bayes theorem.
- Detection of guard rails of switch point using laser sensor.

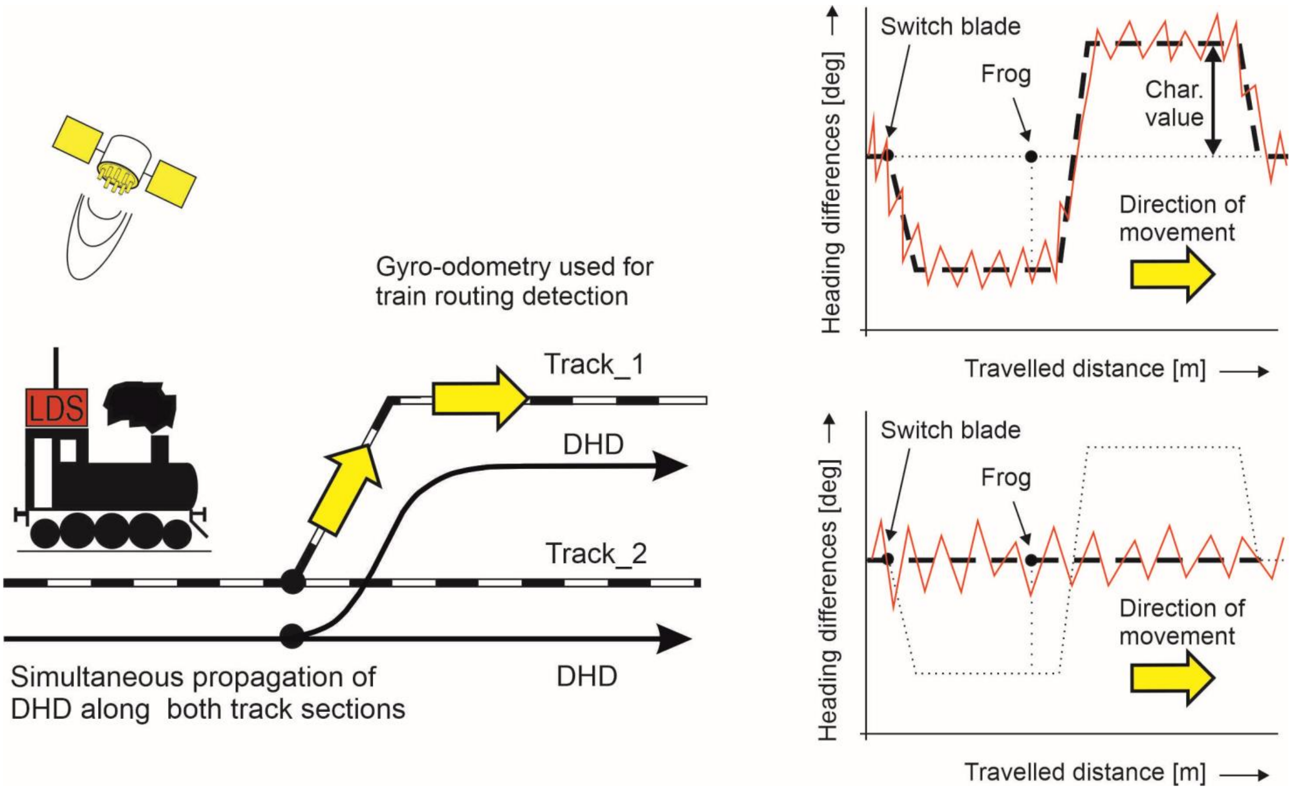
Train routing detection on switch point based on gyro-odometry and Bayes theorem [7]-[9]

The probabilistic safety qualification method presented in this paragraph is based on knowledge of the precise reference trajectory and gyro-odometry data during movement of a train on the track or switch. This method requires statistical independence of the measured heading data which has been already experimentally demonstrated and described in [8].

Note (year 2020): The statistical independence of heading data measurement can be assured from today’s point of view by using several diverse gyros, since these MEMS sensors are very cheap now.

The differences between two successive heading measurements and the travelled distance data provided by an odometer can be used for train trajectory calculation (dead reckoning) from the known initial point. However, these heading differences are still influenced by a drift of the gyro, which introduces an error in the computed trajectory. In order to compensate the gyro drift effect on decision making on a switch, the *double* heading differences (DHD) have been introduced with an aid of the precise reference track axis map [8], [9].

$$\begin{aligned} &\delta^{n}(t) = \Delta\varphi^{meas}(t) - \Delta\varphi^{ref-n}(t), \text{ where} \\ &\Delta\varphi^{meas}(t) = \varphi^{meas}(t-\Delta t) - \varphi^{meas}(t) \text{ and} \\ &\Delta\varphi^{ref\_n}(t) = \varphi^{ref\_n}(t-\Delta t) - \varphi^{ref\_n}(t). \end{aligned} \tag{8}$$



(a) (b)

Figure 16: Train routing detection on switch by means of gyro-odometry: (a) based on double heading differences (DHDs), and (b) complementary diagrams of heading differences for ride in deflecting direction (above) and in straight direction .

The *double* heading difference $\delta^n(t)$ according to eqn. (8) means the difference between the measured heading difference $\Delta\varphi^{meas}(t)$ of the vehicle and the corresponding heading difference $\Delta\varphi^{ref\_n}(t)$ computed from the precise *n-th* reference trajectory, where Δt is a time interval between two heading measurements. Obviously, the consistency of the measured and the calculated heading differences on the switch mainly depends on the accuracy of travelled distance measurement.

The principle of train routing detection on the switch by means of double heading differences is outlined in Figure 16. Figure 16 (a) shows that DHD propagate along both reference trajectories depending on the distance travelled. DHD are used for decision making on which of tracks the train is located during passing the switch. A characteristic dependence of heading differences obtained from heading measurement by gyro(s), and calculated heading differences from the reference trajectories (Track_1 and Track_2) on travelled distance for ride in deflecting (above) and straight directions are shown in Figure 16 (b). DHD are calculated using the measured and calculated heading differences (8).

The decision process evaluating train routing detection on a switch is based on the conditional probabilities and Bayes' theorem (9) [8], [9]:

$$P(H_1 \mid A) = \frac{P(H_1)P(A \mid H_1)}{P(H_1)P(A \mid H_1) + P(H_2)P(A \mid H_2)} \qquad (9)$$

H_1 and *H_2* are two inconsistent hypotheses. The hypotheses *H_1* and *H_2* mean that the train is located on the tracks No. 1 and No. 2, respectively. The term *$P(H_1)$* is the *prior* probability (known before measurement) that the train is located on the track No. 1. The term *$P(H_2)$* means the same but for the track No. 2. Before the decision process of routing detection begins (the first axle of a vehicle is located on the blade of the switch), the *prior* probabilities *$P(H_1)$* and *$P(H_2)$* equal 0.5 . The term *$P(A| H_1)$* means the conditional probability that the train is located on the track No. 1 after the experiment *A*, i.e. heading and distance travelled measurements were performed. The term *$P(A| H_2)$* is the same conditional probability for the track No. 2. The conditional probabilities *$P(A| H_1)$* and *$P(A| H_2)$* can be expressed by means of the successive *double* heading differences (8) as follows

$$
\begin{aligned}
P(A\,|\,H_1) &= \frac{|\,\delta^2(t)\,|}{|\,\delta^1(t)\,|+|\,\delta^2(t)\,|} \\
P(A\,|\,H_2) &= \frac{|\,\delta^1(t)\,|}{|\,\delta^1(t)\,|+|\,\delta^2(t)\,|}
\end{aligned}
\qquad (10)
$$

Finally, the *posterior* probability *$P(H_1|A)$* that the train is located on the track No. 1 is derived in eqn. (11).

$$
P(H_1\,|\,A) = \frac{P(H_1)\,|\,\delta^2(t)\,|}{P(H_1)\,|\,\delta^2(t)\,|+P(H_2)\,|\,\delta^1(t)\,|} \qquad (11)
$$

According to (11), the resulting probability evaluating routing detection on the switch can be computed from the heading data and the instant position of the train in the route map determined by means of the odometric data. In each following step, the computed conditional probabilities (10) replace *$P(H_1)$* and *$P(H_2)$*, respectively. The error of the odometer taken as a parameter enables investigation of the relation between the odometric error and the final *posterior* probability computed by means of eqn. (11).

Sensor data validation during train routing on the switch

A diagram in Figure 17 shows the relation among the heading differences and the travelled distance within the routing detection experiment. The data was recorded on the switch with the crossing angle of 7^{o} 46‘03“ at speed of 40 km/hour.

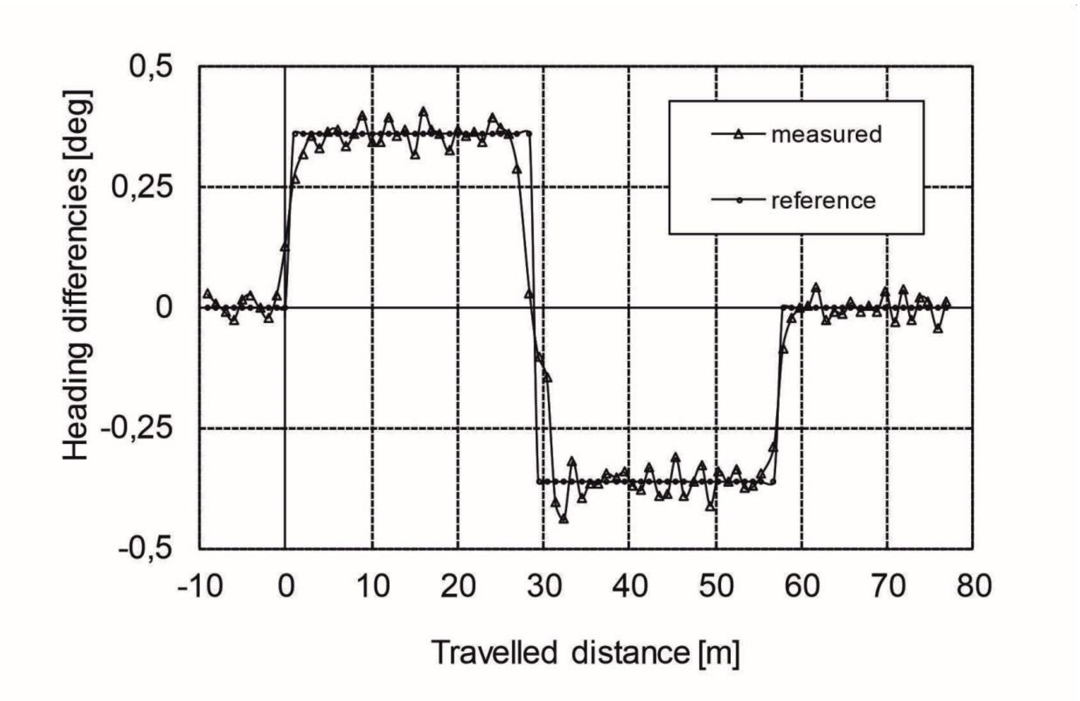


Figure 17: Heading differences vs. travelled distance on the switch

The locomotive was passing the switch in the diverging route. Zero value on the travelled distance axis in this and the next diagram means the front of the switch blade. From this diagram is evident that the heading differences measured by the KVH FOG and the reference heading differences computed by means of the precise map match well. If the measured double heading differences do not match with the computed ones, a fault of gyroscope is indicated.

Train routing detection experiments on the switch

The same odo-gyro data was employed for evaluation of the routing detection process by means of the conditional probabilities and Bayes' theorem according to the eqn. (9) – (10). A diagram in Figure 18 shows three computed probabilities $P(H_1|A)$ of routing vs. travelled distance on the switch for the following error modes of the odometer: a) the real recorded odometric data – i.e. without an error, b) the intentionally introduced error of 2.5 meters and c) the intentionally introduced error of 5 meters. According to the error mode a) the probability $P(H_1|A)$ achieved value of 0.99999 after the locomotive travelled a distance of 11.7 meters from the front of switch blade. The same levels in modes b) and c) were achieved for the travelled distances of 13.9 and 17.4 meters, respectively. These results confirm the fact the routing decision process depends on the performance of odometric system. Since the distance between the front of the switch blade and the frog is 21.8 m, the above

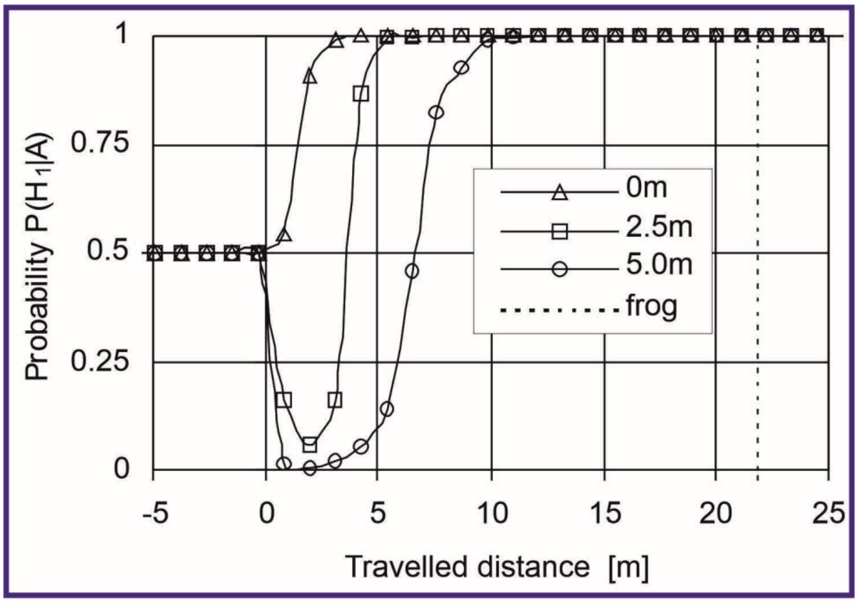


Figure 18: The posterior probability $P(H_1|A)$ of the routing detection vs. travelled distance on the switch

specified probability level is achieved before the train arrives to the frog. Therefore, the odometric error of +/- 5 meters seems also acceptable for the routing decision process. This method is simple, low cost and efficient.

Detection of characteristic switch elements using laser sensor

Many of railway switch points are equipped by a *guard rail* (*check rail*). It is a short piece of rail placed alongside the main (stock) rail opposite the frog – see Figure 19. These ensure that the wheels follow the appropriate flangeway through the frog and that the train does not derail. Generally, there are two of these for each frog, one by each outer rail.

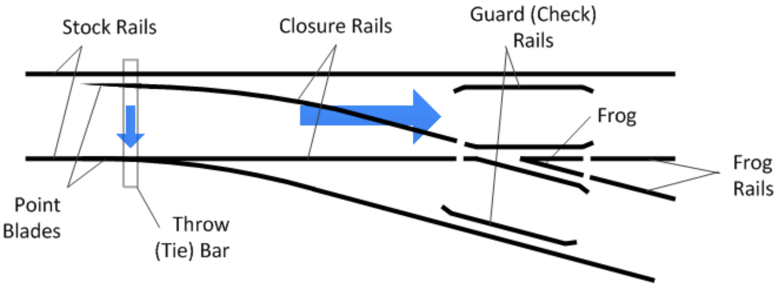


Figure 19. Fundamental elements of rail switch [12]

Guard (Check) rails can be detected by on-board equipment in order to get an additional indication if the train pass the switch in divergent route / turnout or through route - see Figure 20.

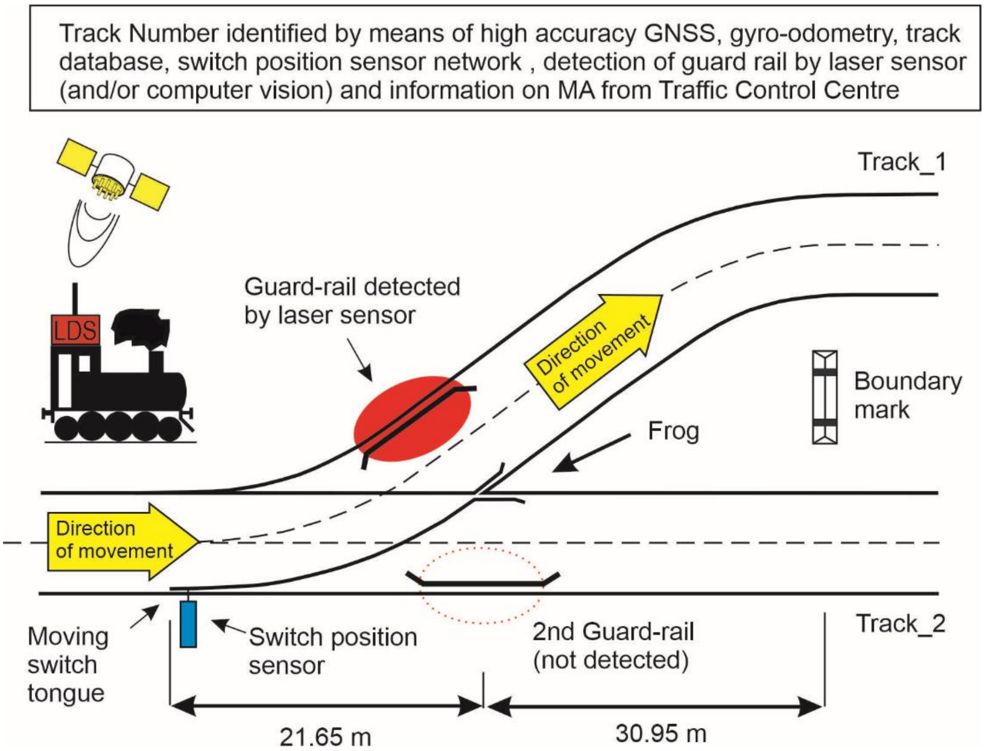

Track Number identified by means of high accuracy GNSS, gyro-odometry, track database, switch position sensor network , detection of guard rail by laser sensor (and/or computer vision) and information on MA from Traffic Control Centre
Track_1
LDS
Guard-rail detected by laser sensor
Direction of movement
Boundary mark
Frog
Direction of movement
Moving switch tongue
Switch position sensor
2nd Guard-rail (not detected)
Track_2
21.65 m
30.95 m

Figure 20: Detection of guard rail to get information on train routing

Guard rails are not required with a "self-guarding cast manganese" frog, as the raised parts of the casting serve the same purpose – see Figure 21 .

