



CLUG

Demonstration of Readiness for Rail

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FOREWORD

GNSS and SBAS (EGNOS) is amongst the “game-changing” technologies for future digital and automated rail operations, as acknowledged on the longer-term perspective for the evolution of the European Rail Traffic Management System (ERTMS) and in the adopted report on railway safety and signalling.

CLUG 2.0, continues the activity of the CLUG project with the same main objective of demonstrating an on-board GNSS+EGNOS-based multi-sensor fusion architecture enabling absolute safe train positioning and navigation whilst also transforming the way of train localisation is done today.

The project focuses on:

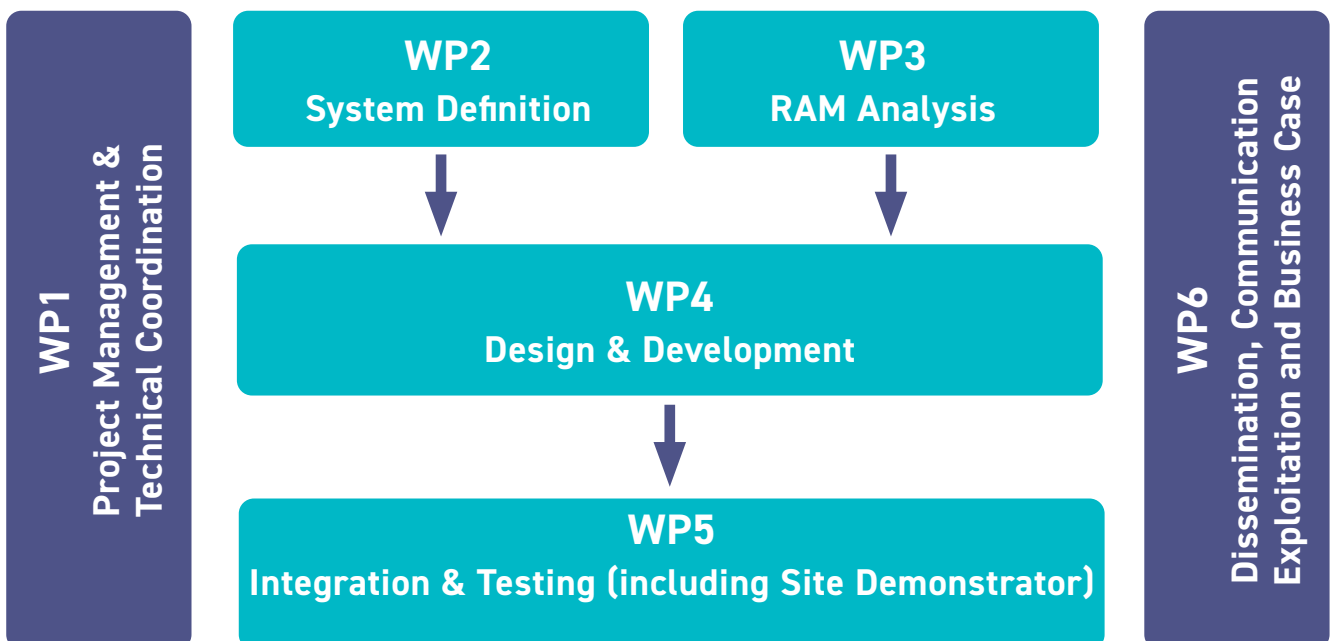
- Improving the safe functional architecture (Localisation On-Board LOC-OB System), notably with the development of Data Fault Detection and Exclusion, and the integrity module.
- Complementing the requirements and solution prototyping with Track Selectivity and Start of Mission
- Testing and demonstrating the performance of the solution through post-processing and live demonstrations.



PROJECT STRUCTURE

The CLUG 2.0 work plan, is organised into six Work Packages (WPs) with different functions in order to fulfil its overall objectives. There are four technical WPs that will develop the necessary tasks to deliver the technical objectives of the project, and two WPs designated for ensuring an efficient management and coordination of the project as well as a dissemination, communication and exploitation of the project results.

The project started with the System definition and RAMS analysis based on the outcomes of previous project. The design/development and test/demonstration activities started in parallel using the CLUG outcomes as the foundation for its implementation.





LOC-OB SYSTEM DEFINITION & REQUIREMENTS SPECIFICATION (WP2)

