CLUG 2.0 Final Conference

22nd July 2025

AGENDA OF THE MEETING

AGENDA

09:30–09:35	Welcome by **J. Bertolín (UNIFE), D. Lopour (EUSPA)**
09:35–09:50	Introduction to CLUG 2.0, **J. Bertolín (UNIFE)**
09:50–10:20	LOC-OB System Definition & Requirements Specification, **A. Irvathraya (DB)**
10:20-10:50	RAMS Analysis, **M. Sarrat (SNCF)**
10:50-11:10	**Coffee Break**
11:10–12:10	Design & Development, **A. Sfeir (ADS), G. Ligorio (ADS), P. Grandjean (ADS)** • LOC-OB High level Functional architecture candidates, A. Sfeir (ADS) • Along-track localization, FDEs, Integrity and Track Selectivity, G. Ligorio (ADS) • LOC-OB sample results focusing on GNSS contributions, G. Ligorio (ADS) • Performance predictions in safe availability (true pos/speed/acc within computed CI and computed CI < Maximum/required CI), P. Grandjean / A. Sfeir (ADS)
12:10-13:10	**Lunch**

AGENDA OF THE MEETING

12:10-13:10	**Lunch**
13:10-14:10	Integration & Testing (including Site Demonstrator), **B. Stamm (SMO), N. Harnger (SMO), G. Durand (SMO)** • Scope of WP5, Cooperation with SBB on test trains and map data, data collection including test trips, B. Stamm (SMO) • Data Flow, Tools, Data Processing, Ground Truth, N. Harnger (SMO) • Data Analysis, Results, G. Durand (SMO) • Demonstrator, B. Stamm (SMO)
14:10–15:20	CLUG 2.0 Cost-Benefit Analysis, **E. Ziese (DB)**
15:20-15:50	CLUG 2.0 Gap Analysis, **A. Gharios (SNCF)**
15:50-16:00	**Coffee Break**
16:00-16:20	Project Results, achievements and future activities, **A. Gharios (SNCF)**
16:20-16:30	Closing Remarks, **D. Lopour (EUSPA), J. Bertolín (UNIFE)**
16:30	***End***

Introduction to CLUG 2.0

J. Bertolin (UNIFE) – Coordinator

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CLUG 2.0 IN A NUTSHELL

Budget: 3.1 M€
2.87 M€ (EUSPA FUNDED)

Partners: 10

Duration: 24 months

Starting date: Feb 23

End date: ~~Jan 25~~
Extension Jul 25

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CLUG 2.0 OBJECTIVES

Develop and demonstrate absolute safe train positioning by applying the existing and future European Global Navigation Satellite System (GNSS) and the European Geostationary Navigation Overlay Service (EGNOS) and multi-sensor functionality for train localization.

The expected objectives of CLUG 2.0 are based on work performed in CLUG (along the track)

- Consolidation of user needs and system requirements (**Along Track**, Start of Mission and Track selectivity)
- Consolidation of safe localization system architecture and prototype new critical functionality
    - Track Selectivity and Safety
    - Sensor and system levels FDE algorithms
    - Confidence Intervals computation and global Integrity concept
- RAMS analysis on the consolidated functional architecture of the system.
- Live demonstration/Replay to consolidate readiness of the CLUG multi-sensor fusion algorithmsv

WP ORGANIZATION

CLUG PROJECT

WP1
Project management and coordination
Duration: M1 to M24

WP2
LOC-OB System Definition & Requirements Specification
Duration: M1 to M8

WP3
RAMS Analysis
Duration: M1 to M24

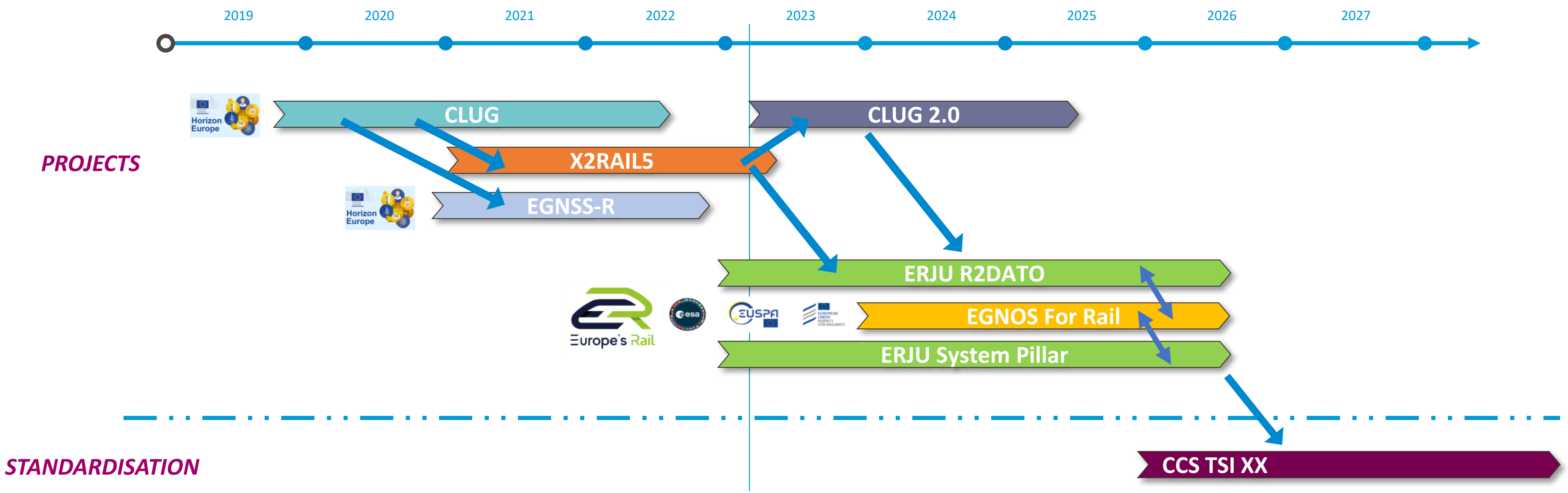
WP4
Design and Development
Duration: M1 to M24