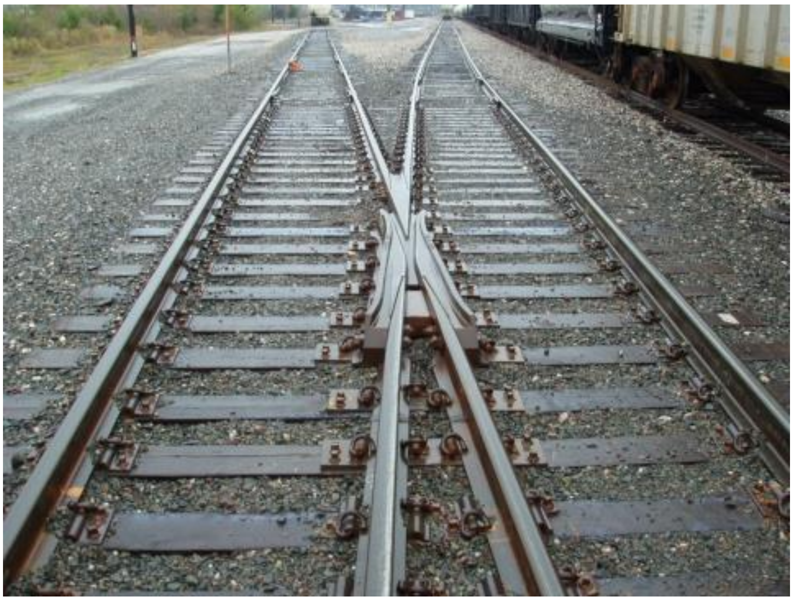


Figure 21: Switch with "self-guarding cast manganese" frog without guard rails [13]

Guard rails are not installed on a switch with movable point frog as well – see Figure 22.

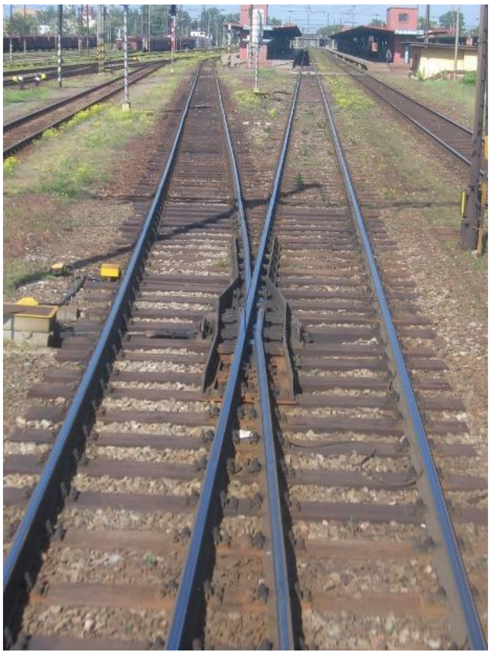


Figure 22: Switch with movable frog without guard rails [14], [15]

Detection of guard rails using laser sensor was designed as a competitive technique to increase safety integrity of train routing detection on switch. The principle is outline in Figure 23.

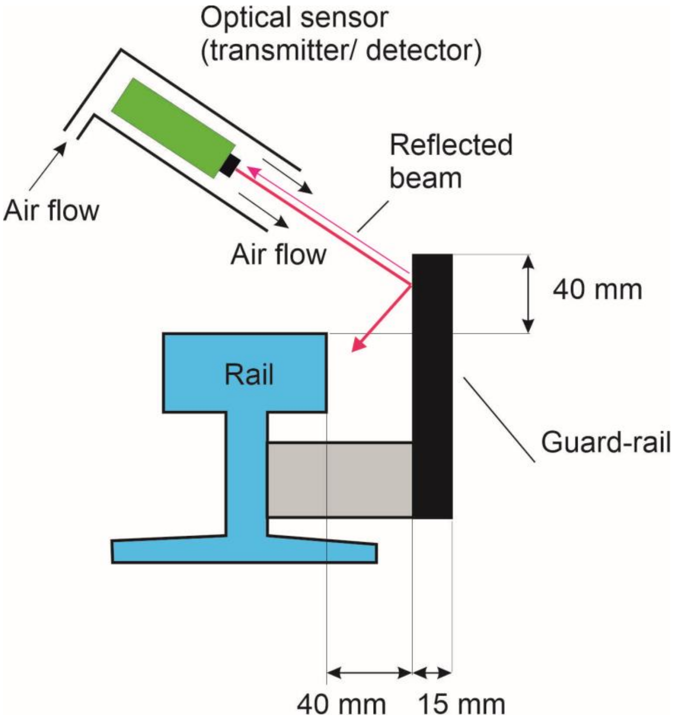


Figure 23: Principle of guard rail detection using laser sensor – works well in snow on track (tested in operations)

This principle was developed and tested at Czech Railways around year 2000. The advantage of the principle consists in fact that it works very well in snow because a wheel clean space between rail and guard-rail (~ 40 mm). It works well in the speed range 0-80 km/ hour. This technique has been successfully used on railway infrastructure diagnostic vehicles.

In cases when guard rail is not installed, characteristic switch features can be detected e.g. by computer vision.

At Czech Railways field tests focused on detection of guard-rail by inductive proximity sensors were also performed in the period of 2000-2003 – see Figure 24.

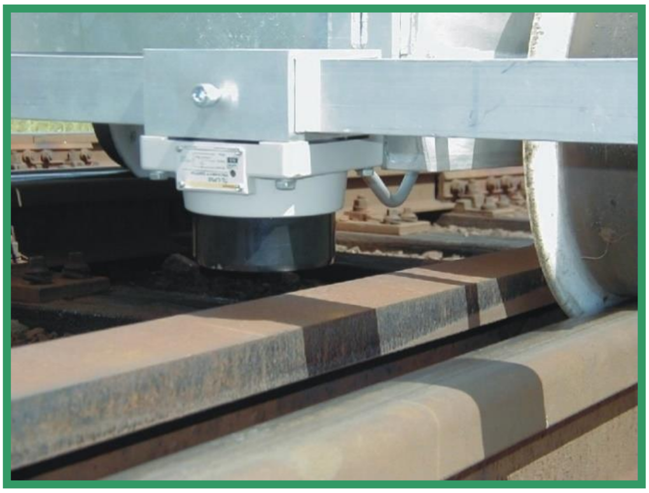


Figure 24: Detection of guard rail using inductive proximity sensor

However, application of such inductive sensors was found inefficient, because these sensors usually work with quite short distance between the sensor and guard-rail (~ 40 mm), which can be a problem on a shunting slope equipped with pneumatic track brakes, where the sensor could be damaged. The laser sensor is much better for this purpose.

5.3.5 High-level composite LDS architecture for Track Identification in stand-still mode

In this section there is analysed what happens if the external safety-related track-side data will not be provided to LDS. So it is assumed that: 1) LDS has a position status UNKONWN (i.e. no last safe train position was confirmed by Cold Movement Detector (CMD), and 2) train position shall be determined in stand-still after OBU with LDS leaving No Power (NP) mode.

Train position shall be determined without knowing, how the train was moved to the current position. The unknown position that shall be determined by onboard LDS. On-board train routing detection cannot be used. Safety provisions based on external technical and operational data also cannot be utilised. Then the FTA depicted in Figure 15 can be modified as shown in Figure 25.

In order to meet the requirement THR_{H9} of 3.3e-10/ h (erroneous reporting of Virtual balise in a different track) – see FTA in Fig. 34 in HELMET D2.3 [2], it is necessary to reduce TFFR of GNSS position determination function to about 1e-6/ hour (from 1e-4/ h) and TFFR of Computer vision to 1e-4/ h (from 1e-3/h). Despite this, it is questionable if would be e.g. possible to determine a train position using on-board computer vision with required level of confidence - for example on the marshalling yard between trains on adjacent tracks or under bad weather conditions.

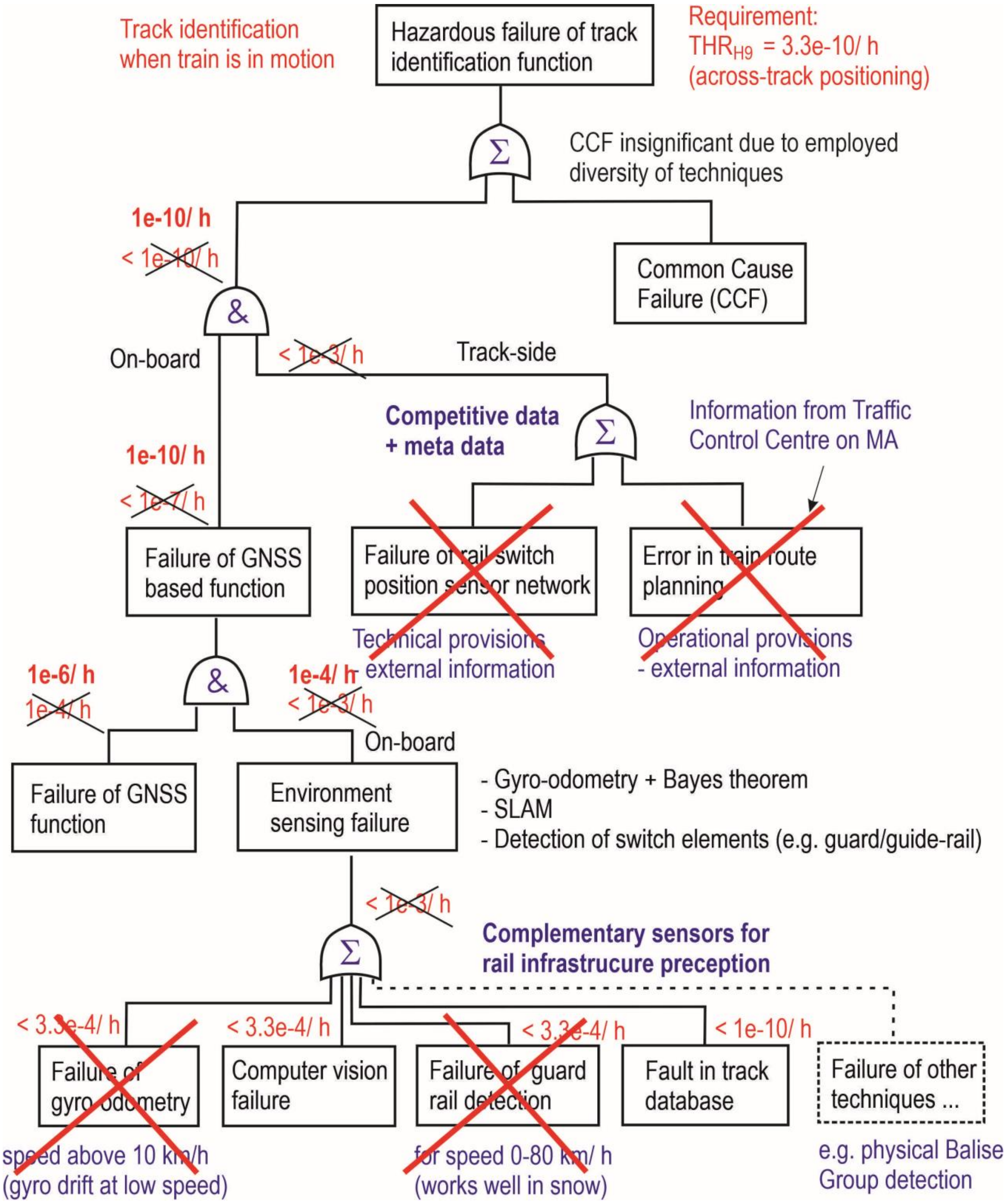


Figure 25: FTA of composite safety LDS in case when train position is determined in stand-still

It is evident that on-board sensor data acquired during train routing detection and logically AND-combined with external track-side technical and operational data can be considered as a very safe, dependable and secured approach for the Track Identification by GNSS + AIMN -based LDS.

The example of THR/TFFR allocation in Figure 15 shows that safety requirements for GNSS + AIMN and other elements of LDS could be significantly reduced. On the other hand the safety requirements for GNSS and its independent diagnosis should we high when safe train position should be only performed in stand-still mode – i.e. when additional complementary data (for routing detection) and competitive data (for safety validation by logical AND combination) cannot be used.

It seems the above conclusions could also impact concept of ERTMS Cold Movement Detector (CMD) if it is considered that GNSS shall be used for this purpose. It is briefly discussed in sections below.

5.3.6 Cold Movement Detector in ERTMS baseline 3

The ETCS onboard subsystem shall include a Cold Movement Detection system (CMD) – it is mandatory for ERTMS/ETCS Baseline 3 – see [10], [11]. CMD function compliant with SIL 4 facilitates the start-up of trains from ‘No Power’ mode. CMD checks whether a train was moved while the ERTMS EVC was in ‘No Power’ mode. In this way, the ERTMS EVC is able to ascertain whether the last determined position is still valid.

After being switched off (i.e. once in No Power mode), the ERTMS/ETCS on-board equipment shall be capable, if fitted with, to detect and record whether the engine has been moved or not, during a period of at least 72 hours (SUBSET-026-1 [10]) – however, a period of 7 days is usually required. The reason for this is that some trainsets will stand still over a longer period of time, for instance when holidays are combined with a weekend. Several UNISIG members noted that certain requirements may be useful for the operating companies but might also cause technical complexity, especially with regards to the CMD power supply (via the train or a special battery).

The ETCS Cold Movement Detection function shall invalidate the stored ETCS position information for any movement in excess of 5 m. The ETCS Cold Movement Detection function shall only be used to validate stored information if the information was known to be correct upon entry to NP mode.

5.3.7 Cold Movement Detector based on GNSS: proposed solution

When a locomotive equipped with LDS based on GNSS is transported in the NP mode from point A to point B by other locomotive or train, the CMD is required to invalidate the last safe position of the locomotive – for movement lager than 5 m. After leaving the NP mode, the LDS (with UNKNOWN position status) shall determine the actual safe train position (in point B) in Staff Responsible. We could assume that the LDS should determine the locomotive position in stand-still.

However as stated above, the very useful external track-side information and train routing detection information provided by the on-board sensing function, which could otherwise significantly contribute to the run-time safety monitoring / evaluation by LDS, cannot be employed when locomotive is in stand-still, because these information are not simply available in LDS.

During train movement from point A to point B (with ETCS EVC + LDS in the NP mode), the enhanced CMD, marked e.g. as CMD+, would acquire all necessary information from on-board and track-side sub-systems related to the vehicle route determination. After the ETCS EVC would leave the NP mode in the point B, then the LDS would utilize this stored information by CMD+ for LDS initialization (with UNKNOWN position status) in stand-still.

Highly safe and dependable CMD+ would guarantee that Track Identification function would be performed before beginning of normal train mission (with full supervision) very seldom, because otherwise the CMD+ would be able to determine and keep train position and track number for vast majority of train rides.

For example, following possibilities for LDS initialization (LDS position status UNKNOWN) after leaving OBU NP mode during train motion can be considered:

- Train is operated in Staff Responsible mode (v< 30 km/h), baseline CMD is used (only movement detection is provided) and LDS is initialized under specific operational rules – i.e. on board train routing detection data and external track-side data are used;
- LDS is equipped with CMD+ (i.e. advanced CMD), CMD+ records all necessary on-board and track-side data during train motion in NP mode. After OBU awaking the acquired data by CMD+ will be utilized for LDS initialization including Track determination.