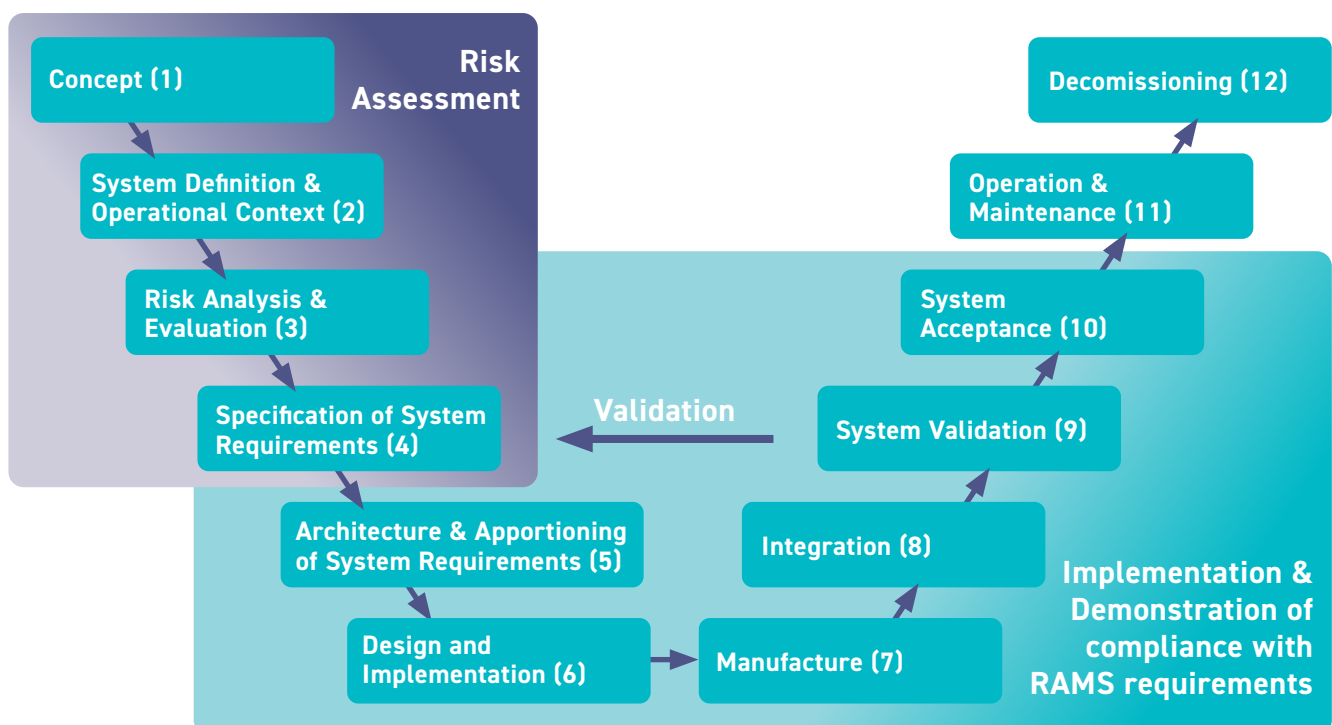
WP2 of CLUG 2.0 started in February 2023 and ended in November 2023. The DB InfraGO, former DB Netz, was in lead of this work package and received joint support and contribution from SNCF, SBB, CAF, ADS and SMO.

The objective of WP2 “LOC-OB System Definition & Requirements Specification” is to consolidate and finalize the system definition and requirements for the LOC-OB. This includes establishing the definitions and specifications to meet localisation needs during start of mission and track selectivity. WP2 is subdivided in the following deliverables:


- D2.1 Operational Needs and System Capabilities for LOC-OB
- D2.2 Start of Mission and Track Selectivity
- D2.3 LOC-OB System Definition and Operational Context
- D2.4 LOC-OB System Requirements

The WP2 deliverables follow the phases 1, 2 and 4 (Figure 1) of system definition according to EN50126 standard, published by CENELEC. While D2.1, D2.2 and D2.3 cover the topics related to phases 1 and 2, D2.4 covers phase 4 by defining the set of LOC-OB system requirements. Phase 3 (Risk analysis and evaluation) is covered by WP3 RAMS analysis. Previous work performed in other initiatives and working groups (RCA, OCORA, LWG, X2RAIL, CLUG (1)), like specifications or system descriptions, have been considered as input and are referenced where applicable. The CLUG 2.0 WP2 deliverables are considered by the WP4 System Design and Development and in the WP5 Integration and Testing.

As an important remark, CLUG 2.0 is a research project and does not aim to develop a certifiable product. For this reason, it is neither intended to cover all necessary content as defined in EN50126 nor to carry all CENELEC phases within CLUG 2.0.



V-cycle representation according to EN 50126-1:2017



The following paragraphs give a brief overview of the WP deliverable content and methodologies.

D2.1 Operational Needs and System Capabilities of LOC-OB

This document specifies a set of high-level user requirements that address the needs of the railway users for LOC-OB¹. These requirements establish the key objectives for the localisation system, serving as the basis for the system definition, design and evaluation.

In addition, with focus on the capabilities and functionalities expected from the LOC-OB system, the constraints of the LOC-OB are identified. The discussed variants (focused on potential supporting information required by LOC-OB) are provided as input for the boundary definition in D2.3 “LOC-OB System Definition and Operational Context”.

D2.2 Start of Mission and Track Selectivity

As previously stated, the main objectives of CLUG2.0 WP2 “LOC-OB System Definition and Requirements Specification” are defining the LOC-OB system and providing the LOC-OB system requirements specification as input for the later design tasks in WP4.

The scope of CLUG2.0 and specifically of this deliverable includes the analysis and recommendations to accomplish the localisation needs during start of mission and for track selectivity.