WP5
Integration & Testing (including Site Demonstrator)
Duration: M1 to M24

WP6
Communication, Dissemination, Exploitation and Business Case
Duration: M1 to M24

CLUG REASONING & ROADMAP

- Demonstrate the feasibility of using EGNSS in rail signaling solutions (in term of operations and performance)
- Validate the critical points regarding standardization (migration, interfaces, etc)



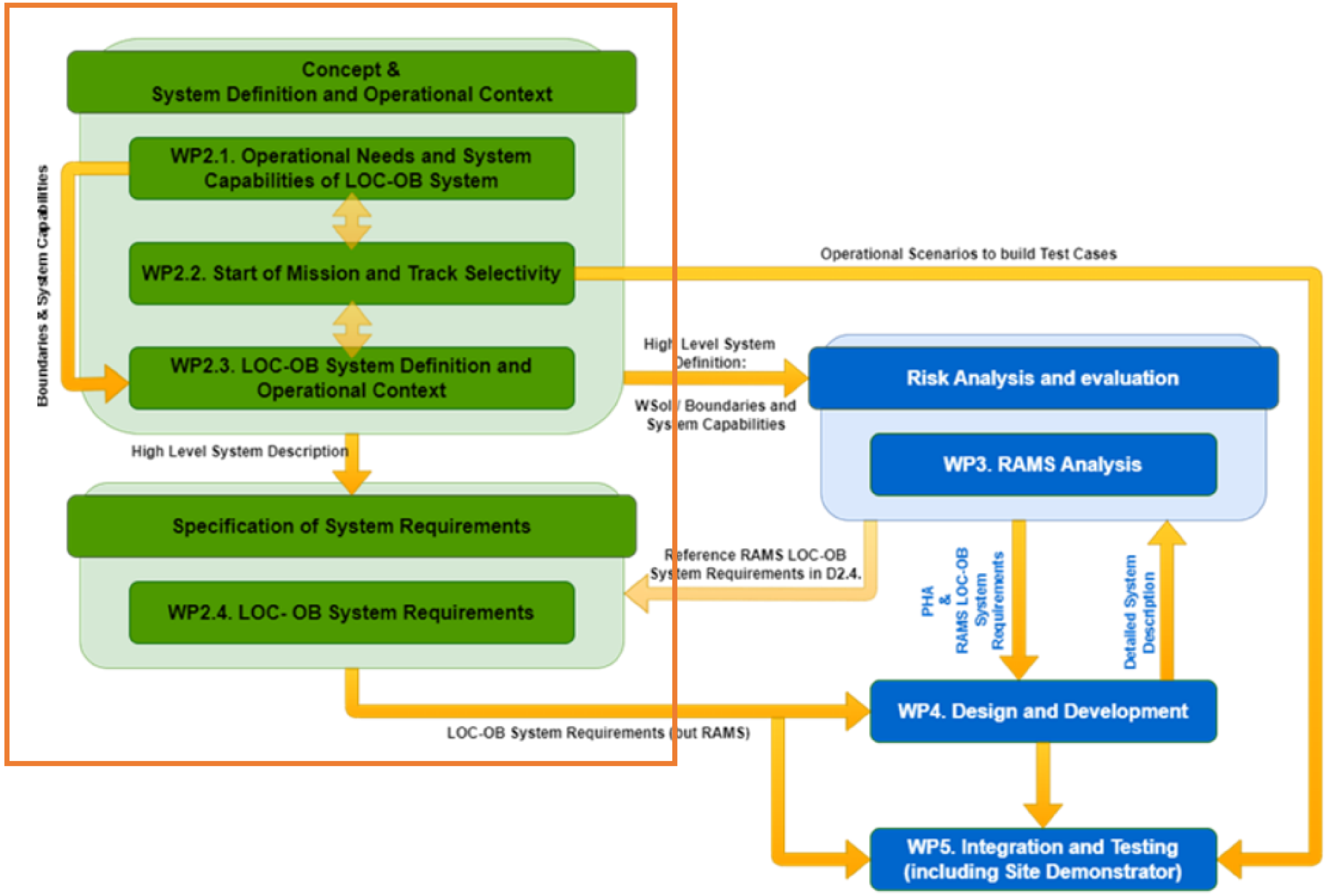
Video

CLUG 2.0 VIDEO

CLUG 2 LOC-OB System Definitions & Requirements Specification

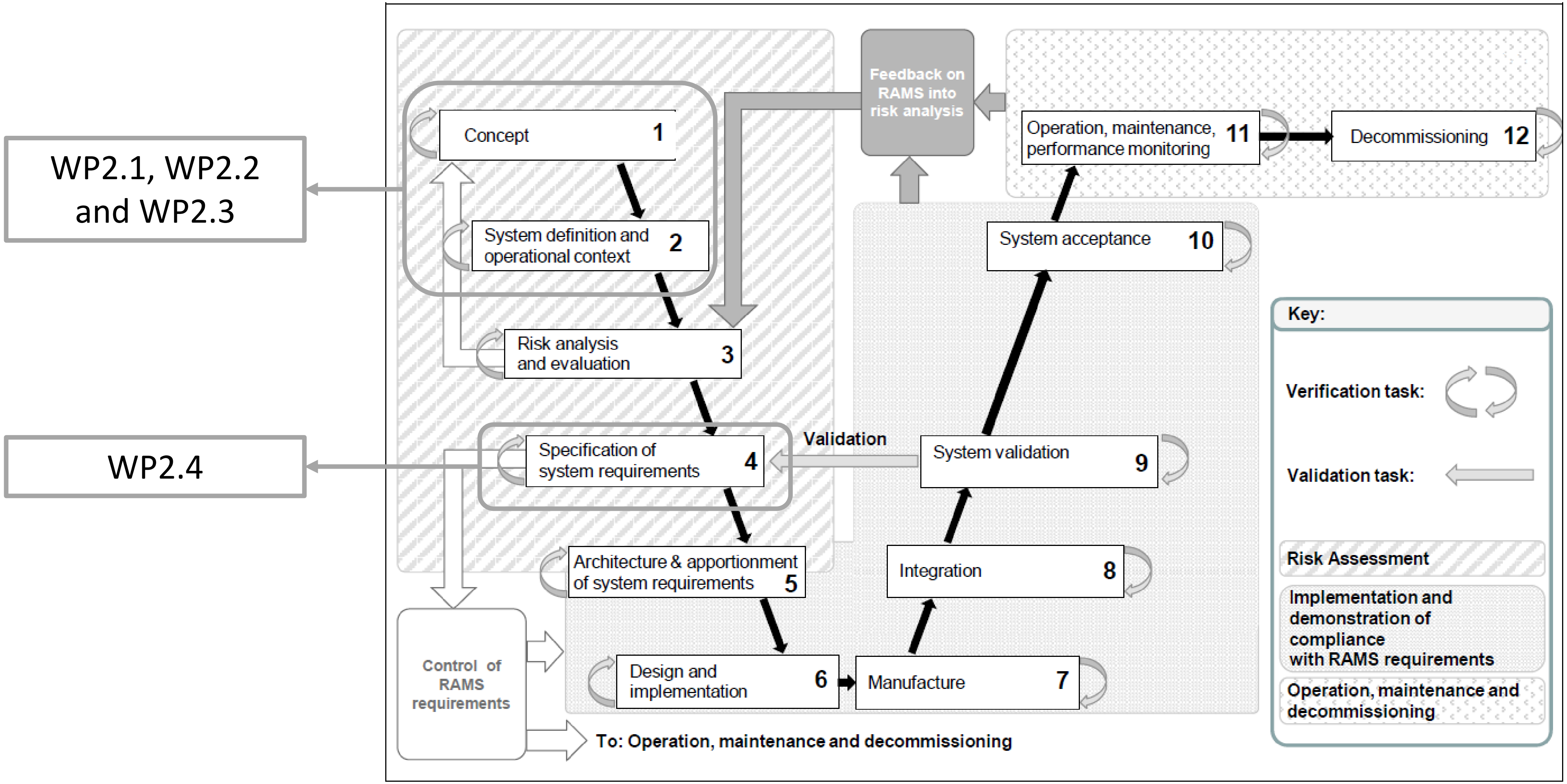
Ananthakrishna Irvathraya (DB)
Zoltan Abram (DB)

WP2 "LOC-OB System definition and Requirement specification



- Objective of WP2 is consolidating and completing the LOC-OB system definition and requirements specification.
  - WP2.1 Analyse operational needs and operational context to derive system capabilities and define high level user requirements – **In the lead DB**
  - WP2.2 Nominal and degraded operational scenarios focusing on Start of Mission and Track selectivity – **In the lead DB**
