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2nd Newsletter

CLUG

Demonstration of Readiness for Rail

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TABLE OF CONTENTS

Bernina Red Train, Switzerland

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

This 2nd Newsletter gathers additional outcomes and achievements in WP4 (Design and Development) and WP5 (Integration & Testing – including Site Demonstrator) to the one already presented in the 1st Newsletter and main project conclusions and next steps.

Bernina Red Train, Switzerland

WP4: DESIGN AND DEVELOPMENT

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 and algorithms.

The main mission of the LOC-OB is to continuously produce and output safe train along-track localization data at high safety level (Tolerable Hazard Rate (THR) < 1E-9/h).

The CLUG 2.0 functional architecture relies on using multi constellation Global Navigation Satellite Systems (GNSS), in dual frequency mode (GPS L1&L5 and Galileo E1&E5), augmented by EGNOS Dual Frequency Multi Constellation (DFMC), the European Satellite Base Augmentation System (SBAS). First with EGNOS Dual Frequency Multi Constellation (DFMC) data stream, and possibly later with a future EGNOS stream (called "+PR+PV" for pseudo range and range-rate) 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.

Simultaneously, the evaluation of performance, in terms of the availability of the safe Confidence Intervals within the specified Maximum Operational CIs, has been improved through refined models and enhanced simulation tools. This article presents the developed performance simulated environment and the most recent results of performance prediction in safe availability.

LOC-OB functional architecture

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

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

- Sensors with their associated data FDE (Fault Detection and Exclusion):
  - GNSS+EGNOS unit: provides augmented GNSS pseudo-range (and possibly range-rate)
  - Inertial Measurement Unit (IMU): provides 3D acceleration and angular rates
  - Speed sensor (e.g. tachometer): provides along track speed raw data
  - Balise reader: detects trackside balises
- Navigation and Integrity engine, containing several algorithmic functions: Initialization, Track selectivity, Along track fusion, Integrity confidence intervals computation, System Data FDE
- Digital map: provides the data structure containing 3D multitrack segments

The role of Data Fault Detection and Exclusion (FDE) is to detect and exclude faulty sensor data. "Sensor FDE" check each sensor data individually and the "System FDE" check the consistency of all sensor data with the estimated train position and speed.

Dual-chain pragmatic architecture

Achieving a 10^{-9}/h THR with the above architecture raises challenges, including comprehensive hazard analyses and SIL4 certification of EKF algorithms. A pragmatic alternative is a dual-chain architecture, where the GNSS-SBAS chain is competed by a second independent localization chain and a "Combiner" engine. The Combiner computes weighted position and speed estimates and the global Confidence Interval (CI) from the estimates and CIs of both chains.

The global THR is shared between both chains, not equally, consistently with an achievable level of certification for each (e.g. ~10^{-6}/h for the GNSS-SBAS chain and ~10^{-3}/h or for the second chain).