The dedicated analysis of the expectations for on-board localisation during start of mission and regarding track selectivity is based on the study of the challenging scenarios from today's perspective and anticipating challenging scenarios for the system under development.

Finally, the previous analysis on the challenging scenarios is used as base to provide recommendations to D2.4.

D2.3 LOC-OB System Definition and Operational Context

The main goal of this document is to define the high-level architecture of the future LOC-OB system, specifying the required external interfaces and the functionalities

owned by LOC-OB. To achieve this, CLUG2.0 adopts a “black box” approach, focusing on the description of external interfaces and functions. The D2.3 considers the ERTMS SUBSET-026 and future CSS on-board architecture evolutions developed by UNISIG, ERA and EUG. After consolidation of D2.1 LOC-OB Operational Needs and System Capabilities the LOC-OB operational context is derived. Based on this operational context, the external interfaces required by LOC-OB to provide the necessary localisation information and acquire the required supporting information are outlined. Finally, the high-level LOC-OB architecture is described by defining all the required LOC-OB functionalities.

D2.4 LOC-OB System Requirements

The purpose of the deliverable D2.4: LOC-OB System requirements is to define a set of requirements derived from the information available in:

- **CLUG2.0 D2.1:** Operational Needs and System Capabilities of the LOC-OB System
- **CLUG2.0 D2.2:** Start of Mission and Track Selectivity
- **CLUG2.0 D2.3:** LOC-OB System Definition and Operational Context

Even if the CLUG 2.0 project is structured around the use of GNSS and EGNOS augmentation in the railway environment, requirements are presented technology-agnostically. The main goal is to provide a set of requirements that can be used by any proposed safe train localisation solution, not only the CLUG context.

Since CLUG 2.0 is an R&D project involving uncertainties and assumptions toward the needs and external interfaces, the set of requirements may not be used for an industrial project without reworking.

Conclusion

The LOC-OB operational and system contexts consolidated in CLUG2.0 WP2 and, utterly, the set of LOC-OB system requirements provided shall be used for two main purposes:

- 1) As input for CLUG2.0 WP4 Design and Development and WP5 Integration and Testing
- 2) As input for future initiatives and projects, notably the Europe's Rail IP project FP2-R2DATO.

¹ LOC-OB stands for Localisation on-board unit.

RAMS ANALYSIS (WP3)

WP3 started in February 2023 and will end in March 2025. SNCF is leading of this work package, and DB InfraGO, SMO, ADS and CAF contribute to this activity.

The objective of WP3 is to specify and demonstrate the safety targets for the CLUG Localisation On-Board (LOC-OB) system developed as part of the project. In order to achieve this objective, the partners performed Reliability, Availability, Maintainability and Safety (RAMS) studies which allowed to define RAMS requirements in line with the overall SIL4 criteria of a railway embedded systems.

These safety analyses were performed in compliance with rules or standards applicable for the targeted Safety Integrity Level (SIL) of the CLUG LOC-OB System.

The RAMS activities provided during CLUG2.0 project gave detailed results that lead to the conclusion that the system can reach a high-level safety target. It gives confidence that a certifiable product based on the solution with a two-chains architecture, as proposed in WP4, could be developed to reach a SIL4 target. This architecture is based on some strong assumptions: an EGNOS for rail service is used to improve the safety level of GNSS observables, a safe digital map is necessary, balise are necessary for a safe initialization of the system if Cold Movement Detector (CMD) information is not available.

The following chapters give an overview of each task performed in WP3.

T3.1: CLUG LOC-OB System context analysis and RAMS Plan

The Reliability, Availability, Maintainability and Safety (RAMS) plan describes the RAMS objectives and activities that are performed in the WP3 of in order to cover the CLUG 2.0 objective "E04: To perform an analysis of Reliability, Availability, Maintainability, and Safety (RAMS) on the consolidated functional architecture of the system". The document follow the recommendations of the CENELEC standards applied in the railway domain (as all documents of WP3). It reaffirms the perimeter of the system and the operational context followed by the project, gives the RAMS objectives to

follow during the project and details the RAMS activities planned for WP3.

T3.2: LOC-OB Preliminary Hazard Analysis

The Preliminary Hazards Analysis (PHA) of the LOC-OB system aims to identify hazards, to assess the severity of the potential accidents that could occur and to mitigate the risks associated with the hazards. This study identifies a list of RAMS requirements on the system as a black box as it was assumed in WP2 deliverables.