Note: The presented idea of LDS initialization in motion including use of CMD+ functionality is very fresh and will be further discussed in next phases of HELMET solution.

5.4 OVERVIEW OF SAFETY TECHNIQUES SELECTION FOR LDS

This section provides a brief summary of main features of railway safety techniques (EN 50129) and their applicability to LDS depending upon LDS application in ERTMS – i.e. mainly for a) Along Track Position (ATP) determination, and b) Track Identification. It recapitulates findings regarding this topic described in sections 5.1 - 5.3 of this document and clarifies reasons why certain safety techniques were selected for the above mentioned tasks.

Safety architecture for ATP determination

It is a position estimation problem. A fail-safe state of equipment under control (train) can be defined – train can stop or reduce speed. Fast safety reaction in case of a critical LDS failure, i.e. short Time to Detection and Negation (T_{DN}), can significantly contribute to reduction of safety requirements for GNSS + AIMN.

In principle following safety techniques can be applied for LDS:

- Composite fail-safety
- Reactive fail-safety

In case of composite solution, two diverse absolute train position determination principles are required. Function A can be performed by GNSS. However, there are currently not available another efficient and independent technology for absolute position determination (Function B), which could be combined using AND logic with GNSS (see Figure 6(a)). Due to this reason reactive fail-safety was proposed for LDS for ATP determination. In this case absolute train position determination provided by GNSS (Function A) and potential GNSS failure is checked by fault detection based on relative position determination performed by ETCS odometry compliant with SIL 4. This solution was used for ARCHITECTURE_1.

Safety architecture for Track Identification

Track Identification by LDS is a decision problem. This function is required before train starts its mission / journey and its safe position is not a priory known – it was not stored in on-board EVC before last ETCS OBU transition to NP (No Power) mode or not confirmed validity of the last position by Cold Movement Detection.

In this case it is impossible to define a fail-safe state from the system point of view. We cannot say that determined position of train one track is safer than on the other one.

In fact, is it not even necessary to define a fail-safe state because LDS initialization / train identification on parallel tracks is performed under Staff Responsible (SR) mode with a given low ceiling speed limit (e.g. 30 km/ h).

It has been shown in 5.3 that fast failure detection and negation (T_{DN}), which is beneficial is case of ATP determination, is not applicable for Track Identification. It is due to the fact since there is not defined any fail-safe state for Track Identification. Safety during Track Identification is under responsibility of driver. Duration of Track Identification can be only limited by operational reasons. For example, the average duration of ERTMS SR mode is 3% of mission, 108 s [6].

In order to meet the THR requirement for Track Identification, i.e.THR_{H9} of 3.3e-10/ hour, then AND combinations of on-board position determination techniques (GNSS + infrastructure sensing) and track-side technical provisions together with operational provisions should be used. It will enable to reduce safety requirements for GNSS + AIMN. Meta data related to the technical and operational provisions sent to train are used for run-time LDS safety evaluation. The described composite solution corresponds to the ARCHITECTURE_2. When a failure of GNSS or applied provisions is detected, then the execution of Track Identification is interrupted, and the failure state is notified. It is evident from the comparison of FTA examples in Figure 15 and Figure 25 that Track Identification function should be performed by LDS in motion, preferably by passing through switch(es), because all mentioned benefits of on-board sensing and track-side provisions could be efficiently utilised for the required safety achievement. It seems that Track Identification in stand-still would not be possible in some cases without a dedicated track-side equipment (e.g. cameras on towers) e.g. on marshalling yards between trains.

6. HIGH LEVEL ARCHITECTURE FOR AUTOMATED VEHICLES APPLICATION

In this section we present a high-level architecture for a localization system for automated vehicles. After some general consideration concerning a safety architecture in section 6.1 we explain the high-level architecture design in section 6.1.1 in more detail. This section also contains a list of high-level tasks and interfaces. In the following section 6.2 we introduce several High-level Modes of Operation which can be used to determine the exact position of an automated vehicle. We close the section with preliminary analysis of the Fault Trees for Automated Vehicles.

6.1 GENERAL APPROACH AND CONSIDERATIONS

High level architecture design techniques for automated vehicles must ensure in the presence of a failure that the vehicle either transmits its control to a fallback-ready user (for driving automation level 3) or that is able to safely stop, move out of the lane or achieve a different condition to minimize risk (level 4, 5).

Depending on the nature of the failure, one or another strategy would be more suitable.

In the context of HELMET, the high level design is driven on one side by the operational scenarios described in Table 1, and the possible localization modes of operation. In this sense the localization high-level design is fail-operational and should be able under the presence of a failure to react:

- By compensating or adapting its solution (fault-tolerancy)
- By working on a degraded operational mode, with reduced achievable accuracy/integrity for a potentially period of time.

The definition of a degraded operational mode is a combination of the current operational scenario and the current localization mode of operation. This high level design ensures a high level of availability of a localization solution, which is considered safety-critical in automotive domain.

6.1.1 High-level Architecture Design

Figure 26 shows a general architecture with the main necessary components of the Multisensor Onboard Unit.

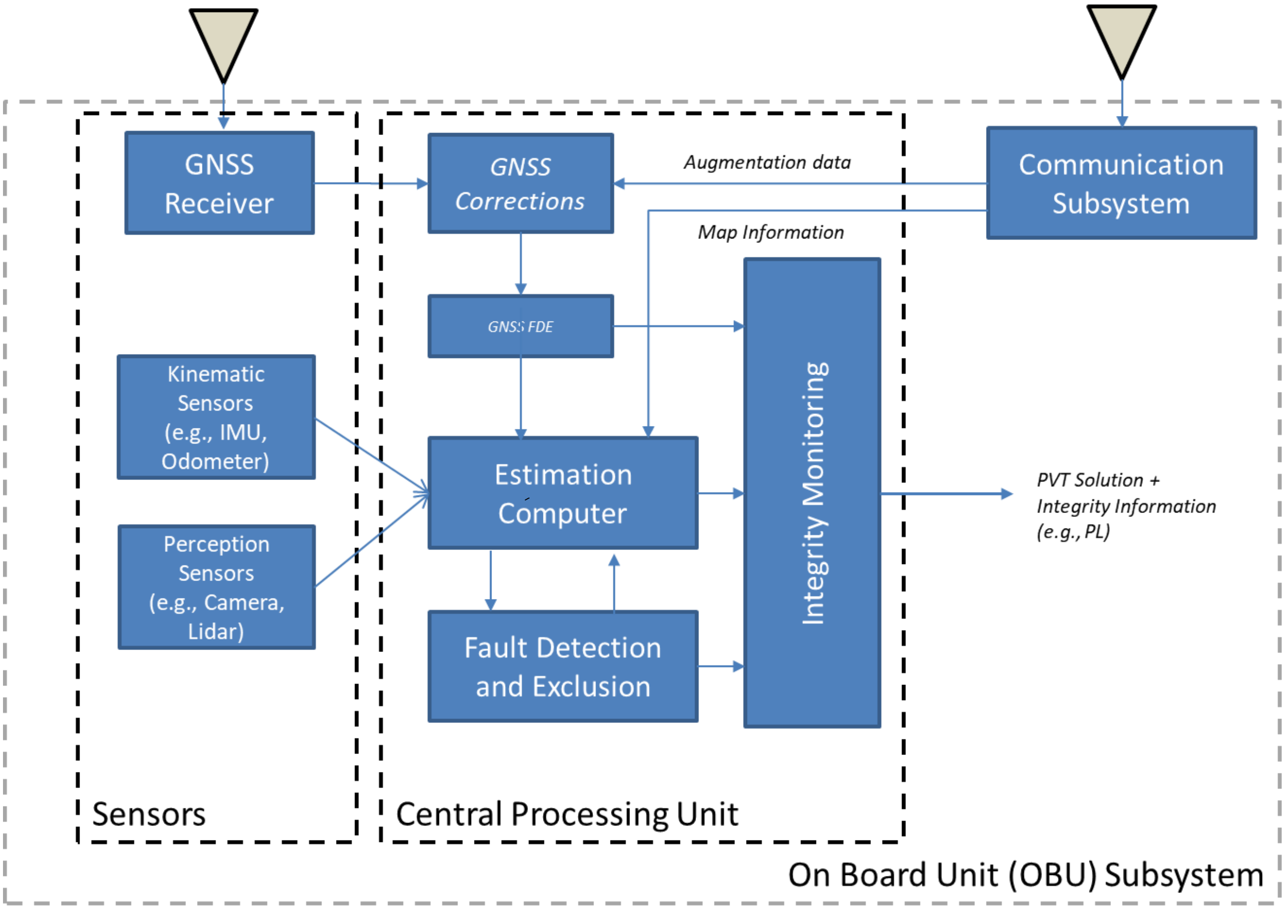

GNSS Receiver
GNSS Corrections
Augmentation data
Communication Subsystem
Map Information
GNSS FDE
Kinematic Sensors (e.g., IMU, Odometer)
Perception Sensors (e.g., Camera, Lidar)
Estimation Computer
Fault Detection and Exclusion
Integrity Monitoring
PVT Solution + Integrity Information (e.g., PL)
Sensors
Central Processing Unit
On Board Unit (OBU) Subsystem

Figure 26: General Onboard unit Subsystem Architecture

The high level OBU consists at least of the following parts:

- The **communication subsystem** part related to the vehicle. This is responsible of:
  - Communicating and receiving the augmentation subsystem corrections and integrity information

  - Communicating with the infrastructure side to obtain relevant augmentation or map data.
- A set of **sensors** that could include:
  - A GNSS Antenna and receiver: This is considered available for all target applications
  - Kinematic sensors: This may include the use of Inertial Measurement Units (IMU) and/or Odometers.
  - Perception sensors: Sensors that capture information from the environment like cameras or LIDAR can be also considered for localization or positioning purposes.
- A **processing** unit: The processing unit is responsible of integrating the measurements from GNSS receivers, correct them and integrate them together with the other sensors data when applicable. This unit compute the position (and attitude) solution and provides information about the integrity of it.

This architecture can be considered as a general structure for the different HELMET segment applications. The specific set of sensors that are available or considered the specific functional safety design approach and the localization algorithms and modes of operation that it implements will be particularized for each transport application in next deliverables. In the following we provide already some high level specific designs architectures and decisions for each of the segments.

6.2 HIGH-LEVEL LOCALIZATION MODES OF OPERATION

The combination of a specific augmentation service with specific on board sensors results into a specific localization processing mode. The nominal performance of a localization mode can be determined taking into account the expected performance of the augmentation, sensor and algorithms that support it. Furthermore, Integrity information is expected to be provided by the system at all times so that it can be determined in a certain localization mode is available in a certain situation. This is handled by a mode manager.

The operational scenarios for the applications under consideration can be started or continued only if the minimum required localization mode is available.

This multimodal structure also establishes reverted or degraded modes of operation so that the user system can take better decisions.

In Table 2, a preliminary map of the possible localization modes depending on the augmentation service level and available sensor is provided. The shaded modes are those that are more relevant during HELMET.

Table 2: Localization Modes of Operation

On board Sensors	**+ Perception (Camera/Lidar)**	*M0.2*	*M1.2*	*M2.2*	*M3.2*
	+ Kinematics (IMU/Odometer)	*M0.1*	*M1.1*	*M2.1*	*M3.1*
	MFMC GNSS	*M0.0*	*M1.0*	*M2.0*	*M3.0*
		SL0 (NO AUG)	**SL1 (SBAS/DGNSS)**	**SL2 (RTK/NRTK)**	**SL3 (PPP/HAS)**

Augmentation Service Levels

A preliminary assignment of the minimum localization mode that is expected to satisfy the requirements of Table 1 for each of the application scenarios is provided in Table 3.

Table 3: Preliminary operation modes supporting application scenarios

Scenario	Operation Mode	Enabling Localization Modes
Automated Driving on Highway	Along Track	>M1.0
	Cross Track	>M2.0
Automated Driving on Local Roads	Along Track	>M2.0
	Cross Track	>M2.2
Automated Driving on Narrow and Curved Roads	Along Track	>M2.2
	Cross Track	>M2.2

Table 2 provides a general overview of all the possible localization modes of operation that future automated vehicles should consider. In the next deliverables of WP3, HELMET will select the most relevant localization modes of operation that the project will target. For each of the modes of operation, different possibilities of algorithms can be also considered, this is for example the decision of loosely coupling or tightly coupling of sensors or the use of float or fixed ambiguities. This will be further developed in D3.3.

6.3 FAULT TREE ANALYSIS FOR AUTOMATED VEHICLES

Based on the fault tree assessment for automated vehicles as described in Figure 41 of D2.3, we provide in Figure 27 a first general Fault Tree Analysis that splits on one hand the different localization dimensions (longitudinal, transversal) and then track the localization failure risk to the positioning failure risk including the possible failure of the map information.

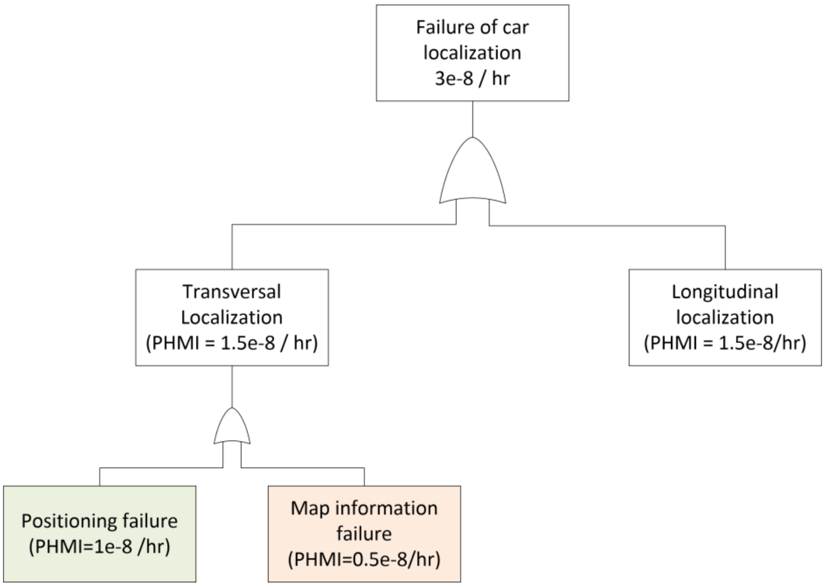

Failure of car localization 3e-8 / hr
Transversal Localization (PHMI = 1.5e-8 / hr)
Longitudinal localization (PHMI = 1.5e-8/hr)
Positioning failure (PHMI=1e-8 /hr)
Map information failure (PHMI=0.5e-8/hr)

Figure 27: General FTA Auto

In order to satisfy the stringent requirements from Figure 27 a first candidate solution is provided in Figure 28. This solution would be mainly relevant for the transversal positioning in automotive applications since the relative positioning with perception sensors like camera with respect to the lanes can be considered independent from the GNSS/INS positioning module.

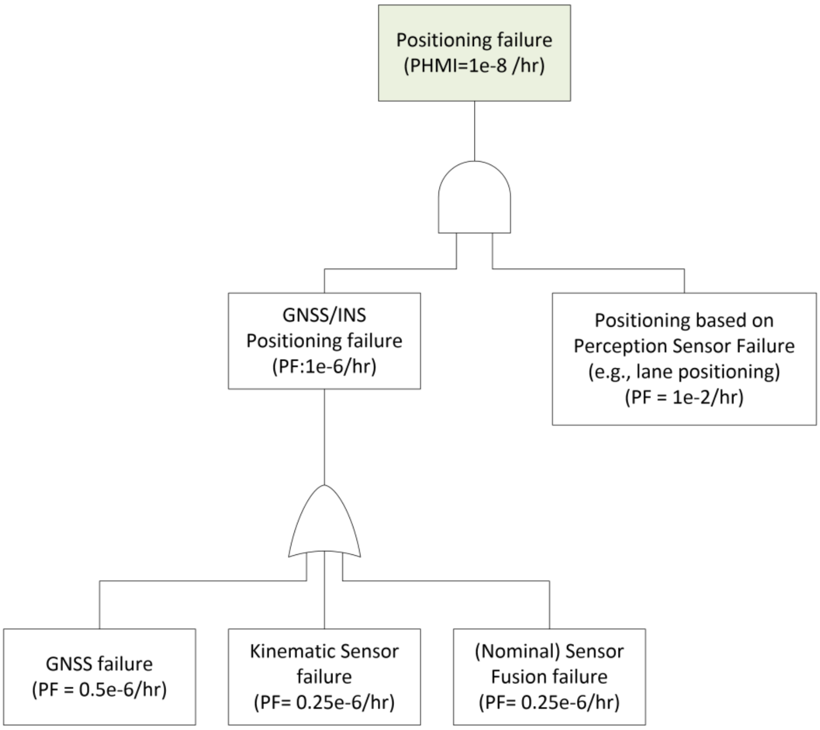


Figure 28: Auto Candidate solution 1 (FTA)

We also study a second candidate solution by considering that the integrity requirements can be relaxed from 1e-8/hr to 1e-6/hr as provided by GSA user requirements reports [16]. This can be the case for instance for longitudinal positioning scenarios. Following a similar split share between map information and positioning system a preliminary general FTA for the positioning function is presented in Figure 29. A failure in the positioning may be due to a failure of the nominal sensor fusion algorithm (Kalman filter) or a failure in the sensor measurements, as GNSS, kinematic or perception.