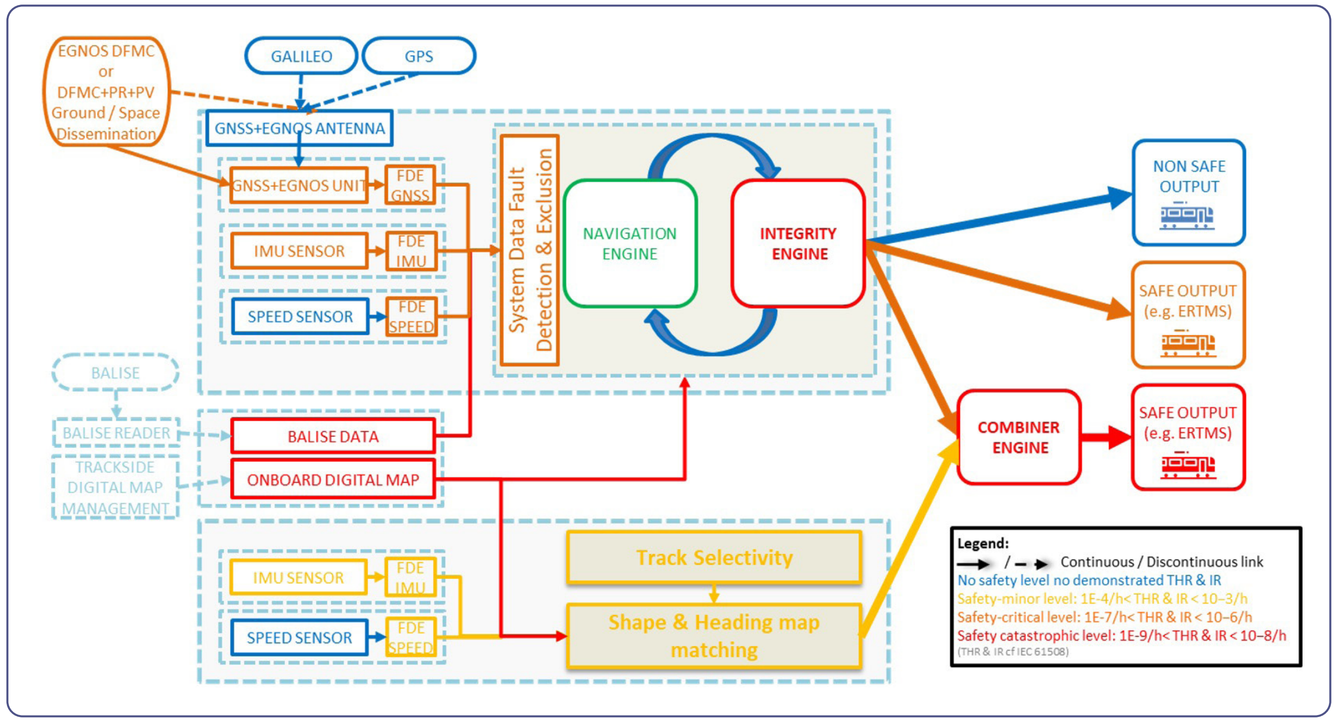

Figure 1: CLUG 2.0 LOC-OB functional architecture
The single chain "GNSS+SBAS" corresponds to the top part of the Figure; In the dual-chain architecture, this GNSS+SBAS-based chain is completed with a "Shape & Heading map matching" chain and the Combiner engine

Confidence Intervals size drivers

The LOC-OB is stated available with respect to Confidence Interval (safety availability performance) when LOC-OB outputs position and speed Confidence Intervals (CIs) and they are smaller than the required Mission Confidence Intervals (MCIs).

The size of Confidence Intervals mainly depends:

- "GNSS+SBAS" chain: on the train local environment, i.e. the GNSS constellations geometry versus the train heading, the GNSS masking (clear sky to GNSS-denied area), and the train speed;
- "shape map matching" chain: on track geometry (curved to straight) and the train speed.

Focusing on the "GNSS+SBAS" chain, the size of Confidence Intervals will vary significantly along a train trip, as illustrated on the Figure 2 below. GNSS masking is modelled through four environment categories with different masking probabilities: open sky, suburban, urban, and GNSS-denied (tunnels).

The size of Confidence Intervals depends on LOC-OB configuration parameters and models set in the Airbus LOC-OB performance tool: GNSS/SBAS errors and integrity models (GPS, Galileo, EGNOS DFMC and +PR+PV services), GNSS errors time correlation model, residual local error models (depending on environment – 6 categories), as well as the IMU, Tachometer and Track Map error models.

Finally, predicting CI size also require to model multi-sensor fusion, CI computation, including the Combiner part, and data FDE algorithms (in terms of statistical performance).

Performance simulated environment

The general approach consists in computing statistical distributions of predicted values of Confidence Intervals size for different use cases, over a large set of representative potential environmental and system configurations. From these statistical distributions is determined the half-MCI value that can be achieved for reaching the target availability of 99.9%, as illustrated on Figure 3 below.

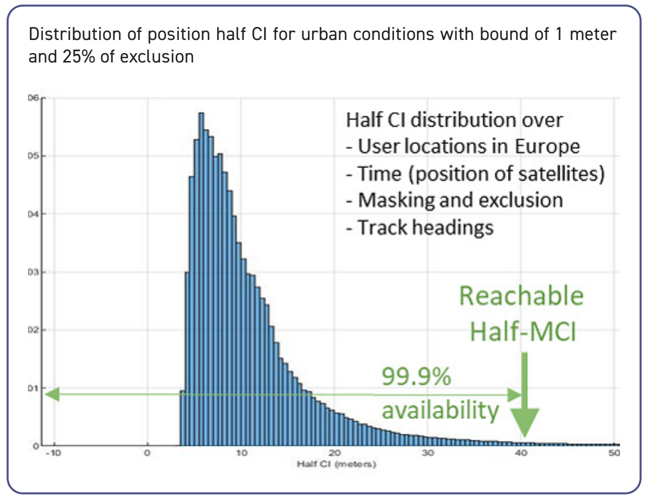

Figure 3: "Predicted position Confidence Interval statistical distribution and estimated reachable half-MCI