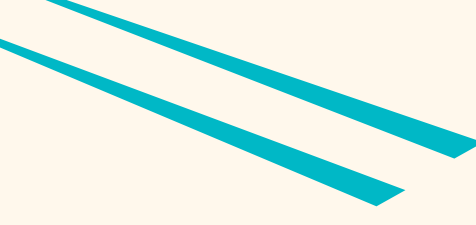
The method used to carry out this analysis follows the principles applicable to the risk-management process defined in the Common Safety Methods of the Railway Safety Directives, whose main phases listed in the following figure:



Preliminary Hazard Analysis – Risk management process phases

Following hazard identification at the ERTMS/ETCS system level, derived hazards and fear events have been identified. At the end of the analysis, safety requirements were established, among which the most important and consolidated are:

- **RA-RAMS-03:** The true train position shall always be inside the confidence interval
- **RA-RAMS-04:** The true train speed shall always be inside the confidence interval.
- **RA-RAMS-05:** The true train acceleration shall always be inside the confidence interval.
- **RA-RAMS-08:** The track-edge ID provided by LOC-OB shall always be the track edge occupied by the real position of the train front end.



These requirements are associated with functions for which the safety target is the most critical in the railway domain (SIL4). For the functions providing 3D data, the user needs are not mature enough to conclude a defined safety level. The deliverable D3.2 is a public document available on the website.

T3.3: CLUG LOC-OB System Failure Modes and Effects Analysis

This task provides a functional safety analysis of the LOC-OB system, identifying how failures of an internal function leads to the failure of the LOC-OB system on its outputs. This analysis is based on a qualitative analysis of the functions of the LOC-OB system and identifies and describes the consequences of these failures.

The document provides a list of safety requirements to be covered in view of the design of a certifiable product, a list of assumptions and open points. It confirms that to reach the safety objectives previously identified for the LOC-OB system, the main functions of the system shall be designed in safety within a functional architecture allowing the prevention, detection and elimination of faults.

T3.4: LOC-OB External Interface Analysis

This task provides a high-level external interfaces safety analysis, identifying how the exchanges between the LOC-OB system and its environment and the internal functional blocks shall be designed to cover the safety requirements already identified. This analysis also provides indications on the selection of safety targets expected on the input measurement means to achieve the TFFR expected on the output functions.

In conclusion, a list of safety requirements, assumptions and open points is provided. The main results of this analysis enhance the importance of safe mechanism for the LOC-OB to receive and provide information. It is also confirmed that the alternative solution with two diversified chains can allow easily to reach the expected safety target of the LOC-OB.

T3.5: CLUG LOC-OB System Functional Analysis

The objective of T3.5 is to analyse the System Functional failure in order to consolidate the Preliminary Hazards Analysis and validate the functional system specification and the architecture defined in WP2 and WP4. The first part of the analysis uses Failure mode effect analysis to analyse the internal functions of the LOC-OB. The second part of the Analysis want to demonstrate that the LOC-OB System meets safety requirements and can achieve Safety Integrity Level 4 in terms of hardware.

The document concludes that the design of the LOC-OB should incorporate Composite Fail-safety. For LOC-OB initialisation function, the Cold Movement Detection is needed to start up fusion algorithm. For the Track Selectivity function, the point position information is required as an input to ensure the safe train movement.

T3.6: CLUG LOC-OB Reliability Availability Maintainability System Analysis

The purpose of this task is to provide the overall documentary evidence of the reliability, maintainability, and availability performance level of the system architecture of the LOC-OB.

This study is based on hypotheses and assumptions that provided a stable framework and operational conditions. This RAM analysis shows that the first approach of the architecture of the LOC-OB does not meet all relevant reliability, availability, and maintainability requirements and gives recommendations in terms of RAM.

T3.7: CLUG LOC-OB RAMS Evaluation report

This task evaluates what has been produced during the project (WP2 + WP3 + WP4) to cover the RAMS objectives defined during T3.1 and to consider Safety and RAM results defined in T3.2 to T3.6. It also focuses on some topics to clarify during these remaining steps. The document is under final review before being published on the CLUG 2.0 website.

DESIGN & DEVELOPMENT (WP4)

WP4 started in February 2023 and will end in June 2025. AIRBUS is leading of this work package, and SBB, SMO, ENAC, SYNTONY, CAF I+D, and DB contribute to this activity.

The CLUG 2.0 project, as a continuation of its predecessor project CLUG (finalized in May 2022), has seen very significant progress on the Localization On-Board (LOC-OB) functional architecture through complementary design focusing on:

- the track selectivity function prototyping,
- the sensors and system data Fault Detection and Exclusion (FDE) algorithms,
- the Confidence Intervals computation for along-track position, speed and acceleration.

These functions are prototyped with algorithmic enhancements in CLUG 2.0, starting to be experimented. Simultaneously, the performance predictions in safety, i.e. the availability of the safe computed CIs within the specified CIs, are improved through refined models and simulation tools.