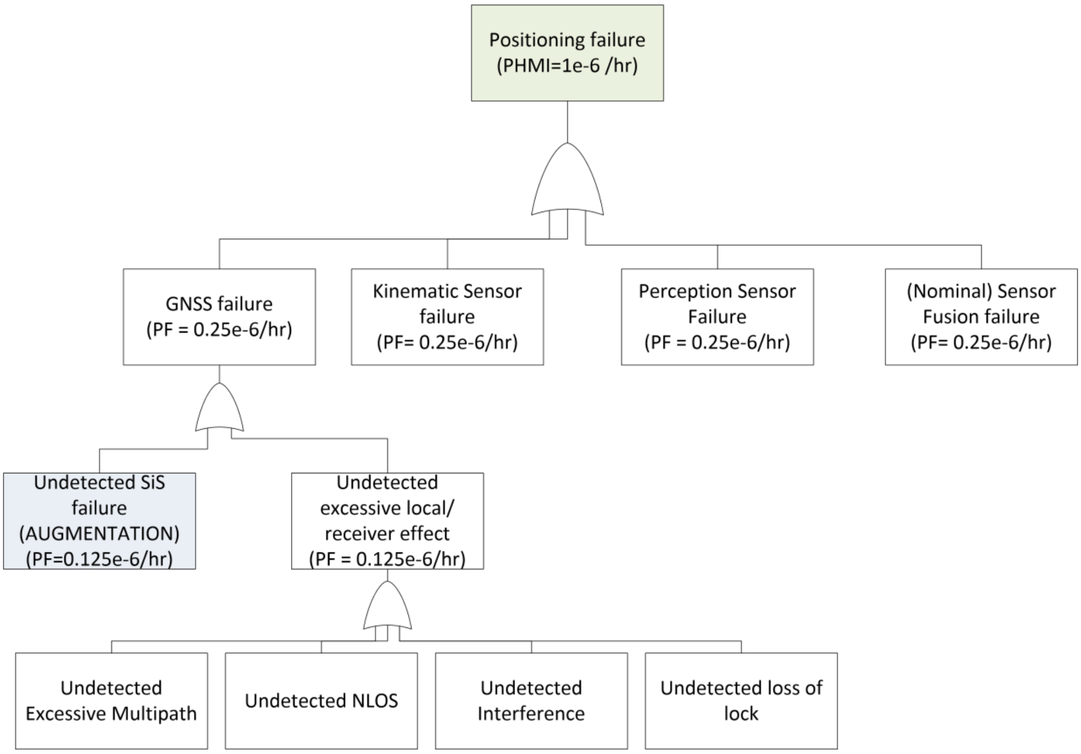


Figure 29: FTA Analysis Positioning Auto (Candidate solution 2)

In the automotive domain the information from an IMU can be considered always present. This is not dependent on the operational scenario or the external conditions like buildings or lighting intensity. In this preliminary FTA we first assume that the combination of kinematic sensors with GNSS and perception is made in a tightly coupled way with respect to GNSS. In this situation, the failure of GNSS sensors is related to the possible faults in the raw GNSS measurements. The remaining probability of faults due to the non-local signal in space propagation is ensured by the augmentation system. The remaining local problems are due to undetected multipath, NLOS, interferences or specific receiver tracking problems, like cycle slips. In this solution, a technology gap is associated with providing high integrity protection against failure in perception systems.

The candidate architecture solutions will be deeper analysed in future deliverables. This will include also the consideration of methods to ensure high-integrity of kinematic sensors and high protection against local GNSS threats, as well as possibilities to quantify and guarantee integrity for camera information.

7. HIGH LEVEL ARCHITECTURE FOR UAS APPLICATION

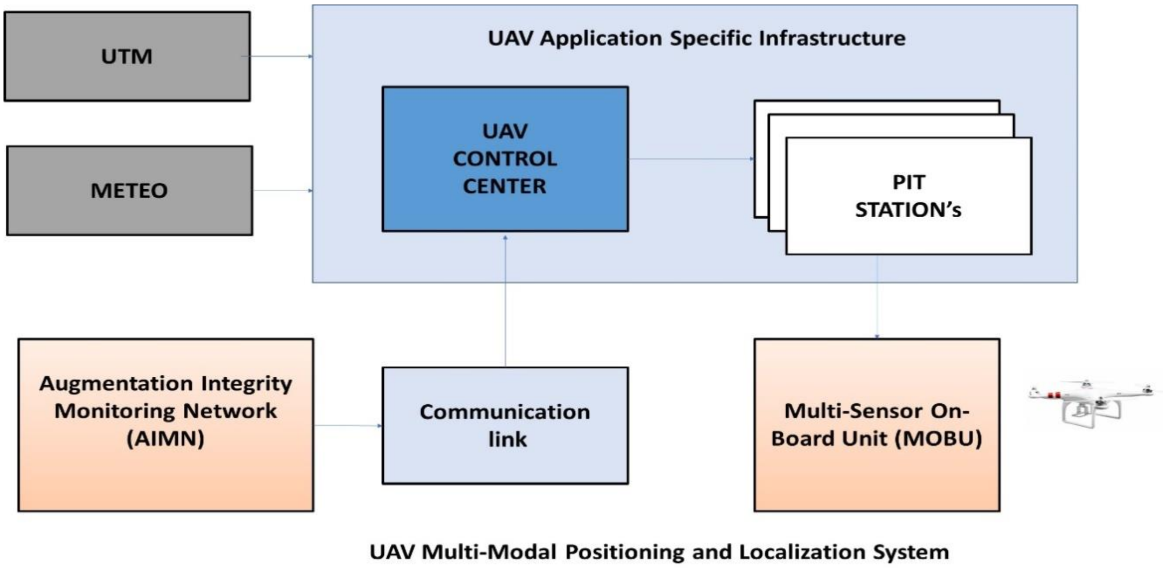

UTM
METEO
UAV Application Specific Infrastructure
UAV CONTROL CENTER
PIT STATION's
Augmentation Integrity Monitoring Network (AIMN)
Communication link
Multi-Sensor On-Board Unit (MOBU)
UAV Multi-Modal Positioning and Localization System

Figure 30: UAV system architecture

In Figure 30 the UAV system architecture is depicted. It differentiates from the other applications because of the need of a specific control center for UAV remote piloting. In addition, the PIT stations have been introduced to support operations particularly in case of UAV autonomous activities.

The IMTM UAS/RPAS for railway and road applications shall be expected to operate within a range of operational constraints as per D2.2 subsection 3.3.2, which shall be used in the detailed architectural design of the segment. Such constraints (UAS-SYS-OPE-REQ-031) shall include the following issues:

1) Geofencing
2) Weather
3) Hours of Operation
4) Remote Operation Range
5) Endurance
6) UA/RPA Weight and Size
7) Operational Altitude
8) Security
9) Noise
10) Privacy
11) Human proximity
12) Human Factors
13) Physical and Operational Safety

In addition, please note from the figure above that the connection with the UTM center for air traffic control and management is a further peculiarity of UAV application. Here below a few specific UAV requirements are discussed:

- UAV characteristics (UAS-EXT-PER-REQ-03)

Basically, the selected UAV are based on a single or double fixed rotors that can be easily manoeuvred within the PIT station and can embark the monitoring suitable instrumentation. Those UAV however have a limited service operation time generally in the order of 30 m. this is the reason to look at tilt rotors solutions that can still operate in VOTL condition but can reach longer endurance even up to two hours.

- Environmental EM noise (UAS-COM-PER-REQ-16)

In order to assure the UAS/RPAS IMTM railway and road operations it is essential that the respective infrastructure does not produce interference with GNSS signal and UAS communication infrastructure.
This requirement can be associated to the communication safety requirement. In case of a PIT station, it is conceived to monitor the EM environment and signal service degradation so active in a predictive manner and improve system operation safety.

- position accuracy requirement (UAS-AUG-PER-REQ-19)

UAV application in order to navigate doesn't require extremely high position accuracy. Therefore 1-10m would be enough. However for geolocalization of images, 3D imaging and operation in proximity of specific sites of interest cm accuracy as derived from RTK may be requested. A possible alternative for image geo-localization is the utilization of PPK approach.

- PIT station (UAS-PIT-FUN-REQ-95)

PIT station capabilities and requirement are also extensively dealt with in D2.3. Here we want to underline their relevance to support all the activities needed for UAV take-off preparation, maintenance and landing. This is not in common with the other applications rail and auto. In any UAV mission the aircraft needs to be refuelled and prepared by updating internal maps and other data. The PIT station may support take-off and landing providing additional features such RF beacon or operator optical assistance.

- OBU shall support automatic or assisted landing based on VBN (UAS-OBU-FUN-REQ-114)

As previously mentioned the UAV must land in the PIT station landing area. To realize this, it should be equipped with a specific equipment and SW. In case of assisted landing we have the OBU camera that in combination with the PIT station camera allows the operator to command UAV landing in the best way.
In case of automatic landing the OBU will proceed in automatic ways by using the on board camera and the support PIT station infrastructure that may consist in same RF beacon for attitude control for accurate approach.
Because of the application OBU shall embed specific features to support operations in case of GNSS signal absence or degradation and aeronautic specific integrity based on ABIA concept.
It is worth to mention that the operation of a vehicle when in presence of multipath, obscuration and interference environment request specific precautions to not degrade RAIM and RTK performance.

The on-board unit (OBU) design and function is designed to cope with different missions and phases of flight in order to comply with specific current requirements in terms of accuracy/integrity with a layered configuration that allows timely failure detection and system reconfiguration. It will be basically designed for the ABIA integrity approach leaving the ARAIM as option for specific mission modes.

In Figure 31 we show the block diagram of OBU functional architecture. It implements the ABIA approach but with the addition of a panoramic camera (based on a patented lens) on the top where it is embedded the GNSS antenna.

The panoramic camera allows mitigation of multipath, by satellite masking, and antenna obscuration effects and could contribute to navigation providing “GEO referenced pseudo satellites” (geo features) in case of poor open sky visibility in specific areas and also speed evaluation for comparison with GNSS speed. In practice all the navigation data are achieved from different sources and combined in a version of the Kalman filter. The WFOV panoramic camera is useful for Detect and avoid function also.

In addition, satellite masking is provided by Helmet to be combined with image processing. A second camera can be placed on the bottom and used for landing support and further precision geo-fencing. In practice we have an optical chain that provides navigation assistance in any phase of flight. The optical processing operates at different levels with two data sets for geo localization and sky plot.

A key issue is timely updating of UAV position and attitude for optical masking processing. Just behind the FEE (filters and LNA) there is a SDR FE that includes algorithms to immediately detect jamming or spoofing in pre-correlation operations. A second analysis of jamming and spoofing is done after signal correlation. The SBAS signals are decoded and used as usual for correction and integrity in combination with ABIA. Also a ARAIM function is added. This can be operated to detect integrity of the selected constellation of SIS and to compute HPL/VPL.

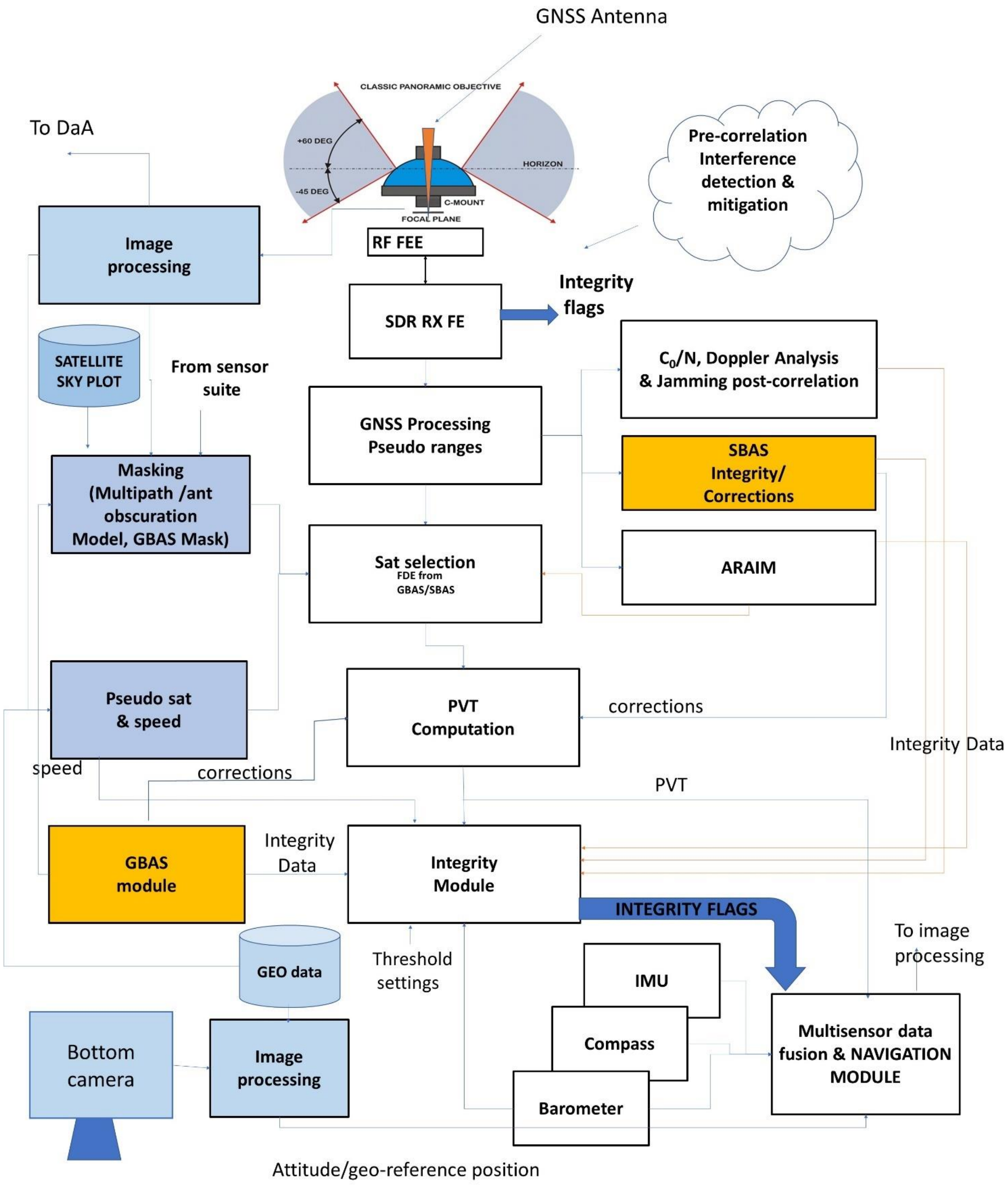


Figure 31: Integrated functional architecture of UOBU for navigation

Figure 32 depicts the optional solution with two WFOV cameras.

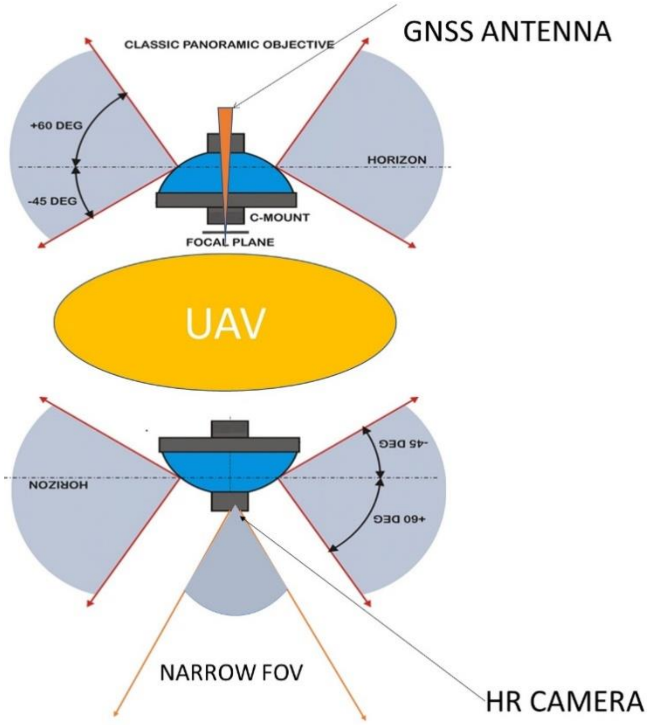


Figure 32: UOBU conceptual design with two WFOW cameras

Finally, in Figure 33 includes a block diagram more related to the real implementation units.