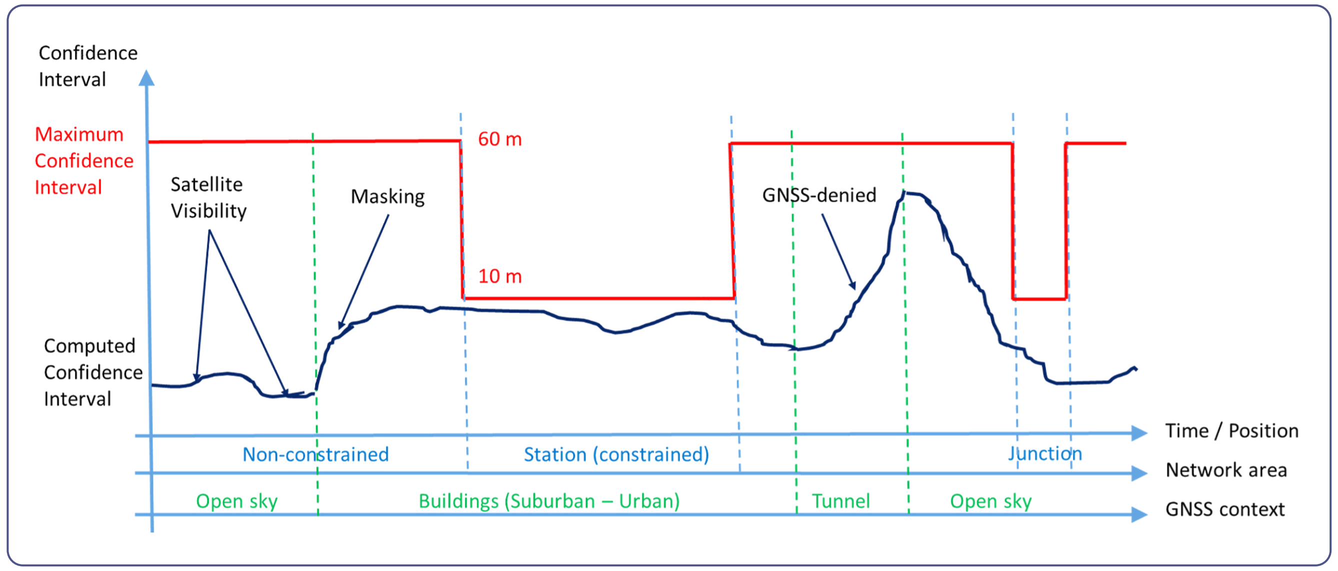

Figure 2: "GNSS+SBAS" chain computed position Confidence Interval behavior versus local environment contexts, and Maximum Confidence Interval requirements, depending on operational contexts.

The performance tool, called Salsa4Rail, has been developed by Airbus based on representative models of rail environment, GNSS and SBAS performance macro-models and CLUG 2.0 LOC-OB algorithmic models.

Statistical distributions are estimated in several ways:

- For the GNSS-SBAS chain when GNSS is available, achievable CI is estimated for an exhaustive sampling of configurations: user locations, dates, operational (train heading) and environmental conditions (masking, local events leading to data rejection).
- For the GNSS-SBAS chain in GNSS-denied areas, CI size prediction was based on experimental data set with various track shapes and on assumptions on distance between balises.
- For the "Shape Map Matching" chain, CI statistical distributions were extrapolated from SBB experimental results and track shape assumptions.

Noted CLUG 2.0 specified two operational requirements on the position half-MCI size (10m in constrained or 60m in not-constrained areas), the reachable MCI values were evaluated for both values for various configurations, depending on LOC-OB architecture (single chain or dual-chain), EGNOS service level (DFMC, DFMC+PR+PV), GNSS environment (Open sky, Suburban, Urban, GNSS-denied) and track curvature (straight, average, very curvy).

Performance prediction results in safe availability

The performance prediction results in safe availability mean two conditions to fulfill:

- The real/true posisition/speed is within the computed CI;
- The computed CI is smaller the required operational maximum CI (MCIs).

Considering the results presented in the Figure 4, main outcomes at 99.9% availability, noting CLUG 2.0 LOC-OB availability budget is 1mn/2h i.e. 99.2%, in {fault-free + faulty} CI @1E-9/h, without balise, are:

- The along-track **position half-MCI 60m** requirement in "non-constrained" areas is achievable in all environment contexts, in dual chain or in single chain architecture;
- The along-track **position half-MCI 10m** requirement in "constrained" areas is achievable in opens sky and suburban environment in single chain architecture, but not in dual-chain architecture except with curvy areas.
- In GNSS-denied areas, CI performance depends on heading variations and on the maximum distance