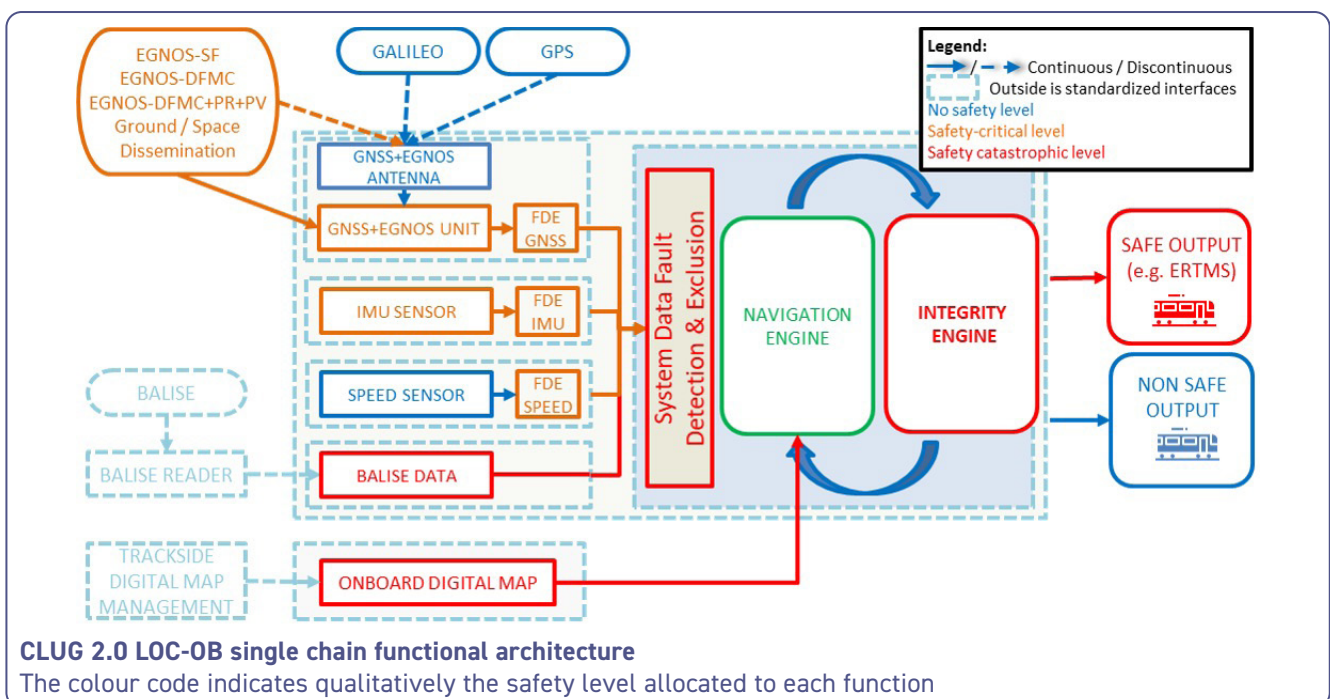
The mission of the LOC-OB is to continuously produce safe train localization data, along-track position, speed and acceleration with a high safety level (Tolerable

Hazard Rate (THR) < 1E-9/h), and other data like the train attitude and 3D kinematics. These localization data are inputs for many train control applications including CTMS, Train Protection Trackside, Train Protection on-board, Passenger Information System, ATO, ...

The CLUG 2.0 approach relies on using multi constellation Global Navigation Satellite Systems (GNSS), in dual frequency mode (GPS L1&L5 and Galileo E1&E5), augmented by EGNOS, the European Satellite Base Augmentation System (SBAS); firstly with its Dual Frequency Multi Constellation (DFMC) data stream, and possibly later with a future EGNOS stream designed to increase performance for Railways end-users. These EGNOS streams would be granted by the European Agency for Space Programs (EUSPA) as "EGNOS for Rail" services.

LOC-OB functional architecture

The LOC-OB functional architecture relies on multi-sensor tight-coupling fusion, empowered with integrity algorithms. It consists in merging Galileo and GPS, safely augmented by EGNOS, with other sensors (e.g. IMU and speed sensor) especially required in the rail operational environment where GNSS satellite visibility is discontinuous.



Accordingly, the LOC-OB is composed of the following functional blocks:

- Sensors with their associated data FDE:
 - GNSS+EGNOS unit: receives Galileo and GPS signals via roof antenna, safely corrected by EGNOS data, received preferably via the rail network, otherwise via the 2 EGNOS geostationary satellite
 - Inertial Measurement Unit (IMU): provides 3D acceleration and angular rates
 - Speed sensor (e.g. tachometer): provides along track speed raw measurement (not an “odometry system” embedding several independent speed sensors)
 - Balise reader: detects trackside balises, necessary in constrained areas where GNSS is not available for too long (e.g. in long tunnels)
- Navigation and Integrity engine, containing several algorithmic functions:
 - Initialisation,
 - Track selectivity,
 - Along track fusion,
 - System Data Fault Detection and Exclusion (FDE),
 - Integrity confidence intervals computation
- Digital map: data structure containing the 3D multitrack layers enabling the navigation engine to constrain the along-track train kinematics and to determine track selectivity

The role of Data Fault Detection and Exclusion (FDE) is to detect and exclude faulty sensor data. There are two