  - WP2.3 Consolidation of existing approaches (e.g. OCORA) in the definition of a system architecture – **In the lead SBB**
  - WP2.4 Set of system requirements for the on-board localisation subsystem – **In the lead SNCF**

WP2 "LOC-OB System definition and Requirement specification



WP2.1 OPERATIONAL NEEDS AND SYSTEM CAPABILITIES OF LOCALISATION ON-BOARD SYSTEM

Objective : Describe and analyse the operational scenarios in order to identify constrains and provide recommendations for the localisation on-board unit, with a particular focus on the Start of Mission and Track Selectivity

Identify the users that need localization information

↓

Identify the functions of each system in the wider system of interest

↓

Identify the operational needs

↓

Define the system capabilities to fulfill the operation needs

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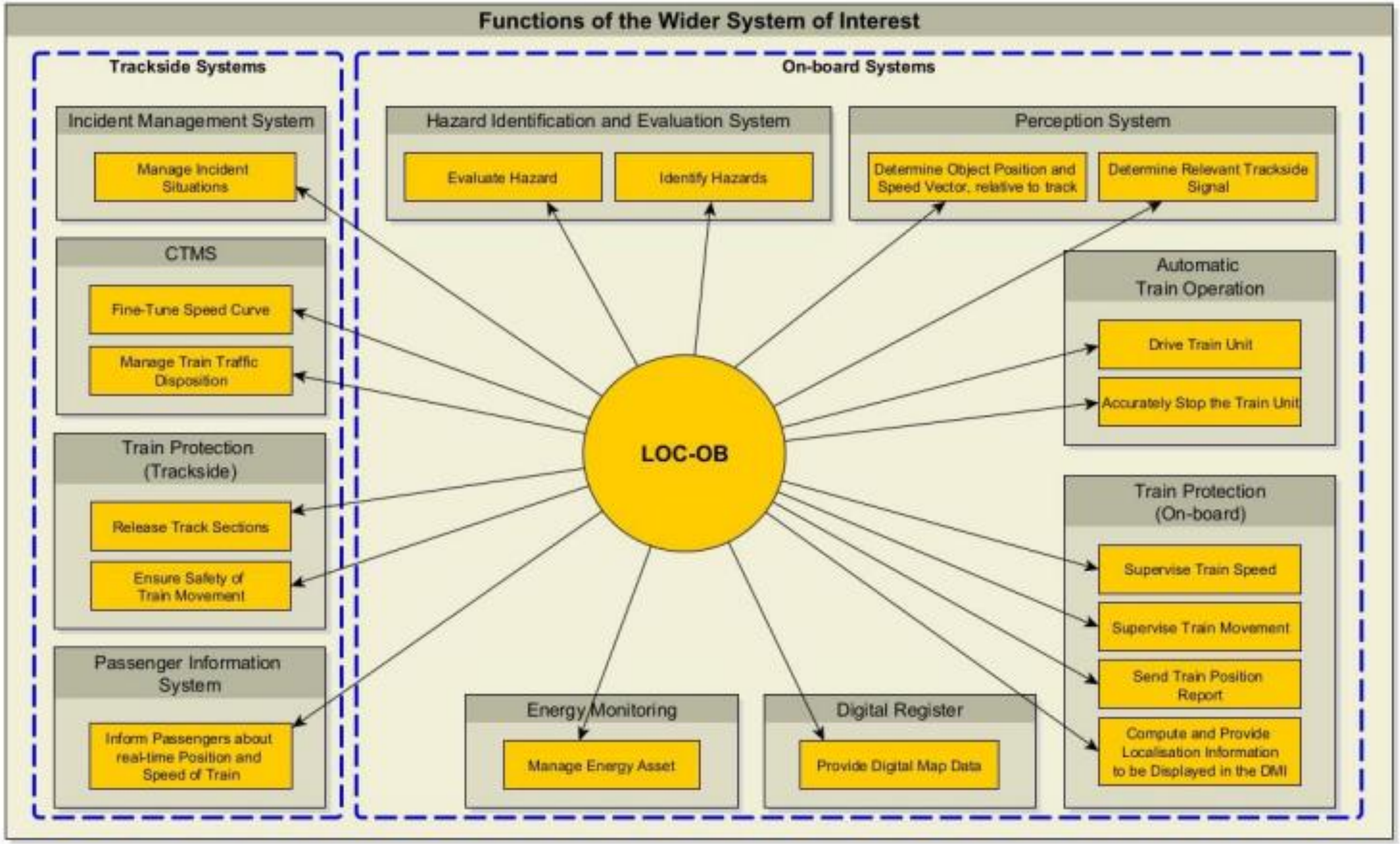
Define function and non-functional high-level user requirements