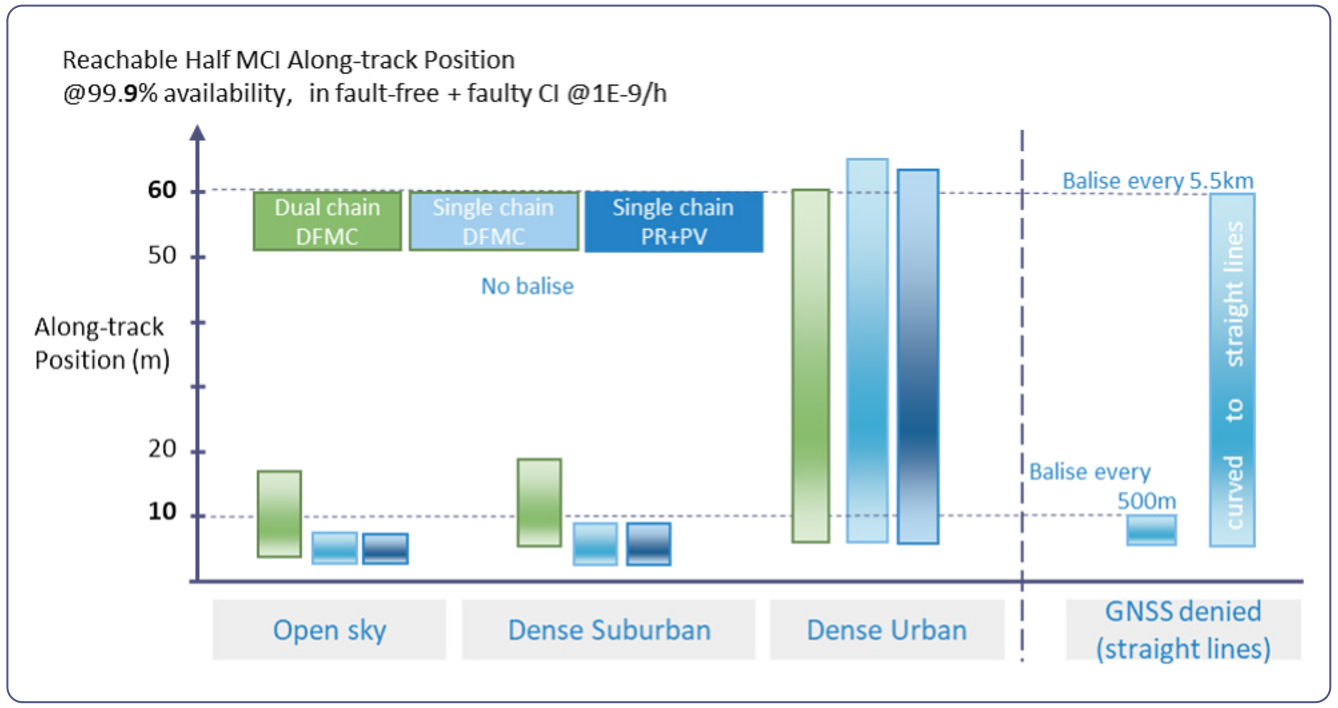

Figure 4: Performance prediction results in safe availability for position CI

Domino Test Train, Switzerland

between successive balises. On straight lines (worst case), compliance with the maximum 10 m position half-MCI would require balises every 500 m, and achieving 60 m half-CI would require balises every 5.5 km approximately. These values depend strongly on the IMU and tachometer sensor performance assumptions.

- The achievable MCI on **speed** does not depend significantly on the GNSS environment. Current prediction results are not compliant with LOC-OB requirement. This is probably related to IMU and tachometer sensors performance assumptions in faulty CI being too coarse with respect to reality.

  Note: real experimentations in single chain architecture are encouraging in fault free CI: the along track-speed half-MCI requirement ([2 12] km/h) is achieved in almost all tested trips; in rare worst case trips (GNSS-denied / tunnel and straight track), rare balises are needed.

  On top of it, prediction speed results demonstrate also that the future EGNOS service PR+PV would improve significantly (20%) speed CI performance.

- Considering faulty scenarios in CI computation (and not only fault-free CIs based on EKF state covariance) is mandatory to ensure safety, because faulty CIs are usually larger than fault-free CIs.

- Sensitivity to several parameters of the faulty CI model is significant, and results are to be taken as still approximate. Using conservative values for these parameters leads to pessimistic performance figures. More realistic values are also proposed in the document, leading to better performance, that must be confirmed and justified by further work.

Re450 Test Train, Switzerland

WP5: INTEGRATION & TESTING: PROGRESS, METHODS, AND RESULTS

Work Package 5 (WP5) of the EU-funded project **CLUG2 (Certifiable Localisation Unit using GNSS in the railway environment)** is dedicated to the integration, testing, and performance evaluation of the LOC-OB (Localisation On-Board), an innovative GNSS-based platform for sensor fusion enabling precise and certifiable train localization. The goal was to test laboratory-developed technologies under real operating conditions and to demonstrate their performance in European railway operations.

At the heart of WP5 was the development of a seamless data and analysis pipeline, ranging from automated acquisition of extensive raw data, through the generation of highly accurate ground truth, to real-time visualization and performance evaluation. The results show that LOC-OB, as the core of sensor fusion, can make a decisive contribution to the digitalization and automation of European rail transport.

Test Vehicles and Data Foundation

The performance evaluation of LOC-OB is based on a unique data set created within WP5. Over a period of 278 operational days, more than 6.4 terabytes of raw data were collected on two specially equipped trains from SBB, the Swiss Federal Railway, the Domino and the Re450. Both vehicles were equipped with harmonized sensor suites, including multiple GNSS receivers, inertial measurement units, wheel sensors, radar and optical speed sensors, and Eurobalise readers. The setup was complemented by cameras for context documentation and environmental sensors, such as for weather data.