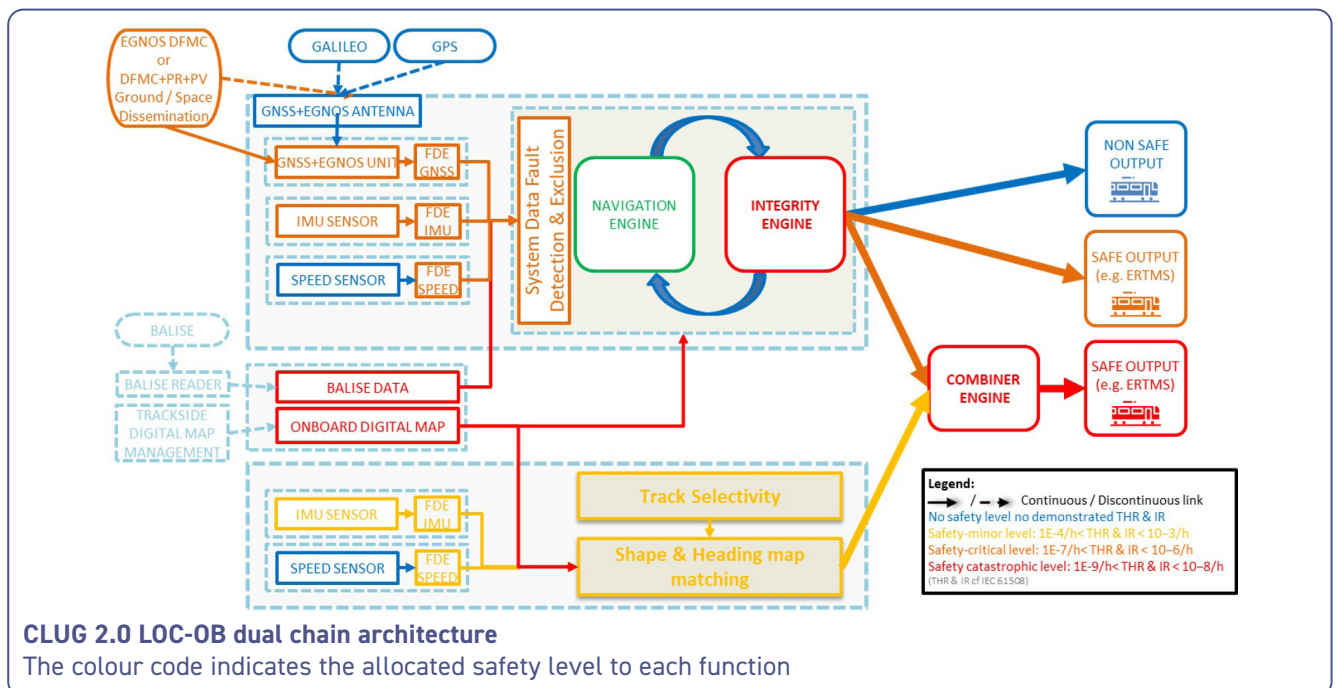
types of FDE, “Sensor FDE” are checking each sensor data individually, and “System FDE” are checking the consistency of sensor data with the estimated train position and speed.

CLUG 2.0 achieved improvements on the LOC-OB overall architecture and on track selectivity, fusion, FDE and confidence interval computation algorithms. In this article, insights are provided on two specific CLUG 2.0 areas of improvement, the dual-chain architecture and on the track selectivity algorithm design.

Dual-chain pragmatic architecture

Achieving a 10^{-9} /h THR with the above functional chain raises several challenges, including comprehensive hazard analyses and certification of complex algorithms at SIL4 development level. A dual-chain architecture is proposed as a pragmatic alternative, where the LOC-OB is completed with a second independent localisation chain, based on a “Shape and heading map matching” algorithm, and a “Combiner” function.

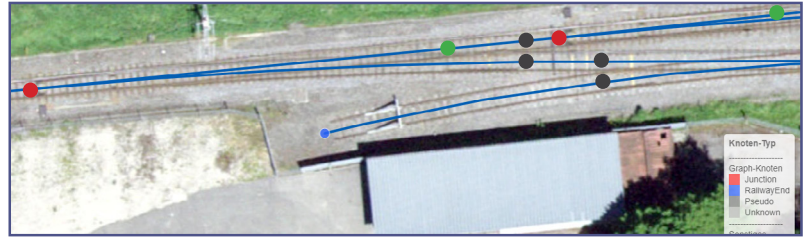
The global THR is split between the GNSS+EGNOS-based chain, at a level compatible with the current SBAS certification level, and the second chain at a lower level. Each chain delivers along track pos./speed/acc. estimates and their associated Confidence Intervals (CIs) to the Combiner function, that computes weighted estimates and the global CI as the union of the CIs from both chains. This function is simple enough to be developed at SIL4 level.



Track Selectivity algorithm

The Track Selectivity function design relies on mixing a set of independent shape recognition algorithms running in parallel using measurements provided by non-coupled sensors. Each independent solution provides its own most probable track ID selection with an estimated probability of error. These inputs are merged through a Decision Fusion algorithm selecting the track edge option minimizing the probability of error. The Track Selectivity function is triggered when the train approaches a track switch, and runs until the probability of error matches the required Tolerable Hazard Rate (THR). Combining several algorithms allows to reduce significantly the distance and time delay required for issuing a safe decision for a given THR.