WP2.1 User Functions of Wider System of Interest



WP2.1 System capabilities and allocation to users and operational needs

System	Function	Operational Need	SysCap [1] **Provide 1D Train Front End Position**	SysCap [2] **Provide 1D Train Speed**	SysCap [3] **Provide 1D Train Acceleration**	SysCap [4] **Provide Train Movement Direction**	SysCap [6] **Provide Vehicle Attitude**	SysCap [7] **Provide 3D Position**	SysCap [8] **Provide 3D Speed**	SysCap [9] **Provide 3D Acceleration**	SysCap [10] **Provide Track Edge ID**
CTMS	**Fine-tune speed profile**	**[1]**	**x**	**x**		**x**					**x**
CTMS	**Manage Train Traffic Disposition**	**[2]**	**x**	**x**		**x**					**x**
Train Protection Trackside	**Release Track Sections**	**[3]**	**x**								**x**
Train Protection Trackside	**Ensure Safety of Train Movement**	**[4]**	**x**			**x**					
PIS	**Inform Passengers about real-time Position and Speed of Train**	**[5]**	**x**	**x**		**x**		**x**			
ATO	**Drive Train Unit**	**[6]**	**x**	**x**	**x**	**x**					**x**

SysCap [1] Provide 1D Train Front End Position

SysCap [2] Provide 1D Train Speed

SysCap [3] Provide 1D Train Acceleration

SysCap [4] Provide Train Movement Direction

SysCap [5] *Intentionally deleted*

SysCap [6] Provide Vehicle Attitude (yaw, pitch and roll)

SysCap [7] Provide 3D Position

SysCap [8] Provide 3D Speed

SysCap [9] Provide 3D Acceleration

SysCap [10] Provide Track Edge ID

WP2.1 Derive high level user requirements

Req ID	UR[001]
Requirement	LOC-OB shall provide 1D localisation information: - Acceleration (estimated, underestimation, overestimation). - Speed (estimated, underestimation, overestimation). - Position (estimated, underestimation, overestimation). - Train movement direction - Train orientation - Side of the position from/to reference location - Track Edge Id.

Req ID	UR[014]
Requirement	LOC-OB shall be designed as an independent constituent of the Control Command and Signalling On-Board (CCS-OB) with standardised interfaces.

Req ID	UR[020]
Requirement	The safety of the LOC-OB shall be ensured and demonstrated according to the Common Safety Methods [ERA CSM] and the [EN 50126] standard.