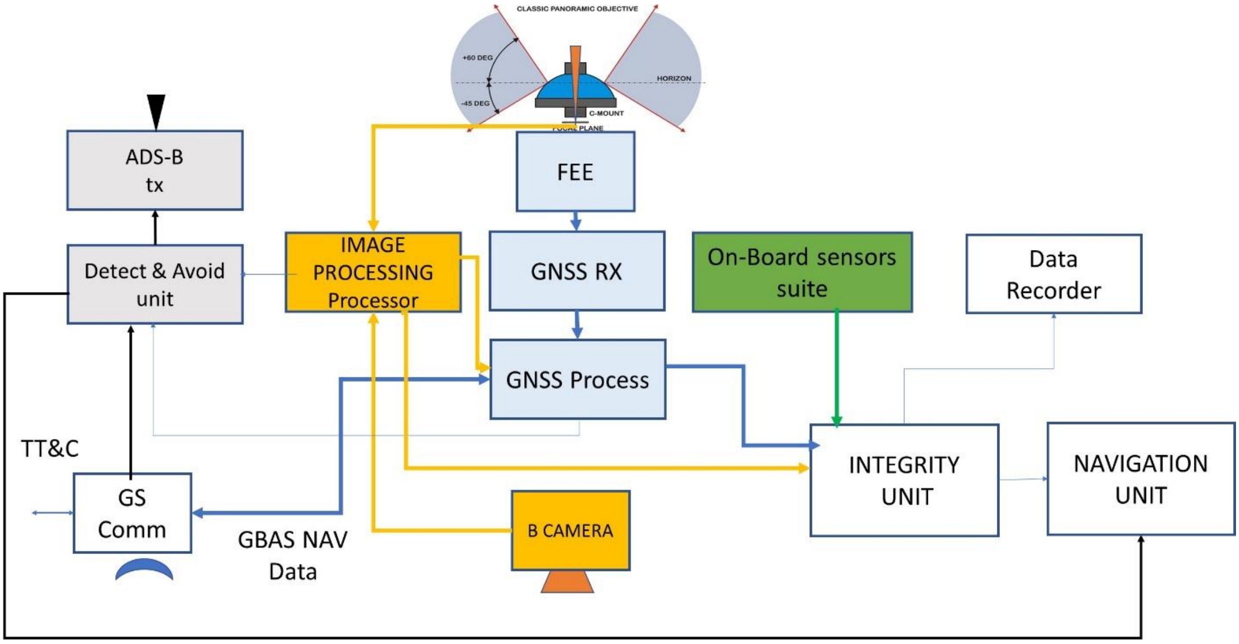


Figure 33: UOBU conceptual simplified internal architecture

The integrity will be acted at three levels and controlled by FDIR function:

Level 0: Verification of all the data/equipment operation that enters in the Navigation module (i.e. Kalman filter)
Level 1: Comparison of results from different sources (optical, mw, ect) and external integrity assessment
Level 2: Verification of consistency of residuals out of navigation unit filter against prediction
Level 3: Check integrity flags internal and external.

In Figure 34 the integrity process that leads to recovery action for both caution and warning flags. This process is in line with the safety requirement of 10^{-7} as for relevant table and document D2.3.

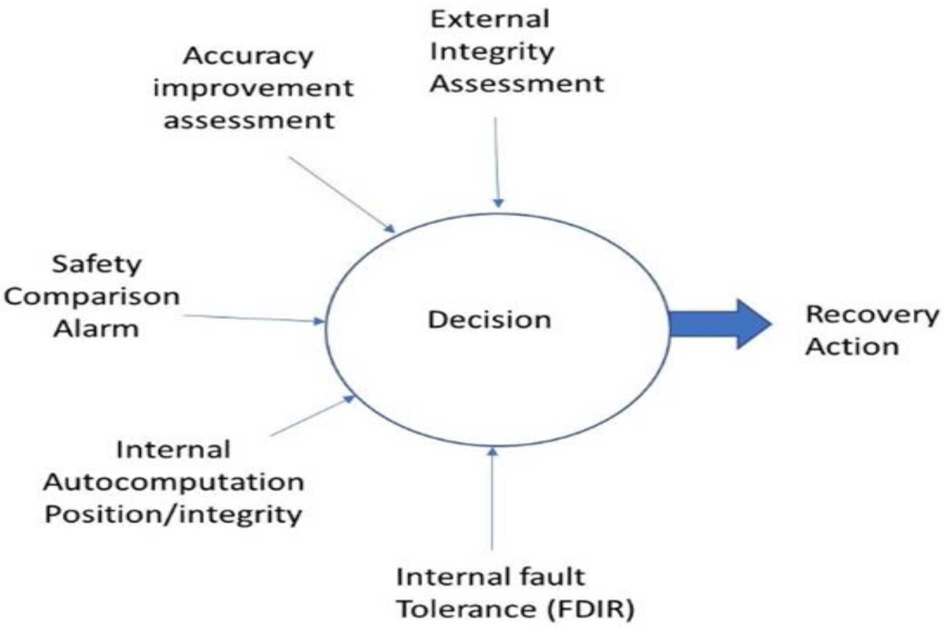

External Integrity Assessment
Accuracy improvement assessment
Safety Comparison Alarm
Decision
Recovery Action
Internal Autocomputation Position/integrity
Internal fault Tolerance (FDIR)

Figure 34: UOBU conceptual simplified internal architecture

8. CONVERSION OF SYSTEM REQUIREMENTS TO SUBSYSTEM LEVEL

This section describes the conversion of the defined system requirements from Section 2 to the subsystem design.

The system requirements need to be fulfilled by combining the AIMN and MOBU. The conversion of the overall system requirements to the subsystems depends on the redundancy to realize the task. The AIMN provides different service levels with corresponding enhancement on the onboard GNSS performance. On the other hand, the MOBU can achieve better performance than GNSS-only approach through sensor fusion. If a system requirement of a particular localization mode can only be achieved by combining the augmentation data and the multi-sensor fusion, the risks in both AIMN and MOBU should be added up as an OR logical operation in safety (fault tree) analysis, since the failure in either subsystem will result in a risk in the mode. If the requirement of a mode can be achieved with redundancy, e.g., the localization can be achieved by either augmented GNSS or by another sensor set that is independent of the AIMN, the risks from AIMN and MOBU can be multiplied as an AND logical operation.

The current chapter also serves to report the Requirements Traceability Matrix (RTM) for RAIL, AUTO and UAV (UAS) applications. The RTM is a table which maps User Requirements and related System & Subsystem Requirements. The RTM including the mapping of User Requirements and System requirements has been shown already in section 7 of deliverable 2.3. It is therefore not necessary to detail the individual mapping of User requirements to System requirements again and we merely direct the dear reader to section 7 of deliverable 2.3.

Furthermore, the System requirements which have been listed in section 5 & 7 of deliverable 2.3 already contain the respective subsystem (i.e. AUG, OBU, COM, EXT), as, e.g., in “SR-OBU-SAF-001.a”. By choosing this requirement nomenclature, the individual mapping of System to Subsystem requirements has already been performed in section 7 of deliverable 2.3 Nevertheless we report again the most important subsystem requirements and their link to system requirements for the sake of clarity and to provide an update whenever there has been a change in the subsystem requirement.

8.1 AIMN SUBSYSTEM REQUIREMENTS

The System Requirements for the multi-modal HELMET solution have been derived from the HELMET high-level User Requirements, with the identification of constraints and limitations, specifying models and architectures of RAIL, AUTO and UAVs in order to perform an accurate safety analysis.

The Augmentation Integrity Monitoring Network (AIMN) is in charge of generating augmentation data in order to meet the requirements specified for the Rail, Automotive and UAVs segments. Within ERSAT-EAV and RHINOS, the 2-Tiers approach has been developed, able to meet SIL-4 requirements for Rail applications. Such an approach is applicable to DGNSS and RTK and allows using commercial receivers and networks for integrity monitoring purposes.

The System Requirements for the multi-modal GNSS Augmentation solution are listed in section 5.4 of D2.3. Reviewing and harmonizing system requirements implies also reviewing the table of generalized Service Levels that we inserted in section 2.2 of the System Requirements document.
In this way, the table related to the Generalized Service Levels and specified in section 2.2 of the System Requirements document has to be modified accordingly. The new table, assuming GNSS to be used only for longitudinal positioning in the automotive context, should be the following:

Table 4: Augmentation System Service Level Definition

Service Id	Technology Enabler	Achievable Accuracy 95%	Integrity (THR$_{GNSS}$)	TTA***	Availability****	Service Coverage
SL 1	DGNSS, SBAS	2 m	~ 1e-5/hr - 1e-6/hr	< 10 s	High	Global (SBAS) 100-200 Km (DGNSS)
SL 2	RTK/NRTK	< 5 cm*	~ 1e-5/hr - 1e-6/hr	< 10 s	High	30 km (RTK) Area covered by sparse network of Reference Stations with maximum interdistance of 70 km (NRTK)
SL 3	PPP-RTK and Galileo HAS**	< 10 cm	~ 1e-5/hr - 1e-6/hr	< 10 s	High	Global

*: Such performance is achievable under nominal conditions, service coverage and integer ambiguity fixing achieved. Harsh environments (e.g. low visibility, high multipath) implies the selection of operational modes, through the use of GNSS in combination with IMU and other sensors on the OBU side to achieve the required accuracy. Initial fixing time (nominally less than 1 min) has to be taken into account. Float of partial ambiguity fixing solutions can lead to 0.5-1m accuracy
**: Currently Galileo HAS is not available and GNSS receivers are not able to decode and apply relevant corrections; it is assumed that, when available, such Service Level can be met through Galileo HAS, if suitable multi-frequency processing techniques or local augmentation aids are adopted for convergence time reduction (please refer to the Technological Gap Analysis section)
***: It is referred only to the Augmentation component of TTA (detection of SIS and Reference Stations Faults). Delays and Fault of the Communication and application specific means is not part of this TTA and have to be included at system level. High demanding TTA at user level can be guaranteed only in combination with other sensors.
****: It is referred to the GNSS Augmentation System, not to the overall system

All possible Augmentation Service Levels reported above are valid under nominal conditions (clear sky above 10°, no interferences, absence of multipath, service coverage). HELMET is focusing on the most mature level (implemented by RTK on SL1) for the Pilot Project implementation. Single environmental and application scenario are managed by the OBU through the most suitable Operational Mode selection.

In the following we describe the conversion of the defined system requirements from Section 2 to the subsystem design: Please note that has been already partially done in D2.3.

For the Augmentation Subsystem, a review has been performed for the following augmentation system requirements, taking into account the Service Levels harmonisation carried out in the table above.

<table>
<tr><th>ID</th><th>Name</th><th>Description</th></tr>
<tr><td><b>SR-FUN-AUG-006</b></td><td>Augmentation to Service Level allocation</td><td>The Augmentation system to service level allocation is reported in <i>Table 5</i>.</td></tr>
<tr><th colspan="3">Rationale</th></tr>
<tr><td colspan="3">
<i>Table 5: Level to Augmentation Systems allocation</i>
<table>
<tr><th>Service Level</th><th>Augmentation System</th></tr>
<tr><td>SL1</td><td>GNSS Multi-Constellation Multi-Frequency DGNSS, SBAS</td></tr>
<tr><td>SL2</td><td>GNSS Multi-Constellation Multi-Frequency RTK/NRTK</td></tr>
<tr><td>SL3</td><td>GNSS Multi-Constellation Multi-Frequency PPP-RTK and Galileo HAS</td></tr>
</table>
</td></tr>
<tr><th colspan="3">Notes</th></tr>
<tr><td colspan="3">1. The allocation is based on the performance analysis review and experimental data</td></tr>
<tr><th colspan="3">References</th></tr>
<tr><td colspan="3"><b>[22],[23]</b></td></tr>
</table>

An analysis of D2.3 applications System requirements has been performed in order to derive subsystem requirements for the Augmentation System from single applications requirements.

Table 6: Augmentation Subsystem Requirements Review

Subsystems	Application	System Requirement code	Augmentation Requirements	Notes
OBU AUG EXT	Rail – Track Identification Scenario - Across Track Alert Limit	SR-OBU-SAF-005.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-012	The Alert Limit is predefined based on the integration of multiple sensors (e.g. odometer for Rail) and Trackside Monitoring
OBU AUG EXT	Rail – Track Identification Scenario - Across Track Accuracy	SR-OBU-PER-006.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-008 SR-AUG-OPE-009 SR-AUG-OPE-012	To achieve the Accuracy for this scenario the SL2 is required.
OBU AUG COM	Rail – Track Identification Scenario – Time to Alert	SR-OBU-FUN-007.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-012 SR-AUG-OPE-013	
OBU AUG COM	Rail – Virtual Balise Detection – Message corruption	SR-OBU-SAF-008.a	SR-AUG-INF-004 SR-AUG-INF-005 SR-AUG-OPE-011	Message Corruption is related to the communication link failure rate The total THR for application has to include the THR of the Communication subsystem between the RBC and the OBU. It is assumed that the transmission of Augmentation messages from the Control Center to the RBC is implemented through an high QoS . It has anyway to be taken into account for the final delivery of a Multimodal service that the total TTA is defined by the following components: $TTA=\Delta t_{AUG-RBC}+\Delta t_{RBC-OBU}+\Delta t_{AUG\_processing}$ $\Delta t_{AUG-RBC}$, the delay of the Communication link between the Augmentation Control Center and the RBC, depends on the quality of the public Communication Network, while $\Delta t_{AUG\_processing}$ takes only into account the communication processing delays within the Augmentations system Therefore, the Communication Subsystem is in charge of $\Delta t_{AUG-RBC}+\Delta t_{RBC-OBU}$

OBU AUG COM	Rail – Virtual Balise Detection – Communication Delay	SR-OBU-COM-009.a	SR-AUG-INF-004 SR-AUG-INF-005 SR-AUG-OPE-011	THR See above notes
OBU AUG EXT	Rail – Odometry Calibration - Along Track Accuracy	SR-OBU-SAF-010.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-008 SR-AUG-OPE-009 SR-AUG-OPE-012	To achieve the Accuracy for this scenario the SL2 is required.
OBU AUG EXT	Rail – Odometry Calibration - Along Track Alert Limit	SR-OBU- SAF-011.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-012	The Alert Limit is predefined based on the integration of multiple sensors (e.g. odometer for Rail) and Trackside Monitoring
OBU AUG COM	Rail – Odometry Calibration - Along Track Time to Alert	SR-OBU- SAF-012.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-012 SR-AUG-OPE-013	TTA <1s can be achieved only through the integration of non-GNSS sensors (e.g. INS) and External Systems (e.g. Trackside)
OBU AUG EXT	Rail – Cold Movement Detection - Along Track Alert Limit	SR-OBU- SAF-013.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-012	
OBU AUG EXT	Rail – Cold Movement Detection - Along Track Accuracy	SR-OBU- SAF-014.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-008 SR-AUG-OPE-009 SR-AUG-OPE-012	To achieve the Accuracy for this scenario the SL1 is enough.
OBU AUG COM	Rail – Cold Movement Detection - Along Track Time to Alert	SR-OBU- SAF-015.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-012 SR-AUG-OPE-013	TTA <10s may be achieved through the integration of non-GNSS sensors (e.g. INS) and External Systems (e.g. Trackside)
OBU AUG EXT COM	Automotive - Time to Alert	SR-OBU-SAF-108.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-010 SR-AUG-OPE-012	TTA <1s can be achieved only through the integration of non-GNSS sensors (e.g. INS) and External Systems (e.g. Automotive Infrastructures for V2I) TTA depends on the Communication System QoS
OBU AUG COM EXT	Automotive - Availability of Localization	SR-OBU-SAF-110.a		The availability of the localization has to be derived at System Level (including all the application domain subsystems). It is in charge of the OBU to select the operational mode able to meet the Availability requirement in case of single subsystem unavailability
OBU AUG COM	Automotive – Communication Failure from CC to OBU	SR-COM-SAF-115.a	SR-AUG-INF-004 SR-AUG-INF-005 SR-AUG-OPE-011	A Failure is related to the communication link The failure depends on the QoS of the Mobile Communication Network
OBU AUG EXT	Automotive - Automated Driving on Highway – Longitudinal Alert Limit	SR-OBU-SAF-117.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-012	
OBU AUG EXT	Automotive - Automated Driving on Highway – Longitudinal Accuracy	SR-OBU-PER-108.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-008 SR-AUG-OPE-009 SR-AUG-OPE-012	To achieve the Accuracy for this scenario the SL1 is enough.
OBU AUG EXT	Automotive - Automated Driving on Local Road – Longitudinal Alert Limit	SR-OBU-SAF-118.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-012	
OBU AUG EXT	Automotive - Automated Driving on Local Road – Longitudinal Accuracy	SR-OBU-PER-110.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-008 SR-AUG-OPE-009 SR-AUG-OPE-012	To achieve the Accuracy for this scenario the SL3 is required.
OBU AUG EXT	Automotive - Automated Driving on Narrow and Curved Road – Longitudinal Alert Limit	SR-OBU-SAF-119.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-012	The Alert Limit is predefined based on the integration of multiple sensors (e.g. INS, Visual odometer, cameras)
OBU AUG EXT	Automotive - Automated Driving on Narrow and Curved Road – Longitudinal Accuracy	SR-OBU-PER-112.a	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-008 SR-AUG-OPE-009 SR-AUG-OPE-012	To achieve the Accuracy for this scenario is required the SL3 and the integration of multiple sensors (e.g. INS, Visual odometer, cameras)