The Domino train, already used in previous projects like STARS and CLUG1, enabled access to balise through its ETCS equipment and was used on a wide variety

Test trains: Re450 (left) and Domino (right)

of routes, in rural and mountainous regions, including long tunnels. The Re450 locomotive, as part of the Zurich S-Bahn network, allowed targeted data collection in urban area, including underground lines and stations. Both vehicles were selected to cover the broadest possible spectrum of operational and environmental conditions.

All sensor data was stored with precise UTC timestamps in standardized formats (CSV, JSON, RINEX) and is available to project partners for development, benchmarking, and performance evaluation. In total, 549 trips with a total distance of over 110,000 kilometers were recorded.

Ground Truth: The Position and Speed Reference for LOC-OB

A central prerequisite for the performance evaluation of LOC-OB is the availability of a highly accurate position and speed reference, the so-called ground truth (GT). In the CLUG2 project, a dual system was developed that combines the strengths of different approaches.

Firstly, a so called iMAR-GT, based on a real-time GNSS/INS system iNAT-RQT-4003 from the company iMAR Navigation GmbH was used, which continuously provides 3D position, speed, and attitude (roll, pitch, yaw) with the highest accuracy using ring laser gyros and servo accelerometers. This system is particularly suitable for validating dynamic motion parameters and is largely independent from the track topology.

This was complemented by the SMO-GT, a track-map based solution generated in post-processing. Here, balises, odometry, and detailed track data are used to enable the exact determination of the train position along the track to individual track sections and in reference to infrastructure points. Calibration and plausibility checks are also applied to minimize systematic errors.

Both systems are systematically compared, deviations identified, and the two then fused into a common reference (CLUG2-GT). The fusion compensates for ground truth specific issues, such as GNSS shadowing, sensor failures, or map errors, thus ensuring a robust performance, even in long tunnels or in urban areas.

This ground truth serves as reference for evaluating LOC-OB's performance and enables the identification of locations or operational cases which impact the performance of LOC-OB. It forms the basis for targeted optimizations and the traceability of all results.

LOC-OB Toolchain: From Raw Data Acquisition to Real-Time Localization

At the center of WP5 is LOC-OB—the Localisation On-Board system developed in WP4, which, as the heart of sensor fusion, processes all sensor data in real time and generates train location data with high accuracy. The architecture of LOC-OB is modular and allows flexible integration of different sensor configurations and algorithms.

Recorded sets of sensor data are collected from the trains either manually or automatically via 5G download, decoded, and converted into unified MATLAB objects. Data is supplemented with EGNOS, weather, and geolocation data, which is downloaded offline from different sources.