The solution prototyped in CLUG 2.0 relies on a GNSS-based chain and an IMU-based chain. The GNSS-based chain estimates the likelihood of the GNSS carrier phase measurements precise trajectory with respect to the shape of each possible track after the switch, as defined in the Digital Map. The IMU-based chain estimates the likelihood of IMU gyroscope measurements azimuth profile with respect to the azimuth profiles of each possible track after the switch.



Track selectivity test case (switch ID 6077)

Red dots are the location of track switches, green dots are the location where the decision is sufficiently safe, black dots are Digital Map nodes. The train is running from the left to the right.

Tests conducted with real datasets collected on trains operating in Switzerland demonstrated 100% correct detection and that detection at a 10^{-10} Hazard Rate requires only 1 to 3 seconds (or a few meters). This Track Selectivity solution is showing very good performance results to reach the high level of integrity required by Rail operations.

LOC-OB prototyping status

The LOC-OB prototype that will be experimented in a later stage of the project now covers almost completely the single chain architecture (only exception being the Initialisation function), and implements an improved design of algorithms. Prototyping and experimentation of the LOC-OB dual-chain architectural option is planned in the frame of the ERJU/R2DATO initiative.

INTEGRATION & TESTING (WP5)

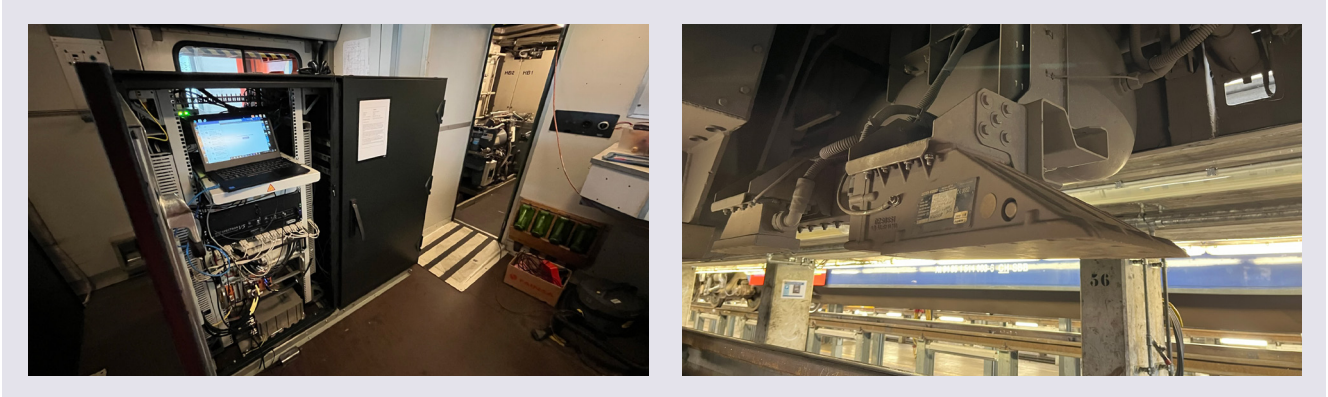
Test trains

For testing the algorithms developed in the CLUG2 project it was decided to not only to reuse the Domino train that was already equipped for the CLUG(1) research project, but to equip in addition a Re450 locomotive. Both vehicles are owned and operated by the Swiss federal railways SBB. The Domino operates mostly in rural regions in the western part of Switzerland, whereas the Re450 operates in the Zurich metropolitan area.



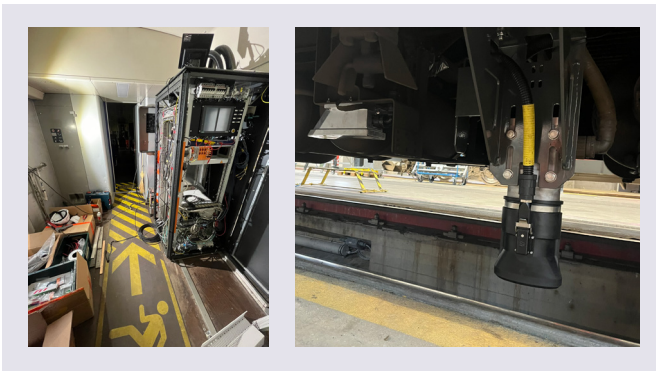
Re450 (left) and Domino (right)

The Re450 was equipped for the CLUG2 project in mid 2023. The installation included a cubicle inside the locomotive, which contains the onboard computers used for data collection, as well as for the demonstrator, IMUs, GNSS receivers and related hardware. Various antennas and speed sensors also had to be installed underneath the vehicle, as well as on the roof.



Test cubicle (left) and speed sensors (right) on Re450

The Domino was then upgraded in February 2024 to an identical set of sensors. This was less time consuming, as the cubicle, cabling and mounting brackets for the sensors, as well as most antennas installed for the CLUG(1) project could be reused. Still, many of the actual sensors had to be replaced to fit with the project goals.