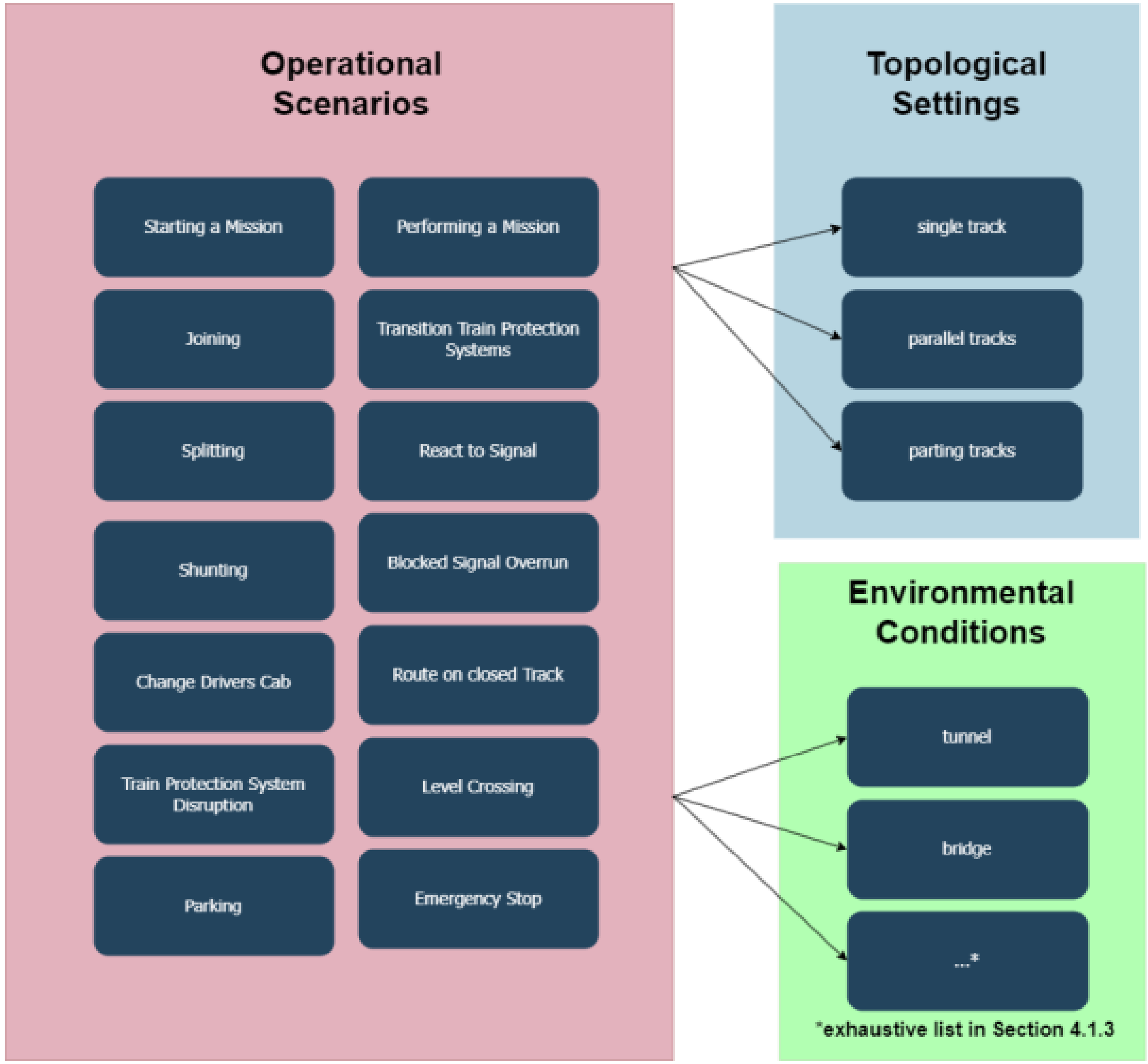
Req ID	UR[022]
Requirement	The true train position shall be always inside the confidence interval.

High-level user requirements for the localisation system were derived based on the needs of two primary railway users—Infrastructure Managers and Railway Undertakings—represented by their trackside and on-board systems.

Due to the evolving nature of certain systems and gaps in available information, key assumptions had to be made to derive the requirements.

These requirements are the basis for the system definition proposed in D2.2, D2.3 and D2.4, the system design in WP4 and evaluation in WP5.

WP2.2 Start of Mission and Track Selectivity

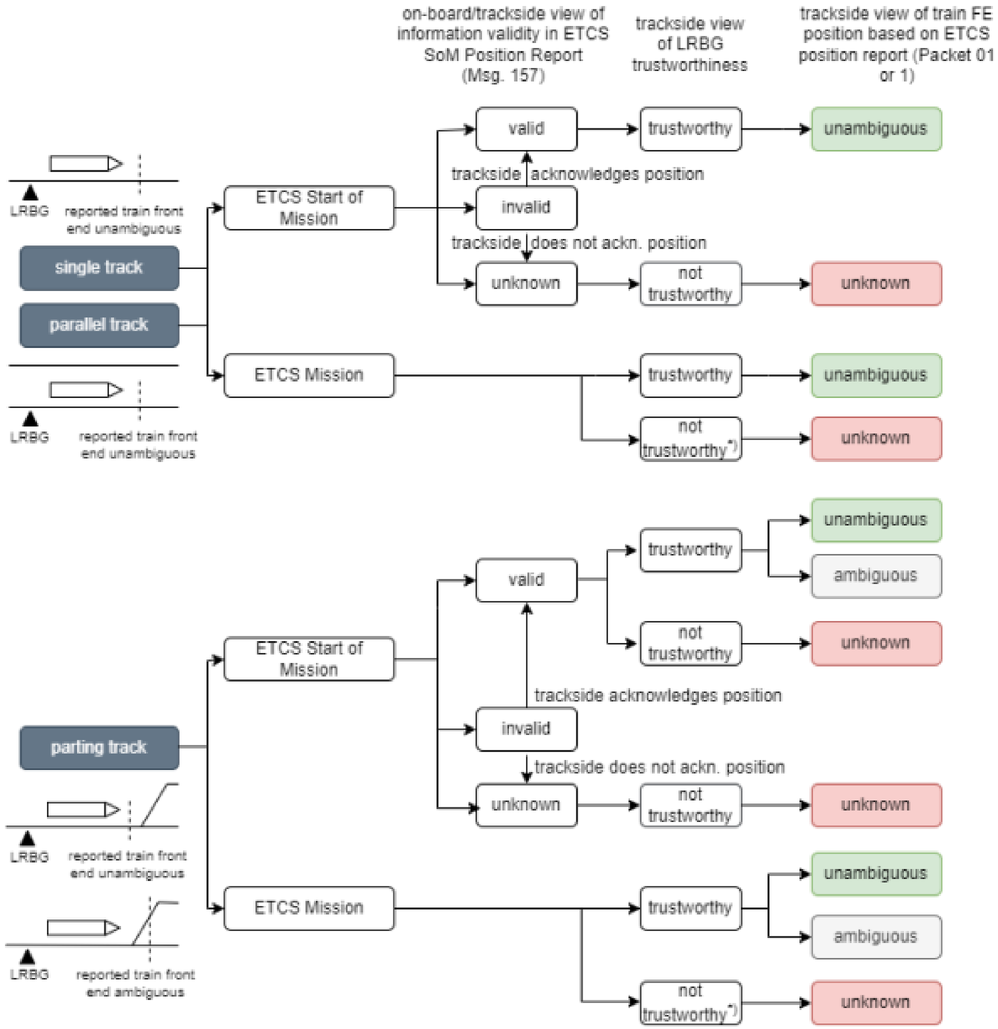


Objective : Describe and analyse the operational scenarios in order to identify constrains and provide recommendations for the localisation on-board unit, with a particular focus on the Start of Mission and Track Selectivity