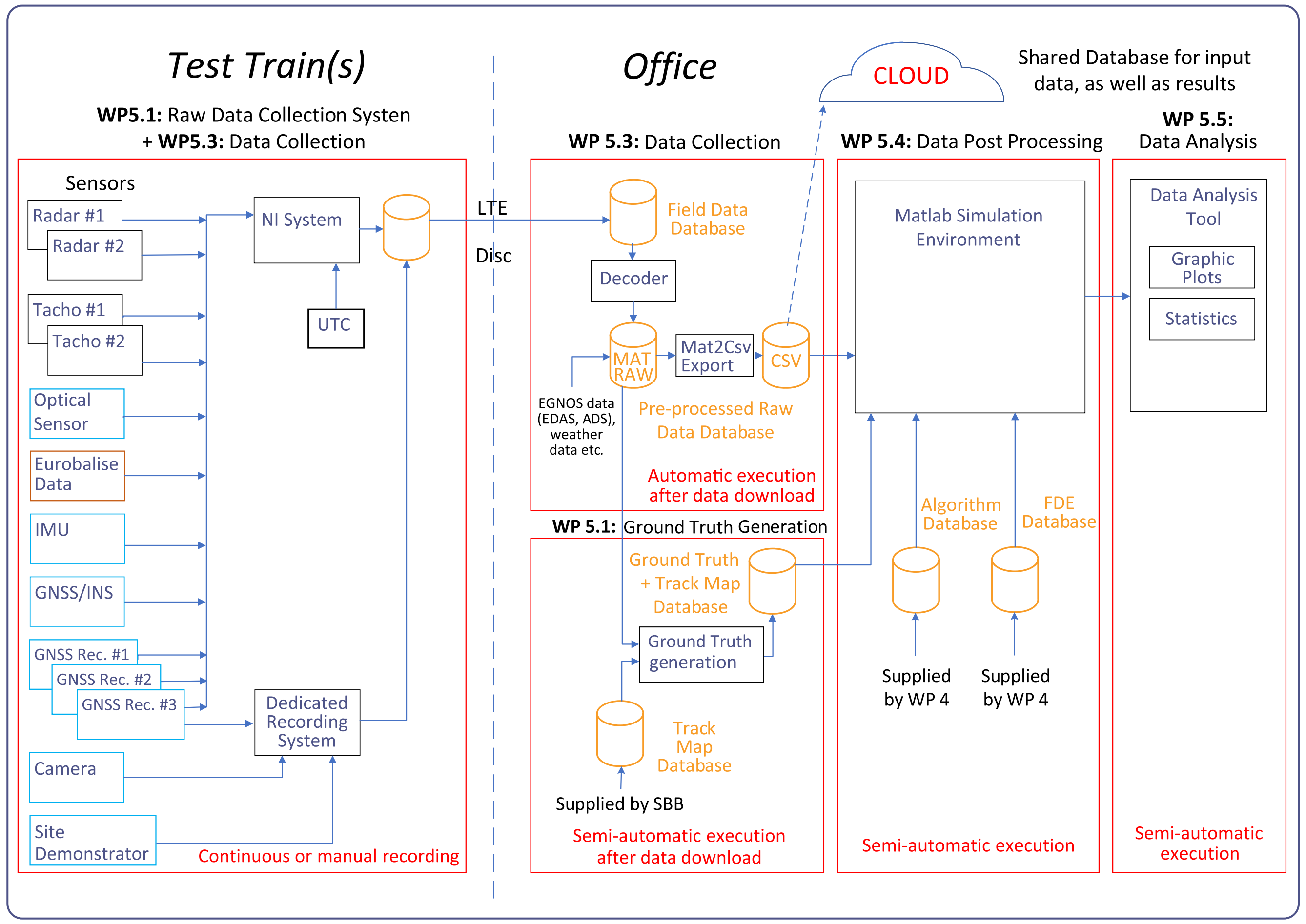

Figure : WP5 – Post-processing toolchain

In post-processing, data sets are then processed using the LOC-OB sensor fusion algorithm. LOC-OB integrates GNSS, IMU, speed sensors, and balises in a software framework. The sensor fusion is based on an Extended Kalman Filter (EKF), which merges all available sensor data into a robust, accurate position and speed solution, as well as confidence intervals. The algorithms are designed to ensure reliable localization even in the event of environmental or operational impacts on sensors, such as wheel slip/slide, GNSS multipath or outages (e.g., in urban environments or tunnels) etc.

The results of LOC-OB sensor fusion are automatically analyzed: speed, distance, position, and confidence intervals are evaluated for mass data, individual trips, and specific events. Real-time and offline visualization via Grafana dashboards enables monitoring and evaluation both in the lab and on the vehicle.

The Demonstrator: Bridging Laboratory and Real-World Railway Operation

An important part of WP5 is the development of the CLUG2 demonstrator, which serves as a technical bridge between offline data fusion and real-time implementation. The demonstrator was installed on the test trains Domino and Re450 and transform essential elements of the LOC-OB offline toolchain into a real-time environment.

During regular operation, the demonstrator continuously records all sensor data—from GNSS, IMU, and speed sensors to balises. This data is stored in its raw form and is thus available for later, detailed offline analysis. Continuous recording ensures that all operating states, environmental conditions, and also rare, exceptional events are recorded. This creates a comprehensive database that can be used not only for analyzing the