COM AUG	UAV – UAS/RPAS CNPC Link Requirements	UAS-COM-PER-REQ-004-015	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-010 SR-AUG-OPE-012	The TTA depends on the QoS of the UAS communication system (CNPC). The required TTA has to take into account the Communication delay
AUG COM	UAV – Connectivity with the Helmet Augmentation Network	UAS-SYS-OPE-REQ-01	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-INF-004 SR-AUG-INF-005 SR-AUG-FUN-006	
OBU AUG EXT COM	UAV – UAS/RPAS Internal and External Communication	UAS-SYS-FUN-REQ-04	SR-AUG-INF-004 SR-AUG-INF-005 SR-AUG-OPE-011	
OBU AUG EXT COM	UAV – GCS Communication	UAS-SYS -COM-REQ -35	SR-AUG-INF-004 SR-AUG-INF-005 SR-AUG-OPE-011	
OBU AUG	UAV – RTK Augmentation	UAS-OBU-FUN-REQ-112	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-008 SR-AUG-OPE-009 SR-AUG-OPE-012	To achieve the Accuracy for all of the UAV scenarios the SL2 is enough.
OBU AUG	UAV – UAS/RPAS Typical Flight Operation Requirements	UAS-AUG-PER-REQ-18	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-008 SR-AUG-OPE-012 SR-AUG-OPE-013	To achieve the Accuracy for all of the typical flight operation scenarios the SL1 is enough. TTA of the precision al approach (PIT station approach scenario) can be achieved only through the integration of non-GNSS sensors
OBU AUG	UAV – UAS/RPAS Specific Flight Operation Requirements	UAS-AUG-PER-REQ-19	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-006 SR-AUG-OPE-008 SR-AUG-OPE-012 SR-AUG-OPE-013	To achieve the Accuracy for all of the typical flight operation scenarios the SL2 is enough. TTA for all the specific operation scenarios can be achieved only through the integration of non-GNSS sensors
OBU AUG COM	UAV – Communication Data Rate with UAV TT&C	UAS-COM-PER-REQ-21	SR-AUG-INF-004 SR-AUG-INF-005 SR-AUG-OPE-011	A Failure is related to the communication link See notes above about the Communication link performances
OBU AUG EXT	UAV – UAS/RPAS Pit Station Segment EXT Interface Requirements	UAS-EXT-AUG-REQ-01 - UAS-EXT-AUG-REQ-04	SR-AUG-OPE-001 SR-AUG-PER-002 SR-AUG-FUN-003 SR-AUG-FUN-006 SR-AUG-OPE-008 SR-AUG-OPE-009 SR-AUG-OPE-012 SR-AUG-OPE-013	

8.2 RAILWAY SEGMENT SUBSYSTEMS REQUIREMENTS

This subsection deals with the subsystem requirement specifications for RAIL. It follows the specification of the fundamental RAIL system requirements presented in HELMET D2.3, Section 5.1. These fundamental requirements remain valid and there are not repeated in this subsection.

Based on the proposed high-level safety architectures (ARCHITECTURE_1 and ARCHITECTURE_2) and performed related safety analyses, the RAIL user and system requirements were converted to the subsystem level. These more detail subsystem requirements for ARCHITECTURE_1 and ARCHITECTURE_2 are summarised in Table 7 and Table 8 below.

Subsystem requirements specification for ARCHITECTURE_1

The ARCHITECTURE_1 was proposed for Along Track Position (ATP) determination – see Section 5.2. It is assumed that LDS has been already initiated and track identified, e.g. by the ARCHITECTURE_2.

A block diagram of the ARCHITECTURE_1 with allocated subsystem requirements is shown in Figure 35. It results from the reactive structure in Figure 6 , related FTA in Figure 9 and also from Figure 39 in HELMET D2.3.

Note: A correct value of THR for GNSS MI ($THR_{GNSS\ MI}$) in FTA in Figure 39 in HELMET D2.3 is 7.5e-6/ h. This value is used for safety analysis in Section 5.2.

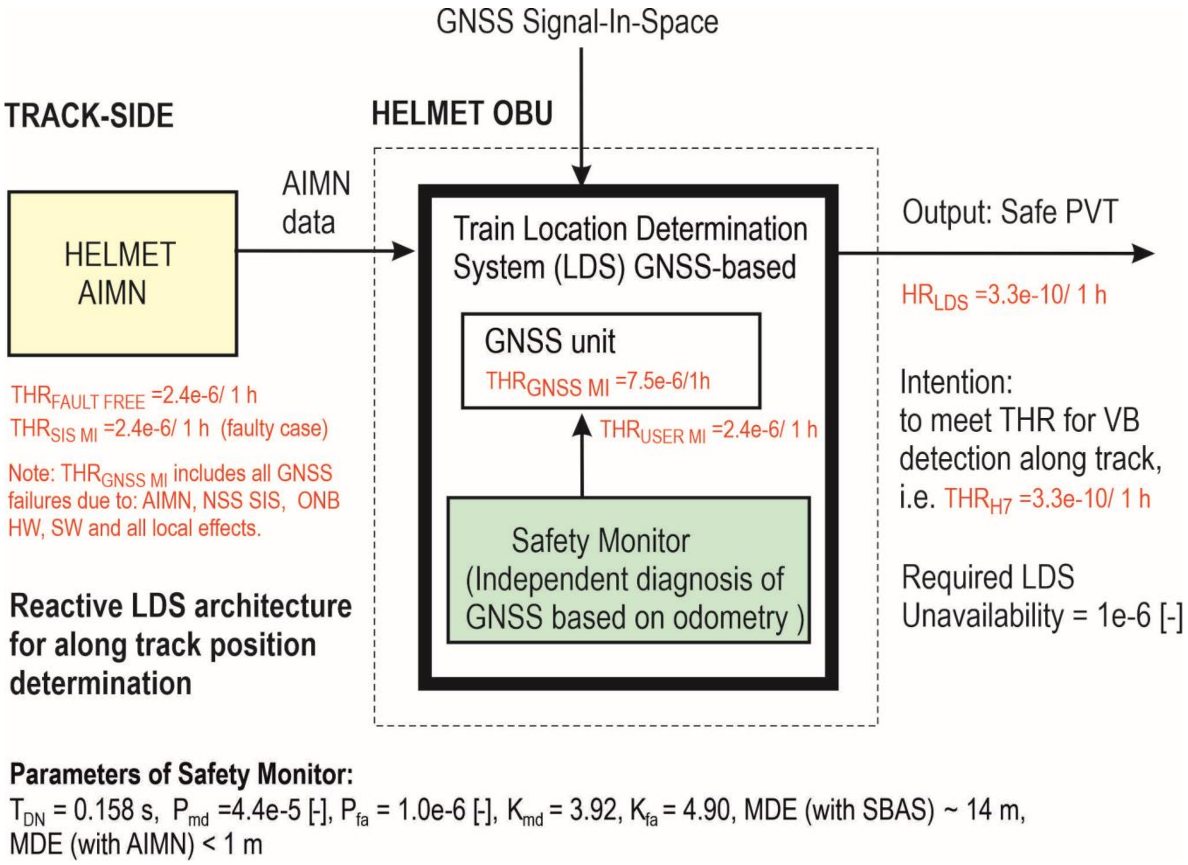

GNSS Signal-In-Space
TRACK-SIDE
HELMET OBU
AIMN data
HELMET AIMN
Train Location Determination System (LDS) GNSS-based
GNSS unit
THR_GNSS MI =7.5e-6/1h
THR_USER MI =2.4e-6/ 1 h
Safety Monitor (Independent diagnosis of GNSS based on odometry)
Output: Safe PVT
HR_LDS =3.3e-10/ 1 h
Intention: to meet THR for VB detection along track, i.e. THR_H7 =3.3e-10/ 1 h
Required LDS Unavailability = 1e-6 [-]
THR_FAULT FREE =2.4e-6/ 1 h
THR_SIS MI =2.4e-6/ 1 h (faulty case)
Note: THR_GNSS MI includes all GNSS failures due to: AIMN, NSS SIS, ONB HW, SW and all local effects.
Reactive LDS architecture for along track position determination
Parameters of Safety Monitor:
T_DN = 0.158 s, P_md =4.4e-5 [-], P_fa = 1.0e-6 [-], K_md = 3.92, K_fa = 4.90, MDE (with SBAS) ~ 14 m, MDE (with AIMN) < 1 m

Figure 35: Block diagram of ARCHITECTURE_1 with allocated subsystem requirements

Note: Integrity Risk for SBAS of 2e-7/150 s required by civil aviation corresponds to 4.8e-6/ 1 h. Sum of AIMN THR$_{FAULT\ FREE}$ and THR$_{SIS\ MI}$ values is just 4.8e-6/ 1 h.

The preliminary subsystem requirements are summarised in Table 7. Note: The numbering of system requirements in this table follows the numbering of system requirements for RAIL in HELMET D2.3.

The System Requirements for RAIL are specified in the format **SR-SSR-TTT-N.a**, with the codes SSR and TTT explained at the beginning of Section 5 in the HELMET D2.3 deliverable.

Table 7: System Requirements for Localization System Rail – ARCHITECTURE_1

Subsystem	Application	System Requirement code	Name	Value
OBU	Rail	SR-OBU-SAF-20	THR requirement related to overall GNSS Misleading Information in OBU, i.e. THR$_{GNSS\ MI}$ – see Figure 35. It covers contributions of hazard causes due to HELMET AIMN, GNSS Signal-In-Space, OBU HW + SW, and all local effects. This requirement is in line with the same requirement specified in ERSAT GGC project – see HELMET D2.3, Section 4.1.5.	THR$_{GNSS\ MI}$ = 7.5e-6/ h
AUG	Rail	SR-AUG-SAF-21	THR requirement related to fault-free contribution of AIMN, i.e. – THR$_{FAUL\ FREE}$ – see Figure 35. This requirement is in line with the same requirement specified in ERSAT GGC project – see HELMET D2.3, Section 4.1.5.	THR$_{FAULT\ FREE}$ = 2.4e-6/ h
AUG	Rail	SR-AUG-SAF-22	THR requirement related to faulty contribution of AIMN, i.e. – THR$_{SIS\ MI}$ – see Figure 35. This requirement is in line with the same requirement specified in ERSAT GGC project – see HELMET D2.3, Section 4.1.5. Sum of THR$_{FAULT\ FREE}$ and THR$_{SIS\ MI}$ values equals to 4.8e-6/ h, which corresponds to aviation IR requirement for SBAS/EGNOS, i.e. 2e-7/ 150 s.	THR$_{SIS\ MI}$ = 2.4e-6/ h

OBU	Rail	SR-OBU-SAF-23	THR requirement related to all contributions of hazard causes on USER side (THR$_{\text{USER MI}}$) - i.e. OBU HW + SW, and all local effects – see Figure 35. This requirement is in line with the same requirement specified in ERSAT GGC project – see HELMET D2.3, Section 4.1.5.	THR$_{\text{USER MI}}$ = 2.4e-6/ h
OBU	Rail	SR-OBU-SAF-24	Time to Failure Detection and Negation T$_{\text{DN .}}$ T$_{\text{DN}}$ is depends on fast failure detection capability of Safety Monitor (see Section 5.2) and safety reaction of the reactive LDS.	T$_{\text{DN}}$ = 0.158 s
OBU	Rail	SR-OBU-SAF-25	Probability of Missed Detection P$_{\text{md}}$. It is a parameter of Safety monitor – see Section 5.2.	P$_{\text{md}}$ = 4.4e-5 [-]
OBU	Rail	SR-OBU-SAF-26	Probability of False Alert P$_{\text{fa}}$. It results from the required LDS availability / unavailability.	P$_{\text{fa}}$ = 1e-6 [-]
OBU	Rail	SR-OBU-SAF-27	Missed Detection Coefficient K$_{\text{md}}$ of Safety Monitor. It is determined using Missed Detection probability and Time to Failure Detection and Negation T$_{\text{DN}}$ - see Section 5.2	K$_{\text{md}}$ = 3.92
OBU	Rail	SR-OBU-SAF-28	False Alert Coefficient K$_{\text{fa}}$ of Safety Monitor. It is determined using required LDS Unavailability - see Section 5.2	K$_{\text{fa}}$ = 4.90
OBU	Rail	SR-OBU-REL-29	LDS Unavailability U. This requirement comes from the Unavailability requirement for ETCS OBU – see HELMET D2.3, Section 4.1.6	U=1e-6 [-]
OBU	Rail	SR-OBU-SAF-30	Estimated Minimum Detectable Error for SBAS based solution MDE (SBAS) - see Section 5.2	MDE(SBAS) ~ 14 m
OBU	Rail	SR-OBU-SAF-31	Estimated Minimum Detectable Error for AIMN (high accuracy) based solution MDE (AIMN) - see Section 5.2	MDE(AIMN) < 1 m

Subsystem requirements specification for ARCHITECTURE_2

The ARCHITECTURE_2 was proposed for Track Identification function, i.e. for precise and safe train position determination across track – see Section 5.3. This function is mainly needed when LDS has to be initialized (awoke) with the LDS position status UNKNOWN, when LDS leaves NP mode.

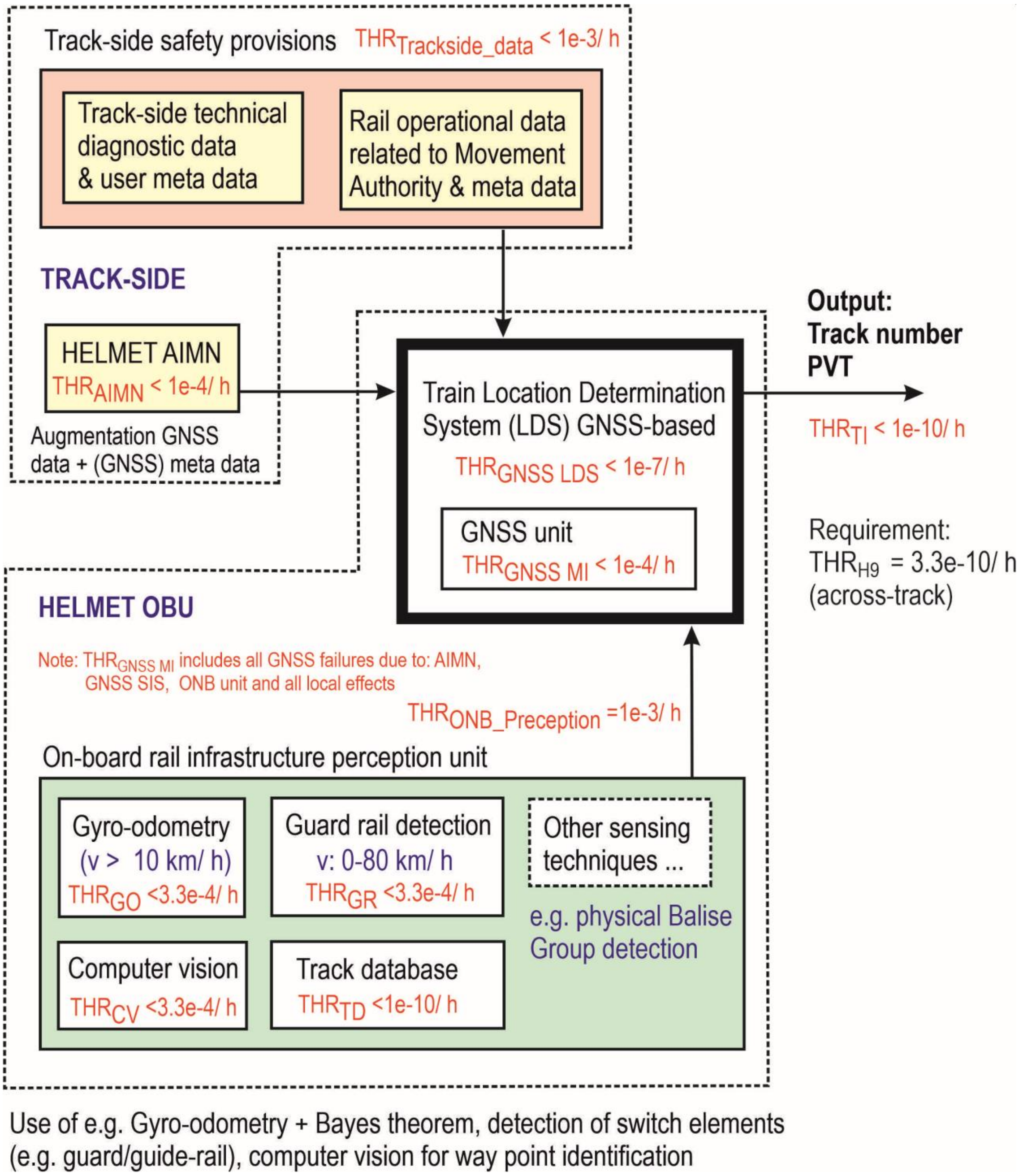

Track-side safety provisions THRTrackside_data < 1e-3/ h
Track-side technical diagnostic data & user meta data
Rail operational data related to Movement Authority & meta data
TRACK-SIDE
HELMET AIMN
THRAIMN < 1e-4/ h
Augmentation GNSS data + (GNSS) meta data
Output: Track number PVT
THRTI < 1e-10/ h
Train Location Determination System (LDS) GNSS-based
THRGNSS LDS < 1e-7/ h
GNSS unit
THRGNSS MI < 1e-4/ h
Requirement: THRH9 = 3.3e-10/ h (across-track)
HELMET OBU
Note: THRGNSS MI includes all GNSS failures due to: AIMN, GNSS SIS, ONB unit and all local effects
THRONB_Preception =1e-3/ h
On-board rail infrastructure perception unit
Gyro-odometry (v > 10 km/ h) THRGO <3.3e-4/ h
Guard rail detection v: 0-80 km/ h THRGR <3.3e-4/ h
Other sensing techniques ...
e.g. physical Balise Group detection
Computer vision THRCV <3.3e-4/ h
Track database THRTD <1e-10/ h
Use of e.g. Gyro-odometry + Bayes theorem, detection of switch elements (e.g. guard/guide-rail), computer vision for way point identification

Figure 36: Block diagram of ARCHITECTURE_2 with allocated subsystem requirements

A block diagram of the ARCHITECTURE_2 with allocated subsystem requirements is shown in Figure 36. It results from the composite safety LDS architecture in Figure 13 and related FTAs in Figure 14 and Figure 15.