- Operational scenarios in context of each Topological Setting.
- Environmental conditions considered in the context of Operational Scenarios

Consequences of performing ETCS SoM and ETCS mission in different topological setting

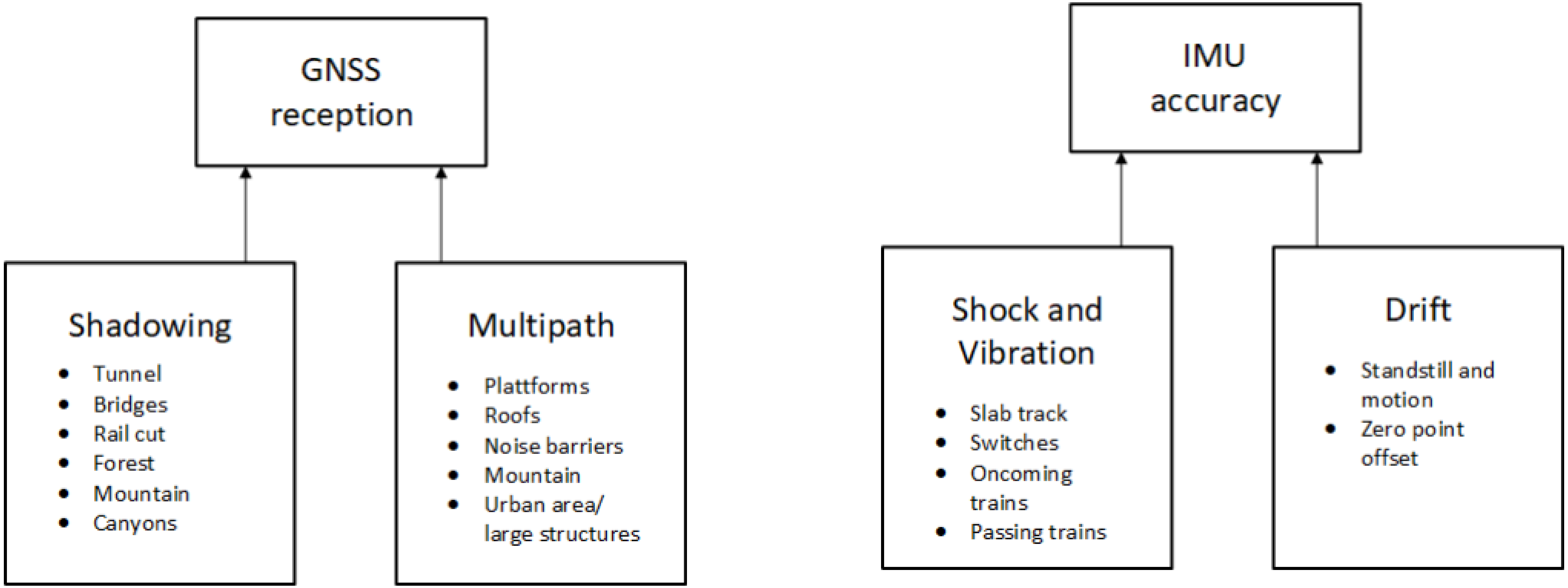
Operational scenarios in context of each Topological Setting.



Please note: not all situations and implementation possibilities are shown due to complexity and clarity reasons.

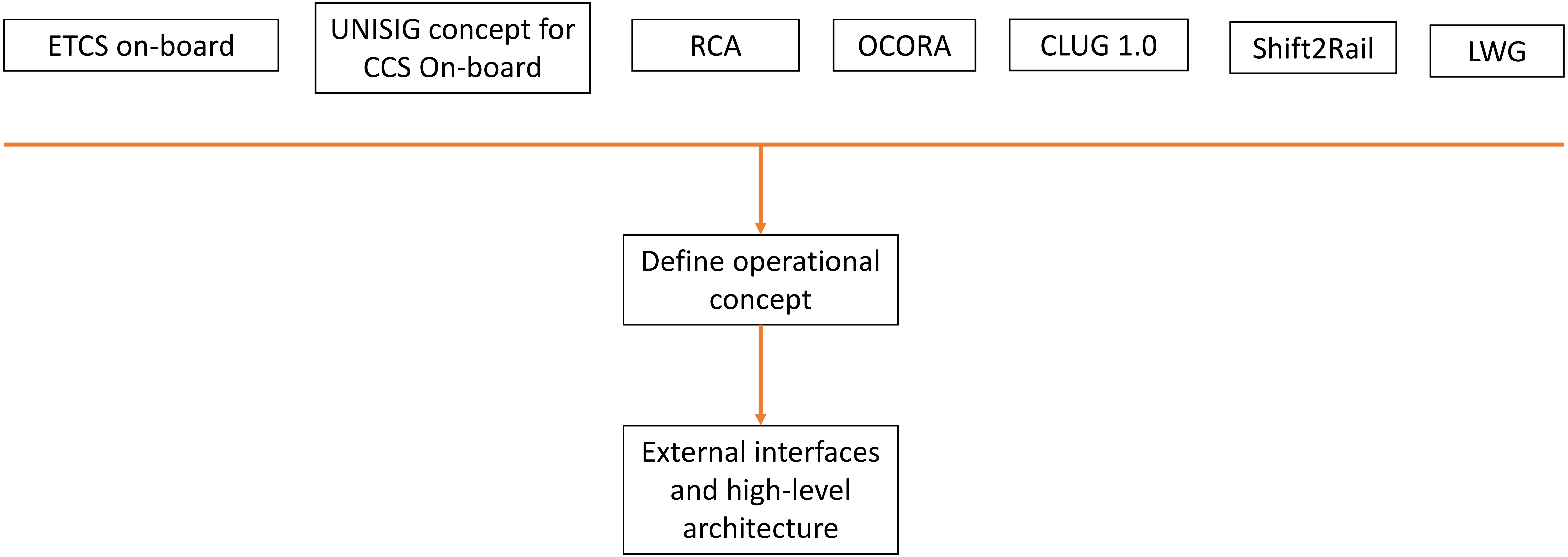
*) At the begin of an ETCS Mission an LRBG may be classified to be not trustworthy until the train passes a new BG and reports it as LRBG. Afterwards, the LRBG remains trustworthy for the rest of this mission.