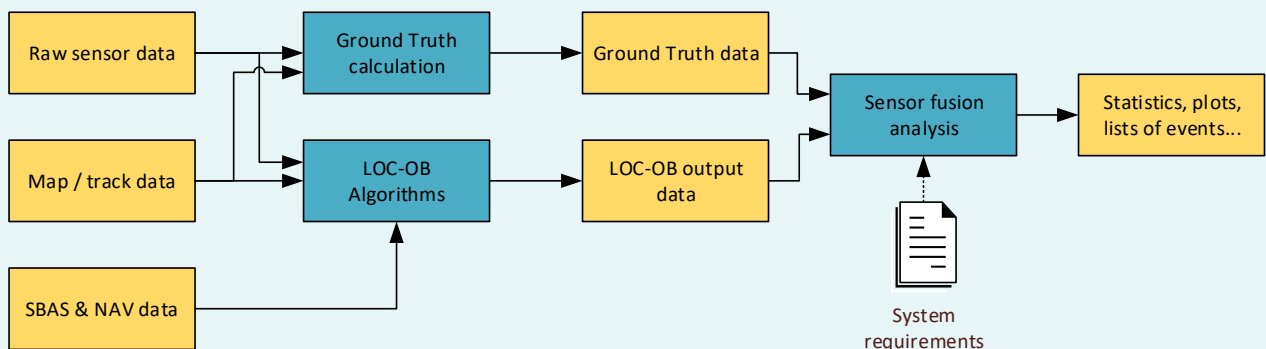


Both trains are used daily for commercial service, allowing data over more than 100'000 km in very diverse environments to be collected since the trains have been equipped, respectively upgraded.

Work being performed on the opened test cubicle (left) and optical speed sensors used for ground truth generation (right)

DATA PROCESSING

Currently the team mainly focuses on "offline"-processing, as this allows the project to continuously improve the algorithms by processing the same, collected data with different versions of the algorithm.



Data processing overview

Raw sensor data processing

Raw data collected on the test trains is stored and processed offline. It is first decoded, and then transformed to formats specifically defined for the project. The processing tool chain creates for each so-called "trip", e.g. from the station where the train starts its journey to where it ends, separate files containing data for each sensor. Although it may sound simple, the processing of 1 hour raw data for all available sensors on a powerful 12 core-CPU based computer takes about 2 hours!

SBAS and NAV data

In addition to the raw sensor data collected on the test trains, SBAS (Satellite Based Augmentation System) data and GNSS navigation data are retrieved offline through different services provided by the European Agency for the Space Programme, EUSPA, as well as by the Swiss Federal Office of Topography, swisstopo. SBAS data includes single frequency (SF) augmentation data from the EGNOS Data Access Service and the newly defined DFMC+PR+PV data computed by Airbus. This data is currently gathered offline because the GNSS receivers on the test trains cannot collect this data online yet.

Map / track data

Last but not least, the LOC-OB algorithm requires map and track data from the railway infrastructure where the test trains operate. This data is provided by SBB and transformed to the format required by the algorithm.

Ground Truth calculation

The computation of a "Ground Truth" is an important prerequisite to analyze the performance of the LOC-OB system. "Ground Truth" refers to true and accurate position, distance and speed information, which serves as a reference for analysing the performance of the respective data generated by the LOC-OB algorithm.

The Ground Truth in the CLUG2 project is computed based on several sensors, one being the Eurobalise antenna. Since the positions of the Eurobalises along the tracks are known very accurately, and since this information is part of the track data provided by SBB, the CLUG2 Ground Truth can determine the position of the train very accurately when it reads Eurobalises. It then determines the route taken when reading Eurobalises, and the ground truth algorithm then generates interpolated positions between the Eurobalises along the track with a high resolution, using a combination of different speed and distance sensors. Designing of the Ground Truth algorithm was particularly challenging, since an accuracy of the position of less than 20cm has been required, considering that the distance between two subsequent Eurobalises can reach up to 1.5 km on the SBB railway network!

LOC-OB algorithm processing

Once the sensor, SBAS and map data are available in the corresponding formats, the LOC-OB algorithms delivered by WP4 can be executed, generating output files. The LOC-OB algorithms perform both fault detection in raw sensor data, as well as the fusion of data from different sensor to generate output data. As mentioned in the introduction of this section, the LOC-OB algorithms are mostly tested "offline". As part of the project, the LOC-OB algorithms is currently being integrated on an onboard computer to perform live demonstrations, including real time visualization & monitoring.

Sensor fusion analysis

The outputs of the LOC-OB algorithm are finally compared with the Ground Truth using multiple scripts, which calculate various types of statistics, list events where data exceeds specific limits specified in the system requirements, and create plots showing the data in a graphical form.

TOTAL PROJECT
VALUE

4.17 M€
(2.87 EU)

DURATION

30

Months

PARTNERS

10

PROJECT MEMBERS

COORDINATOR



TECHNICAL LEADERS



PARTNERS

AIRBUS



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