Since this composite architecture is primarily intended for Track Identification will high demand on across track accuracy of positioning in order to meet a relatively low AL of 1.755 m (together with very demanding THR_{H9} of 3.3e-10/ 1 h), the intention during the ARCHITECTURE_2 design was to reduce (if possible) a safety requirement for GNSS – i.e. to increase the corresponding THR to highest possible value to facilitate future LDS certification and safety approval process. So Table 8 specifies minimum preliminary system/ subsystem safety requirements (i.e. maximum THR values) for the ARCHITECTURE_2 and its sub-functions/ elements.

Table 8: System Requirements for Localization System Rail – ARCHITECTURE_2

Subsystem	Application	System Requirement code	Name	Value
OBU	Rail	SR-OBU-SAF-32	THR of GNSS unit function – i.e. $THR_{GNSS\ MI\ .}$ It also includes THR of HELMET AIMN	$THR_{GNSS\ MI}$ < 1e-4/ h
AUG	Rail	SR-AUG-SAF-33	THR of AIMN function (HELMET augmentation) – i.e. THR_{AIMN}	THR_{AIMN} < 1e-4/ h
OBU	Rail	SR-OBU-SAF-34	THR of on-board rail infrastructure perception function – i.e. $THR_{ONB\_Perception}$ It includes THR of different complementary subfunctions and instruments, e.g. gyro-odometry, guard-rail detection, computer vision, track database, etc.	$THR_{ONB\_Perception}$ < 1e-3/ h
OBU	Rail	SR-OBU-SAF-35	THR of gyro-odometry function – i.e. THR_{GO} It supports on-board track identification.	THR_{GO} < 3.3e-4/ h
OBU	Rail	SR-OBU-SAF-36	THR of guard-rail detection function – i.e. THR_{GR} It supports on-board track identification.	THR_{GR} < 3.3e-4/ h
OBU	Rail	SR-OBU-SAF-37	THR of computer vision function – i.e. THR_{CV} It supports on-board track identification.	THR_{CV} < 3.3e-4/ h
OBU	Rail	SR-OBU-SAF-38	THR related to track database – i.e. THR_{TD} It supports on-board track identification.	THR_{CV} < 1e-10/ h
OBU	Rail	SR-OBU-SAF-39	THR of GNSS-based LDS - i.e. $THR_{GNSS\ LDS\ .}$ It consists of AND combination of $THR_{GNSS\ MI}$ and $THR_{ONB\ Perception}$	$THR_{GNSS\ LDS}$ < 1e-7/ h
EXT	Rail	SR-EXT-SAF-40	THR related to track-side technical and operational provisions – $THR_{Trackside\_data}$	$THR_{Trackside\_data}$ < 1e-3/ h
OBU	Rail	SR-ONB-SAF-41	THR of Track identification/ train position determination - i.e. $THR_{TI\ .}$ It consists of AND combination of $THR_{GNSS\ LDS}$ and $THR_{Trackside\_data}$	THR_{TI} < 1e-10/ h

8.3 AUTOMOTIVE SEGMENT SUBSYSTEMS REQUIREMENTS

The following section contains a revision of the subsystem requirements for the automotive application. Please note that most of the requirements have been detailed already in deliverable 2.3 and are merely updated here with the most recent numbers.

Table 9: Subsystem requirements for Localization System Automotive

Subsystem	Application	System Requirement code	Name	Value
OBU	Automotive	SR-OBU-SAF-101.a	Automotive Safety Integrity Level (ASIL) for car position determination	This requirement defines ASIL D (ISO 26262) for car position determination
OBU	Automotive	SR-OBU-SAF-102.a	Alert Limit (lateral) for automated driving on highway	See Table 1
OBU	Automotive	SR-OBU-PER-103.a	Accuracy (2*sigma) of position determination related to automated driving on highway	See Table 1
OBU	Automotive	SR-OBU-SAF-104.a	Alert Limit (lateral) for automated driving on local roads	See Table 1
OBU	Automotive	SR-OBU-PER-105.a	Accuracy (2*sigma) of position determination related to driving on local roads.	See Table 1
OBU	Automotive	SR-OBU-SAF-106.a	Alert Limit (lateral) for automated driving on narrow and curved roads	See Table 1
OBU	Automotive	SR-OBU-PER-107.a	Accuracy (2*sigma) of position determination related to driving on narrow and curved roads	See Table 1
OBU	Automotive	SR-OBU-SAF-108.a	Time-to-Alert	Time-to-Alert (TTA) < 1s for all automated car driving scenarios
OBU	Automotive	SR-OBU-FUN-109.a	Timing Accuracy	Timing Accuracy < 1us
OBU	Automotive	SR-OBU-SAF-110.a	Availability of car localization	Availability of car position determination/ localization as a High
OBU	Automotive	SR-OBU-SEC-111.a	Security of car localization	Security of car localization as Very high
OBU	Automotive	SR-OBU-SAF-112.a	Speed accuracy	• The indicated speed must never be less than the actual speed, i.e. it should not be possible to inadvertently speed because of an incorrect speedometer reading • The indicated speed must not be more than 110 percent of the true speed plus 4 km/h at specified test speeds. For example, at 80 km/h, the indicated speed must be no more than 92 km/h
OBU	Automotive	SR-OBU-SAF-113.a	Harmonized Design Target for SDC safety systems	Harmonized Design Target for SDC safety systems as a Probability of Failure PFSYS of 1e-7/ h
OBU	Automotive	SR-OBU-SAF-114.a	Probability of Failure of car localization	This requirement defines Probability of Failure of car localization as PFLOC of 3e-8/ h
OBU	Automotive	SR-COM-SAF-115.a	Probability of Failure of Communications used for car localization from the Control Centre to the OBU	This requirement defines Probability of Failure of Communications used for car localization PFCOM < 1e-9/ h
OBU	Automotive	SR-OBU-SAF-116.a	Alert Limit (lane) for automated driving	See Table 1
OBU	Automotive	SR-OBU-PER-108.a	Accuracy (2*sigma) of lane identification	See Table 1
OBU	Automotive	SR-OBU-SAF-117.a	Alert Limit (longitudinal) for automated driving on highway	See Table 1
OBU	Automotive	SR-OBU-PER-108.a	Accuracy (2*sigma, longitudinal) of position determination related to driving on highway	See Table 1
OBU	Automotive	SR-OBU-PER-109.a	System Reaction Time related to driving on highway	dependent on parameters such as road conditions
OBU	Automotive	SR-OBU-SAF-118.a	Alert Limit (longitudinal) for automated driving on local roads	See Table 1
OBU	Automotive	SR-OBU-PER-110.a	Accuracy (2*sigma, longitudinal) of position determination related to driving on local roads	See Table 1
OBU	Automotive	SR-OBU-PER-111.a	System Reaction Time related to driving on local roads	dependent on parameters such as road conditions
OBU	Automotive	SR-OBU-SAF-119.a	Alert Limit (longitudinal) for automated driving on narrow and curved roads	See Table 1

OBU	Automotive	SR-OBU-PER-112.a	Accuracy (2*sigma, longitudinal) of position determination related to driving on narrow and curved roads	See Table 1
OBU	Automotive	SR-OBU-PER-113.a	System Reaction Time related to driving on narrow and curved roads	Dependent on parameters such as road conditions
COM	Automotive	SR-COM-SAF-120.a	Continuity of car localization	High
COM	Automotive	SR-COM-SAF-115.a	Probability of Failure of Communications used for car localization from the Control Centre to the OBU	Probability of Failure of Communications used for car localization PFCOM < 1e-9/h

8.4 UAV SEGMENT SUBSYSTEMS REQUIREMENTS

The following section contains a revision of the subsystem requirements for the UAS application. Please note that most of the requirements have been detailed already in deliverable 2.3 and are merely updated here with the most recent numbers. The following requirements focus on the **positioning system of the UAS**, the full set of requirements for UAS system is given in D2.3.

Table 10: Subsystem requirements for Localization System UAS

Subsystem	Application	System Requirement code	Requirement Description	Remarks/Notes
SYS	UAS	UAS-SYS-OPE-REQ-031	The IMTM UAS/RPAS for railway and road applications shall be expected to operate within a range of operational constraints as per D2.2 subsection 3.3.2, which shall be used in the detailed architectural design of the segment. Such constraints shall be in the following issues: 1) Geofencing 2) Weather 3) Hours of Operation 4) Remote Operation Range 5) Endurance 6) UA/RPA Weight and Size 7) Operational Altitude 8) Security 9) Noise 10) Privacy 11) Human proximity 12) Human Factors 13) Physical and Operational Safety	
SYS	UAS	UAS-SYS-OPE-REQ-032	The entire operational UAS/RPAS-PIT Station Scenarios shall involve the following Framework Components for all Railway and Road IMTM Applications, as per D2.2 subsection 3.3.4: 1) Operational Framework Definition, 2) Flight Planning, 3) Flight Implementation, 4) Data Acquisition, 5) Data Processing and Analysis, 6) Data Interpretation and 7) Optimized Traffic Application.	
SYS	UAS	UAS-SYS-FUN-REQ-05	The Navigate Function shall refer to the ability in obtaining and maintaining knowledge of the ownship current positional and geographic orientation information and of its destination(s) using reference cues (electronic or visual). It shall include the determination of path(s) to fly from its current position to its subsequent position or to its destination(s). The Navigate Function shall mainly include the following sub-functions: 1) Provision for UA/RPA Altitude Information 2) Provision for UA/RPA Heading and Course information 3) Provision for UA/RPA Ground Position Information 4) Provision for UA/RPA Temporal Data 5) Provision for UA/RPA Trajectory Definition	
SYS	UAS	UAS-SYS-COM-REQ-35	The CGS shall be capable to transmit and/or receive information to and from the HELMET network, PIT Station and ancillary services.	
SYS	UAS	UAS-SYS-FUN-REQ-37	IMTM UAS/RPAS avionics suit shall be equipped to support navigation and positioning integrity by suitable equipment supported by SBAS and GBAS in the different phase of flight.	
SYS	UAS	UAS-SYS-FUN-REQ-38	On board avionics shall adopt a VBN (visual based navigation) for geo-localization enhancement, position recovery and landing support,	Used for navigation check-point and attitude calibration.
SYS	UAS	UAS-SYS-FUN-REQ-40	The CGS and PIT-Station shall be capable to receive the estimated UAV/RPAS position.	

SYS	UAS	UAS-SYS-FUN-REQ-43	The UAS/RPAS Estimate Position Function shall use a current altimeter (barometric) setting.	
SYS	UAS	UAS-SYS-FUN-REQ-45	For NAV operations, the UAS/RPAS Define Path Function shall be able to retrieve the procedure by system from the navigation database, not just as a manually entered series of waypoints.	
SYS	UAS	UAS-SYS-FUN-REQ-46	The UAS/RPAS Define Path Functions shall provide required intent information in all airborne phases of flight and PIT Station operations.	
SYS	UAS	UAS-SYS-FUN-REQ-51	The Required Navigation Performance (RNP) Navigation, the UAS/RPAS Steer Along Path Function shall be able to monitor the achieved navigation performance and to identify to the GCS whether the operational requirement is, or is not, being met during an operation.	
SYS	UAS	UAS-SYS-FUN-REQ-52	The navigate function shall provide the capability to load the flight data relevant for the flight.	Flight data includes flight plan information, contingency plans, automated landing plan etc. This requirement makes the assumption of a single access point to load the information; architectures with multiple loading points may need to be accommodated.
SYS	UAS	UAS-SYS-FUN-REQ-53	The navigate function shall provide the capability to verify the loaded flight data.	“Verify” addresses validity, accuracy, and completeness of the flight data relevant for the flight.
SYS	UAS	UAS-SYS-FUN-REQ-54	The navigate function shall provide the capability to distribute the loaded and verified flight data to the other UAS/RPAS functions as required.	
SYS	UAS	UAS-SYS-FUN-REQ-56	The navigation function shall validate navigation database parameters supporting the requirements associated with the other navigation or UAS/RPAS functions, equipment(s) on-board the UA/RPA and the operation(s).	This high-level requirement is to cover the requirements associated with the content of database for flight planning, trajectory computation, GNSS, multi-sensor Nav equipment, avoidance manoeuvring algorithms, and cover all phases of flight and navigation modes.
SYS	UAS	UAS-SYS-FUN-REQ-58	The navigate function shall provide the capability to set and/or reset navigation sensor(s) by either the UAV/RPAS GCS and/or the PIT-Station.	
SYS	UAS	UAS-SYS-FUN-REQ-59	The UAV/RPAS GCS but also the PIT-Stations shall receive information from the Navaids.	
SYS	UAS	UAS-SYS-FUN-REQ-61	The GCS or local PIT-Station shall send flight control information to the UAV/RPAS and the UAV/RPAS shall receive flight control information from the GCS and/or local PIT-Station	
SYS	UAS	UAS-SYS-FUN-REQ-63	The control function shall protect against inadvertent adjustment or engagement by the UA/RPA pilot(s) during UA/RPA flight operations.	
SYS	UAS	UAS-SYS-FUN-REQ-67	The UA/RPA shall send flight control information to the GCS which shall receive it without containing contradictory information.	
SYS	UAS	UAS-SYS-FUN-REQ-69	The control function shall ensure the UA/RPA pilot(s) is made aware of the status of UA/RPA controls.	
COM	UAS	UAS-COM-PER-REQ-06	The UAS/RPAS CNPC Link Integrity(BER/PER) (Acceptable Rate/Flight Hour) shall be for the Forward Link: 1.43 x10^{-6} and for the Return Link: 1.43 x10^{-6} with RCP 10 Separation: 5nm, Transaction Time: 10sec.	
COM	UAS	UAS-COM-PER-REQ-07	The UAS/RPAS CNPC Link Latency (Maximum Permitted) for Real-time safety critical information shall be for the Forward Link: 130ms and for the Return Link: 130ms.	
COM	UAS	UAS-COM-PER-REQ-09	The UAS/RPAS CNPC Link Latency (Maximum Permitted) for Low Priority safety critical information shall be for the Forward Link: 5.2s and for the Return Link: 5.2s.	
COM	UAS	UAS-COM-PER-REQ-10	The UAS/RPAS CNPC Link Latency (Maximum Permitted) for Non-safety critical information shall be for the Forward Link: 20.8s and for the Return Link: 20.8s.	
COM	UAS	UAS-COM-PER-REQ-12	The UAS/RPAS Performance Requirement associated with operational communication in an	

			Unexpected interruption of a transaction shall be 10^{-4} per aircraft per flight hour	
COM	UAS	UAS-COM-PER-REQ-13	The UAS/RPAS Performance Requirement associated with operational communication in a Loss of communication transaction shall be 10^{-5} per aircraft per flight hour.	
COM	UAS	UAS-COM-PER-REQ-14	The UAS/RPAS Performance Requirement associated with operational communication in a Loss of service shall be 10^{-6} per aircraft per flight hour.	
COM	UAS	UAS-COM-PER-REQ-15	The UAS/RPAS Performance Requirement associated with operational communication in an Undetected corrupted transaction shall be 10^{-5} per aircraft per flight hour.	