WP2.2 Environment conditions



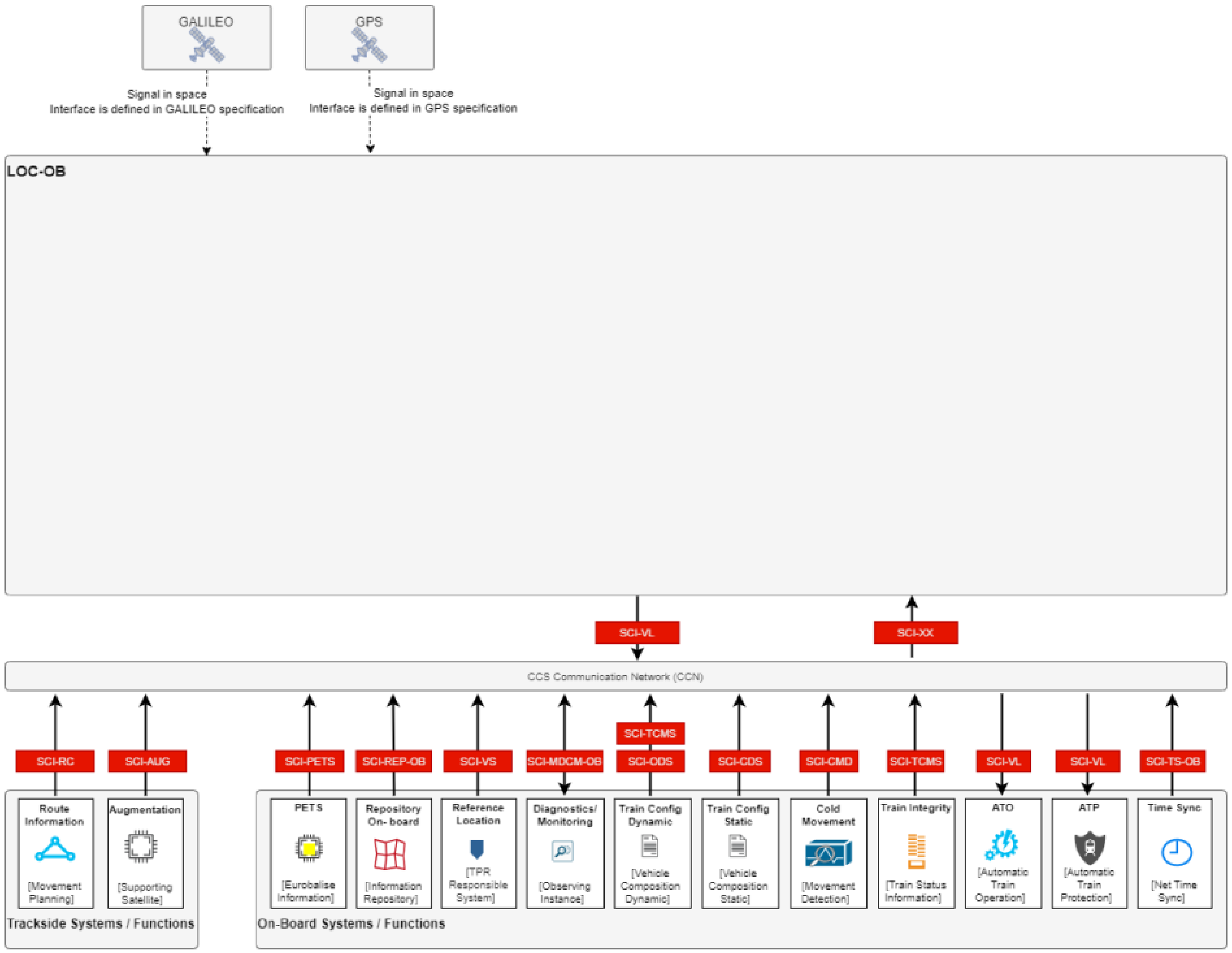
WP2.3 Localisation on-board system definition and operational context

*Objective : Define an **interoperable**, **interchangeable** and **upgradeable** architecture of LOC-OB and the interfaces to the CCS-OB system.*



WP2.3 External Interfaces

- Input interfaces from external systems: LOC-OB receives information through these interfaces.
- Output interfaces to external systems: LOC-OB provides output information through these interfaces.
- Bidirectional interfaces from and to external systems: LOC-OB receives and provides information through these interfaces