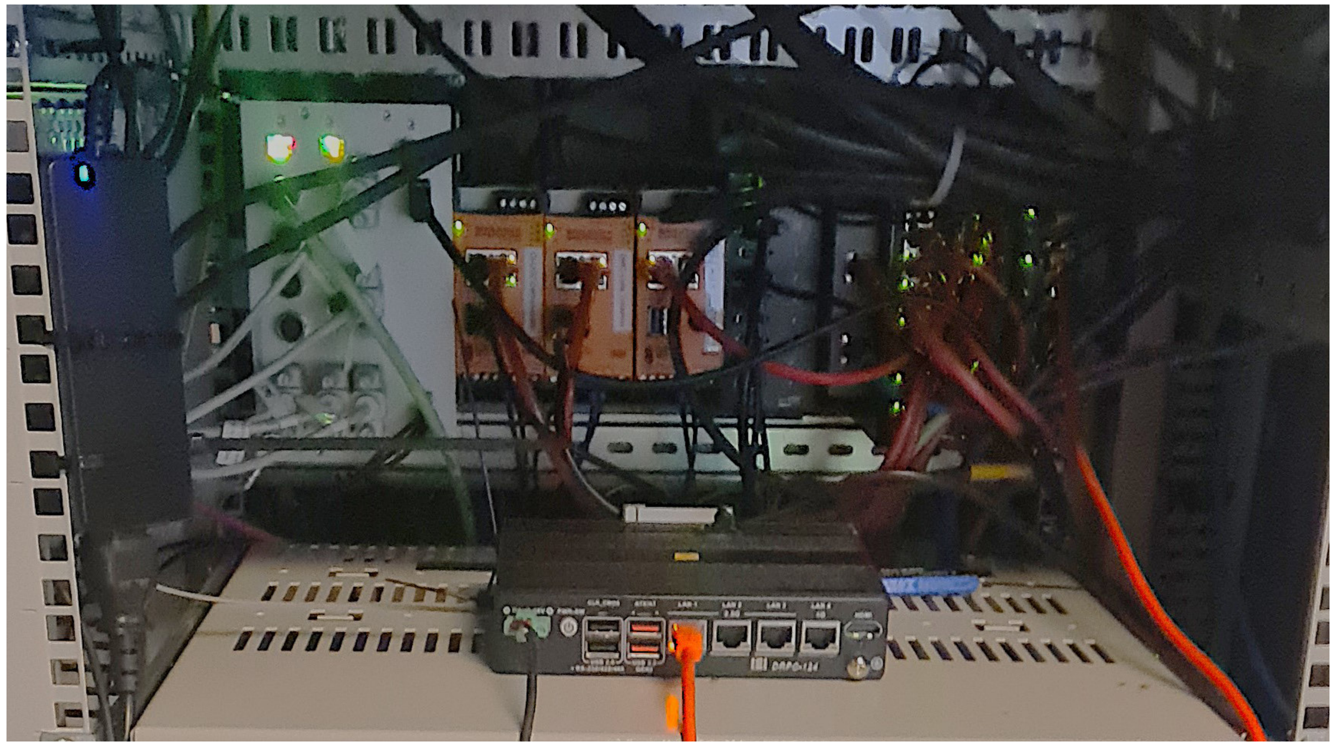

Figure 6 – On-Board Demonstrator installation on RE450

LOC-OB performance, but also for further algorithm development and for investigating specific cases.

In addition to this permanent data acquisition, the demonstrator's toolchain can perform the LOC-OB sensor fusion in real time. This proves that the LOC-OB algorithms work reliably not only in post-processing but also in live operation on the train.

Finally, the integrated visualization, which is accessible both live on board the train and remotely, provides immediate feedback on system status, localization quality, and LOC-OB behavior under real conditions. This facilitates troubleshooting, verification, and communication of results to project partners and external stakeholders.

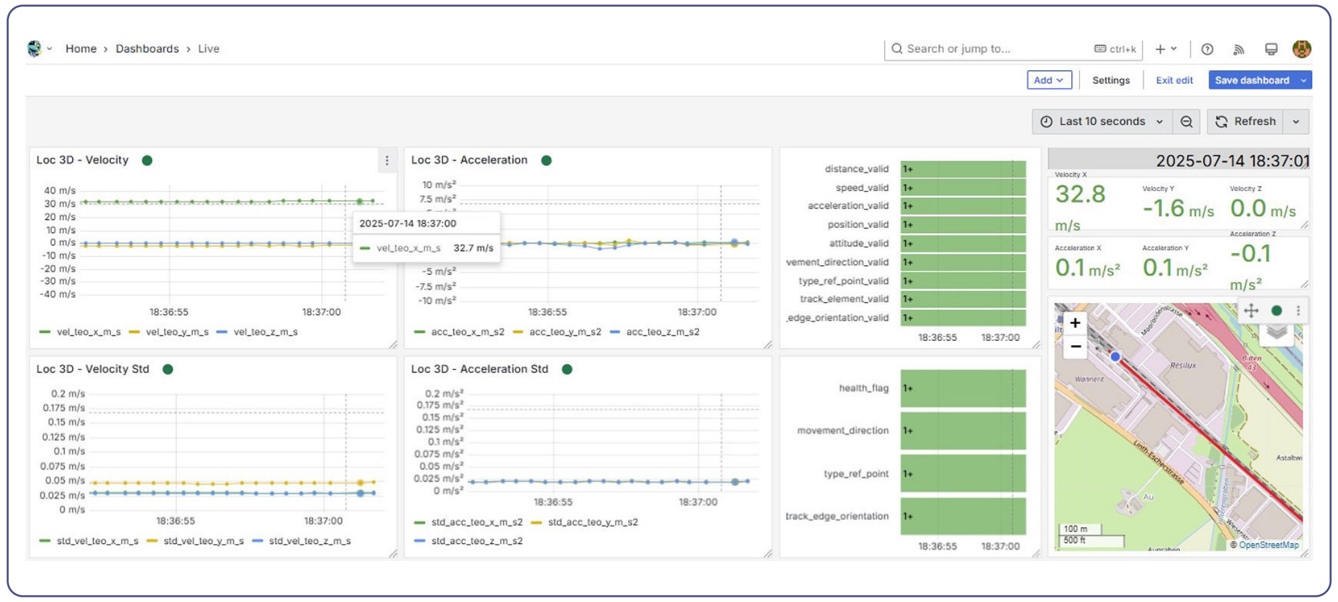

Figure 7: Live overview dashboard

In summary, the demonstrator combines the advantages of continuous, high-resolution data acquisition with the flexibility of targeted, on-demand analyses and tests. It is thus a central tool for performance evaluation, iterative further development, and practical demonstration of the LOC-OB in European railway operations.