9. TECHNOLOGY CAPABILITY GAPS

The goal of HELMET is to study and propose a high integrity high accuracy multimodal solution for different transportation applications. Some of the systems, technologies and algorithms that need to be considered might have still a low level of maturity when used in the intended purpose. In the following we comment on some specific technology gaps that will either be tackle to some extend during HELMET or that will need to be further investigated in future initiatives.

With respect to the augmentation services:

- Currently, GBAS and SBAS Integrity systems have been implemented within the framework of aviation, rigorous extension to other applications is either still ongoing or missing.
- GBAS can guarantee higher level of Integrity with respect to SBAS, but is based on a limited number of Reference Stations and their placement is assumed to be in restricted areas. The use of restricted areas for the placement of reference stations for other applications might be difficult.
- Application of GBAS/SBAS is only based on smoothed pseudorange corrections generation (tentative message exists for Carrier Phase) and parameters needed for use able to calculate the Protection Level on the field. In challenging GNSS scenarios, it might be difficult to guarantee the continuous tracking in order to respect the smoothing times.
- For RTK and NRTK technology, needed for SL2 implementation, several techniques have been implemented at network side for Integrity Monitoring, based on residual checking (e.g. RIM - Residual Integrity Monitoring and RIU- Receiver Interpolation Uncertainty, 2-tiers), on the geometry or solution separation.
- Galileo HAS is expected to transmit precise ephemeris, clock, code and satellite biases. It is relevant to emphasize that such message will allow, depending on the scheduling techniques, to achieve ambiguity resolution with long convergence time. In order to have rapid convergence and ambiguity fixing in a PPP-AR approach, precise local ionospheric and tropospheric corrections are needed. The full availability of Galileo HAS service is still in development.
- The integration of local augmentation sparse network has therefore to be taken into account in a business analysis for the large scale application of Galileo HAS in the automotive, railway and UAV sector.

With respect to the on board unit sensors and processing:

- There is currently no standard solution to handle the presence of multipath, NLOS and interference. Whereas many fault detection and exclusion mechanism exists, a rigorous quantification of their performance is not available that is essential to assess the integrity of the system.
- In the same sense, it is not clear how to handle the multipath model uncertainties that are highly dependent on the environment, either at the error model methodology level or at the position estimator level so that the assessment of the position integrity is rigorous for a safety critical application.
- For RTK, and more for the emerging PPP-RTK technique, it is important to perform robust Integer Ambiguity Fixing validation and cycle slips detection techniques at user level.

Currently, only a few studies are carried out that take into account incorrect ambiguity fixing in Protection Level determination (e.g. [21]). A performance analysis has to be carried out about the possibility to use float ambiguity solutions. HELMET will analyse the impact of float and fixed ambiguities on the final solution in order to understand such impact.

- Localization modes needed for the precise location or fusion of sensors are based on Kalman filter algorithms. However, most error models that overbound the residual error for GNSS are designed for snapshot positioning. New error models and techniques suitable for safety related applications are required that properly takes into account the time-correlation nature of measurements errors in order to provide a good estimation error assessment [24].
- The positioning of the system may require the use of perception sensors like camera in order to satisfy more stringent scenario’s requirements. However, the maturity of these technologies for safety critical applications is still low. Although recent work is targeting this aspect [17][18][19][20], there is no comprehensive solution yet to assess the integrity currently available.

Since the availability of systems is highly depending on the scenario, which is changing continuously in automotive applications, the achievable guaranteed performances must still be investigated. This is of critical relevance in the most stringent situations under curved or narrow roads. These stringent scenarios will be investigated in HELMET in order to obtain realistic performance metrics. The outcome of such innovation actions can be used to support future recommendations and roadmap for the development of localization systems for automated vehicles.

10. RECORD AND PLAYBACK SYSTEM (RPS)

Objective of the Record and Playback System (RPS) is to support the development and validation using a real data. The RPS will be used for the automotive segment, that is on one hand the most demanding in terms of integrity requirements, and at the same time is most straight forward to handle from the implementation point of view (less stringent regulations and better availability compared to RAIL, and no dimensions/weight constraints as UAV). Additionally, the RPS serves as a prototype of the MOBU.

Validation of the integrity algorithms is intended to be done offline as a postprocessing activity. This approach is fully capable to validate the proposed integrity concept but does not address the complexity of the algorithm. Therefore, for higher credibility of the algorithm selection, the complexity of the proposed solution should be evaluated to make sure it has potential to be implemented in real-time applications. This complexity evaluation could be done by analysis.

The high-level architecture of the RPS is shown in the figure below. The system consists of sensors, accurate time source and central computer. Corrections and integrity messages from the AIMN transmitted using RTCM NTRIP protocol could be either recorded or injected during the postprocessing stage.

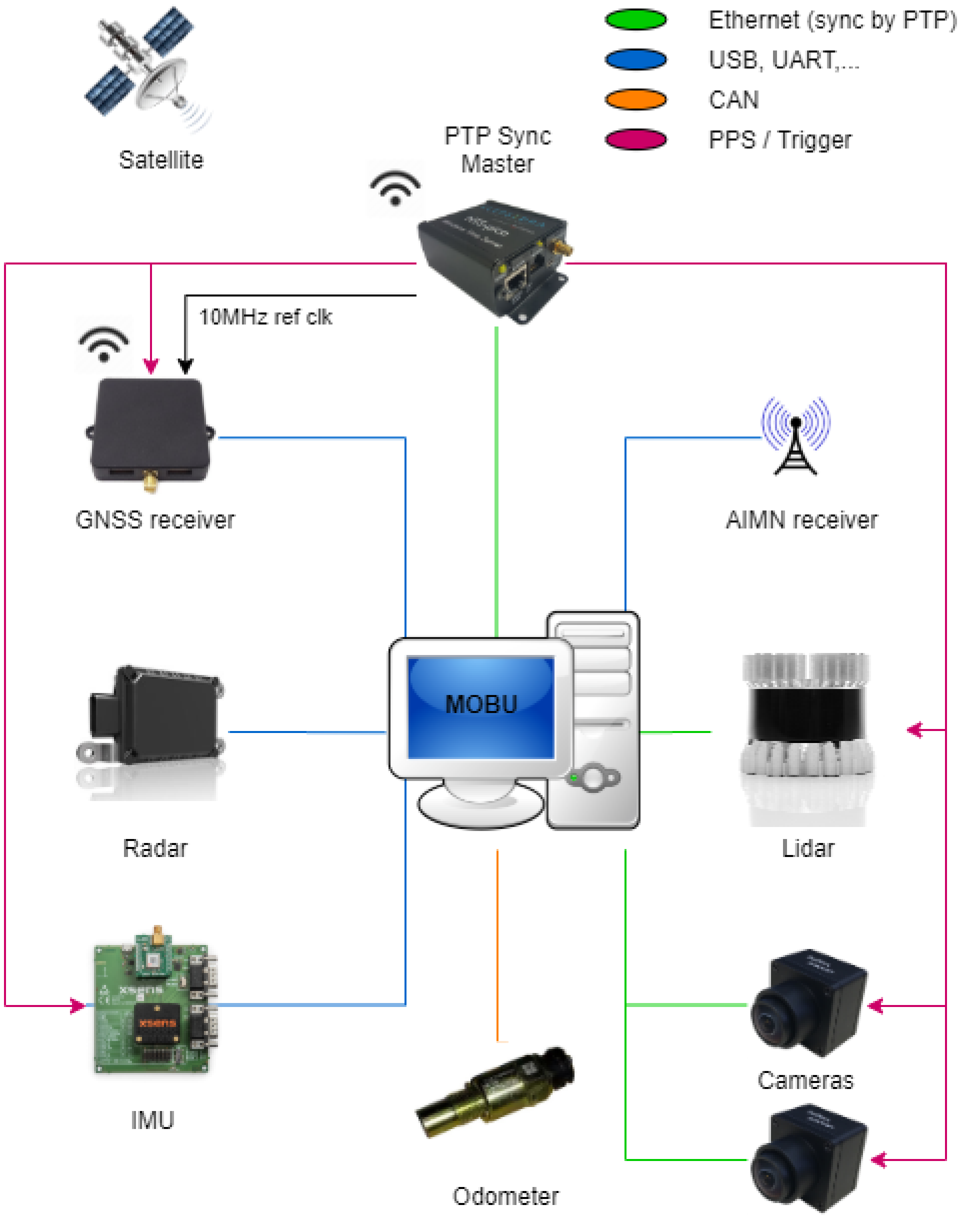


Figure 37: Sensor and Recording unit architecture

To support the GNSS heading activities in WP4 the system needs to be equipped with two GNSS antennas. Additionally, the GNSS receiver must be capable to process dual stream, or the RPS will be equipped with two GNSS receivers.

As stated in D2.3 (section 5.5 PRELIMINARY SELECTION OF SENSORS) the mechanical odometer can be replaced with visual odometry using cameras.

Important aspect during the development and validation is the availability of the true position. This is intended to be provided by high-grade IMU, that will not be part of the final MOBU. The true position data can be recorded by the RPS or could be recorded autonomously and applied in validation phase.

The selected sensors shall meet the ***must*** requirements defined in D2.3 (section 5.5 PRELIMINARY SELECTION OF SENSORS).

10.1 SYSTEM REQUIREMENTS DECOMPOSITION

Following section contains decomposition of the system requirements in D2.3 section 5.6 PRELIMINARY SPECIFICATION OF RECORD / PLAYBACK UNIT.

SR-RPS-001 The timestamping of all sensor measurements **must** be performed with respect to the same common time frame with a minimum accuracy of 1µs.

Solution: Common clock from the highly accurate master clock source is used to discipline all sensors using various synchronization protocols (PPS, PTP, 10MHz clock, external Trigger). When The time error budget consisting of oscillator quality, protocol limitations and network jitter shall meet the target limit of 1µs. The time initialization is based on GNSS.

SR-RPS-002 The alignment of measurements from accelerometer, gyroscope (and magnetometer when applicable) **must** be ensured.

Solution: Achieved with IMU integrating these sensors.

SR-RPS-003 The alignment of measurements from multiple cameras or IMUs (if available) **must** be guaranteed. When possible, this requirement should be extended to multiple LIDAR or Radars.

Solution: Achieved by architecture and synchronization protocols.

SR-RPS-004 When possible or applicable, the alignment of all sensor measurements should be provided between them.

Solution: Achieved by architecture and synchronization protocols. Could be limited by non-compatible measurement rates and/or unavailability of sensors supporting synchronization.

SR-RPS-005 For sensors that do not support time synchronization, the recording system **must** provide the time of measurement arrival.

Solution: Achieved by common clock source and software implementation.

SR-RPS-006 The recording unit must be able to record at least 60 min of sensor data.

Solution: Achieved by implementing compression method and/or sufficient data storage. In case the RPS is powered by battery, it must be dimensioned to maintain power delivery over 1 hour.

SR-RPS-007 The recording unit **must** be able to record data at least from the following sensors:

- GNSS receiver recording at least GNSS raw measurements (code, carrier, Doppler and CN0) + tracking status + navigation message for all in-view GPS (L1/L5) and Galileo satellites (E1, E5a+b) in the same format as the receiver
- IMU raw data in the same format as the sensor
- 2x Camera in a compressed format (H.264 or VP8).

Solution: Achieved by sensor selection, enough connectors on the host computer with sufficient processing power to encode the video.

SR-RPS-008 The recording unit should be able to record raw data from AIMN.

Solution: Achieved by implementing NTRIP recorder.

SR-RPS-009 The recording unit **must** provide for each measurement two timestamps using the same master clock as all sensors: Time of measurement, Time of availability.

Solution: Achieved by common clock source and software implementation.

SR-RPS-010 The recording unit **must** be able to record data on mounted drive.

Solution: Achieved by hardware selection and software implementation.

SR-RPS-011 The recorded trace should contain metadata (configuration and date of record at least).

Solution: Achieved by common clock source and software implementation.

SR-RPS-012 Playback system **must** enable user to select recorded trace to be replayed.

Solution: Achieved by software implementation.

SR-RPS-013 Recorded data **must** be replayed in way that the consumer will not have to differentiate between live data and playback data.

Solution: Achieved by architecture and software implementation.

SR-RPS-014 Playback system **must** order the sensor data according to its time of availability to the system.

Solution: Achieved by architecture and software implementation.

SR-RPS-015 Playback system should HW accelerate video playback (support at least Nvidia and Intel accelerators.

Solution: Achieved by hardware selection and software implementation.

SR-RPS-016 Playback system **must** support Seek functionality when the whole processing chain must remain synchronized

Solution: Achieved by software implementation.

SR-RPS-017 Playback system **must** support control mechanism: Play, Stop, Pause.

Solution: Achieved by software implementation.

SR-RPS-018 Playback system should support Step functionality when the system plays user defined time frame (e.g. 200ms)

Solution: Achieved by software implementation.

SR-RPS-019 Playback system should support Slow and Fast motion.

Solution: Achieved by software implementation.

SR-RPS-020 The visualization engine **must** visualize outputs of customizable workers (filters).

Solution: Achieved by software implementation.

SR-RPS-021 The visualization engine **must** enable user to turn on/off individual layers.

Solution: Achieved by software implementation.

SR-RPS-022 The visualization engine **must** provide UI for the Playback control mechanisms

Solution: Achieved by software implementation.

SR-RPS-023 The visualization engine **must** provide information about the relative time in the replayed trace.

Solution: Achieved by common clock and software implementation.

SR-RPS-024 The visualization engine should provide metadata of the replayed trace (date, trace length, sensor set and their versions, configurations…)

Solution: Achieved by software implementation.

SR-RPS-025 The platform should operate in the temperature range -20°C to 55°C.

Solution: Achieved by component selection.

SR-RPS-026 The platform should operate under standard vehicle vibration conditions.

Solution: Achieved by component selection and assembly.

SR-RPS-027 The platform should support 4x Ethernet, 3x UART, 1x CAN at least.

Solution: Achieved by component selection.

SR-RPS-028 The platform should not exceed the lateral and longitudinal dimensions of the vehicle it is mounted on.

Solution: Achieved by platform design.

SR-RPS-029 The platform should be portable by two persons at maximum.

Solution: Achieved by platform design.

11. CONCLUSIONS

This deliverable has presented high-level architecture solutions for Rail/Auto and UAV applications. In future deliverables D3.2 and D3.3 more detail information about the architecture design at functional level and subsystem level will be provided.

The high-level general architecture of the multimodal augmentation subsystem is designed so that it can support seamlessly the three different transportation segments considered in HELMET (Railway, automotive and UAV). The different service levels described in this document allows for different levels of implementation and achievable performance and coverage.

The high-level design for automated vehicles is based on different localization modes of operation. The current time mode that the vehicle can provide is dependent on the available augmentation service level and the available onboard sensors. Further details about specific algorithms that enable the most relevant modes for HELMET will be described in later deliverables. In this document, we provided a first high-level architecture and candidate solutions for this application.

Some key aspects and conclusions related to the high-level architecture design for rail segment are:

- Reactive fail-safe LDS architecture (ARCHITECTURE_1) and composite safety LDS architecture (ARCHITECTURE_2) have been proposed for ERTMS Virtual Balise detection;
- Composite safety is proposed for LDS initialization / Track Identification for Start of Mission in Staff Responsible mode with the LDS UNKNOWN position status – i.e. when safe LDS position / track number is not known prior the LDS initialization;
- The reactive fail safety is proposed for along track positioning (ATP) during normal train operation (Full Supervision);
- A fail-safe state cannot be defined in case of Track Identification function from the LDS functional safety point of view;
- Required safety of railway operations during performing the LDS initialization/ Track Identification is assured by train driver in Staff Responsible mode with a low ceiling speed (e.g. 30 km/ h). No LDS fail-safe mode is needed in this case;
- After LDS have safely determined the initial train position and track number in SR, then the LDS can switch to reactive operation in full ETCS supervision. A fail-safe state is clearly defined in case of detected failure;
- The presented preliminary safety analysis of LDS with composite safety shows that logical AND-combination of on-board train routing detection on switches together with track-side technical and operational safety-relevant data (including meta data) can significantly reduce safety requirements for GNSS (AIMN + OBU) if the Track Identification function is performed by train in motion;
- It is proposed that Cold Movement Detector (CMD), which is active in the NP mode (in contrast to ETCS EVC), should perform in addition of its main function (i.e. the invalidation of the last stored train position when train moved more than 5 m) also to the train position determination/ Track Identification. Or CMD+ function would be integrated into LDS in order

to enable Track Identification function. This topic regarding CMD+ functionality will be discussed in more detail in next phases of HELMET solution.

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