Performance evaluation and Compliance

The evaluation of the performance of the LOC-OB algorithms on many trips and dedicated test runs shows that LOC-OB is capable of meeting the high requirements for accuracy, availability, and safety in railway operations without the use of balises. In open environments, 95–100% of measurement points are already within ±4 m, and in critical areas such as stations or switches, 50–80% are within ±1.25 m. Over 99% of speed measurements are within ±1 km/h in the range of 0–100 km/h. The confidence intervals for distance and speed also already meet the required limits in 99.8% and 94% of cases, respectively.

Of particular importance is the robustness of LOC-OB: the system remains effective even in challenging environments, such as long tunnels, urban centers, or during GNSS outages. The algorithms detect and compensate for faulty sensor data, outliers, and environmental influences. Most requirements from TSI SUBSET-041 are already met or exceeded. Some requirements beyond Subset-041, e.g., 1.25 m position accuracy in critical areas, remain challenging and are the subject of further research and optimization.

The performance evaluation also shows that the quality and validity of track data are crucial for the reliability of LOC-OB localization.

Outlook and Open Issues

The findings from WP5 form the basis for the further development of a certifiable, GNSS-based localization systems for use on the European rail network.

LOC-OB sensor fusion can be further optimized, especially in the calculation of confidence intervals and error detection. Functions such as track selectivity and initialization strategies should be tested even more intensively in real operation. Some further work will also be required to optimize performance in critical areas, such as e.g., partially covered stations, where high accuracy at stopping locations is required.

The ground truth methodology should also be standardized and further developed for future projects. This will be required if testing should be extended to different vehicles on different networks.

Open topics for future research and development also include the timeliness of map data, interfaces to infrastructure managers, the performance of the track selectivity algorithm and the definition of startup procedures.

CONCLUSIONS AND NEXT STEPS

At the end of the project and in light of the result and achievements obtained, we can conclude that the CLUG 2.0 has complied with the expectation placed at the beginning. The work performed in the different tasks during these 30 months has contributed to advance the TRL levels already achieved in the first project CLUG and the outcomes will be used by future initiatives such as FP2-R2DATO and EGNOS4RAIL to consolidate the change requests for future TSI review.

The next chapters summarizes main achievements and linked next steps.

Requirements

- A set of requirements focused on an assumption of the "certified final product" were provided by CLUG 2.0. Main discrepancies were related to the unavailability of a CCS onboard architecture and unclear functional allocation between the CCS-Onboard constituents.

- Significant effort from the sector is still needed in the requirements definition for technical and non-technical clarifications and decisions.

Architecture, safety concept & prototyping

- Two architecture variants were proposed to comply with the safety concept
  - Single chain focusing on GNSS/INS solution using EGNOS corrections to reach SIL4
  - Dual chain to relax the safety constraints on each chain, with a clear independency between the two chains

- Single chain variant was developed and tested (post-processing and demonstration) targeting the prototyping of the main components

- Dual chain was simply simulated in CLUG 2.0

- The future improvement of the prototype developed in CLUG 2.0 is an essential tasks for continuation of the activity. It must include but no limited to the development of the second chain (Shape map-matching) and the combiner for performance validation and a better characterization of the FDE to consolidate the achievable safety level and associated Confidence Interval.

Performance analysis

- The data collection campaign together with the Live demonstration of the Along track algorithms performed in CLUG 2.0 have been essential elements for the implementation of the performance analysis.

- Main conclusions of the performance analysis results are listed below
  - The LOC-OB (single chain architecture) performs adequately for its intended purpose, with most of the key requirements either fulfilled or nearing fulfilment
  - Requirements for distance at operational surrounding «Stop» defined in CLUG2 (accuracy < 1.25m and confidence interval < 10m) remain demanding
  - Even in challenging urban and mountainous environment, the LOC-OB maintains good performance in line with railway operational need

Cost Benefit analysis

The significant cost savings that implementation of LOC-OB will provide in comparation with the traditional localisation method of using odometry systems and Eurobalises is the main conclusion of the CBA performed in CLUG 2.0. The cost savings are mainly identified from the OPEX rather than CAPEX with a significant increase in the onboard/vehicle costs. Those additional costs could be fully compensated with the possibility of reducing the number of Eurobalises required and the full compensation would depend on the achieved Eurobalise reduction of the IM.

Gap analysis

Three main topics were considered in the CLUG 2.0 GAP analysis: maturity of the LOC-OB specification, maturity of the technology readiness and gap between present day ETCS and LOC-OB compatible ETCS. The need of further investigation on those topics to trigger any TSI change request due to the exitance of open issues is the main conclusion of the Gap analysis.

TOTAL PROJECT VALUE

4.17 M€

(2.87 EU)

PARTNERS

10

DURATION

30

Months

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