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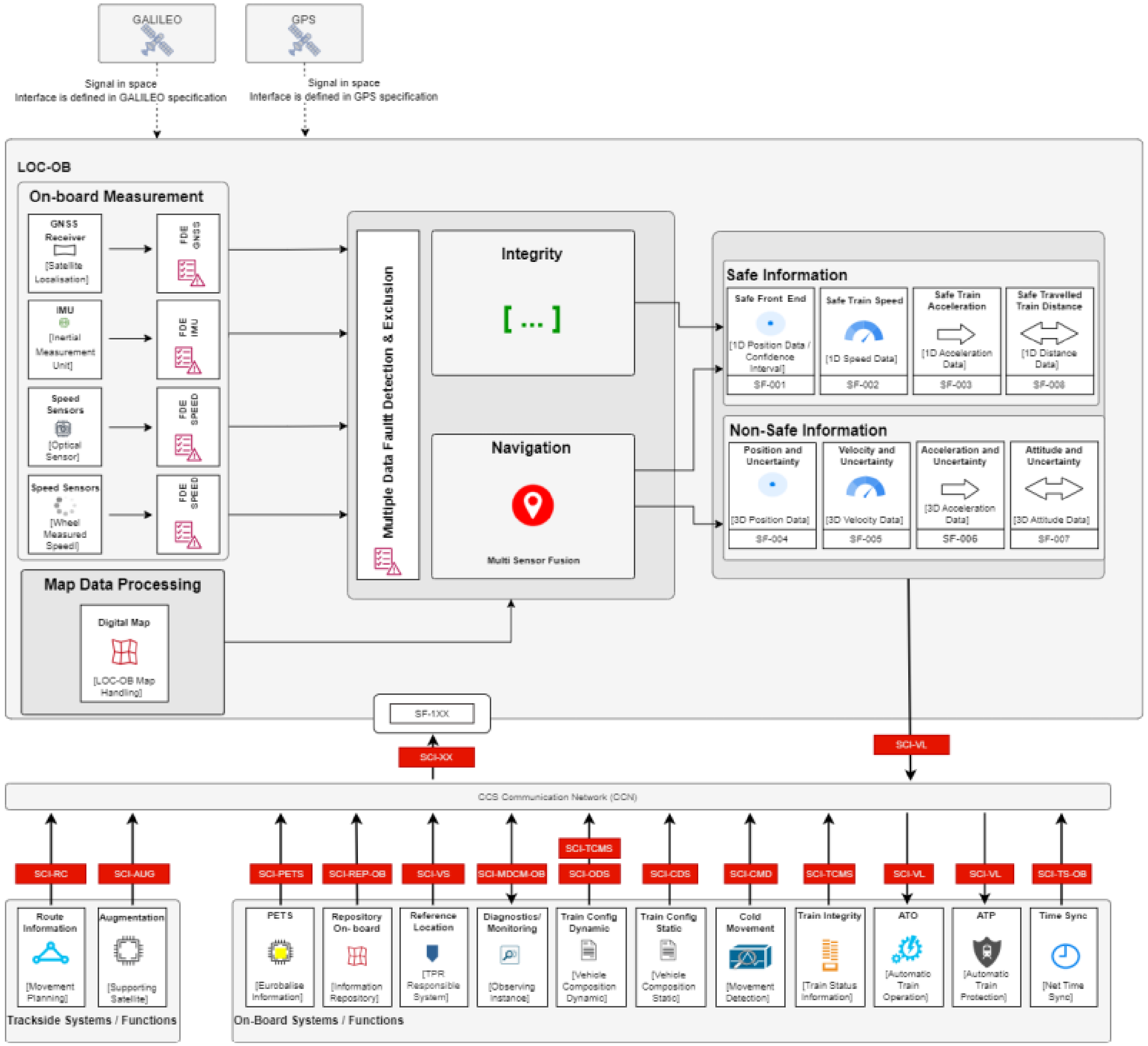
WP2.3 Complete structure of LOC-OB

- The clustered functionalities, such as on-board Measurement, Integrity, Navigation, Map Data Processing, Safe and Non-Safe Information are provided as a guide and aid to enhance comprehension.

- These functionalities are not compulsory for the design or implementation of LOC-OB as a system.



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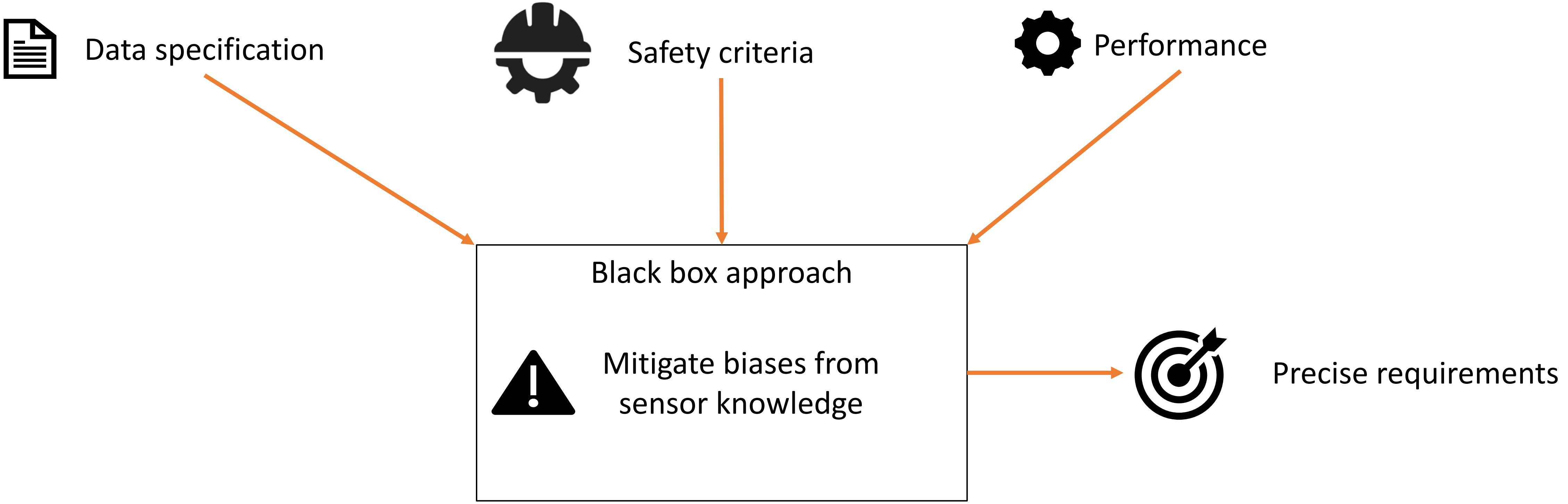
WP2.4 System Requirements of LOC-OB

Objective : Define a set of requirements of an on-board localisation equipment (final product and not a demonstrator)



WP2.4 System Requirements of LOC-OB – Usage of the defined requirements

System Requirements defined in D2.4

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Design and V&V Teams

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Feasibility Assessment

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Feedback & results

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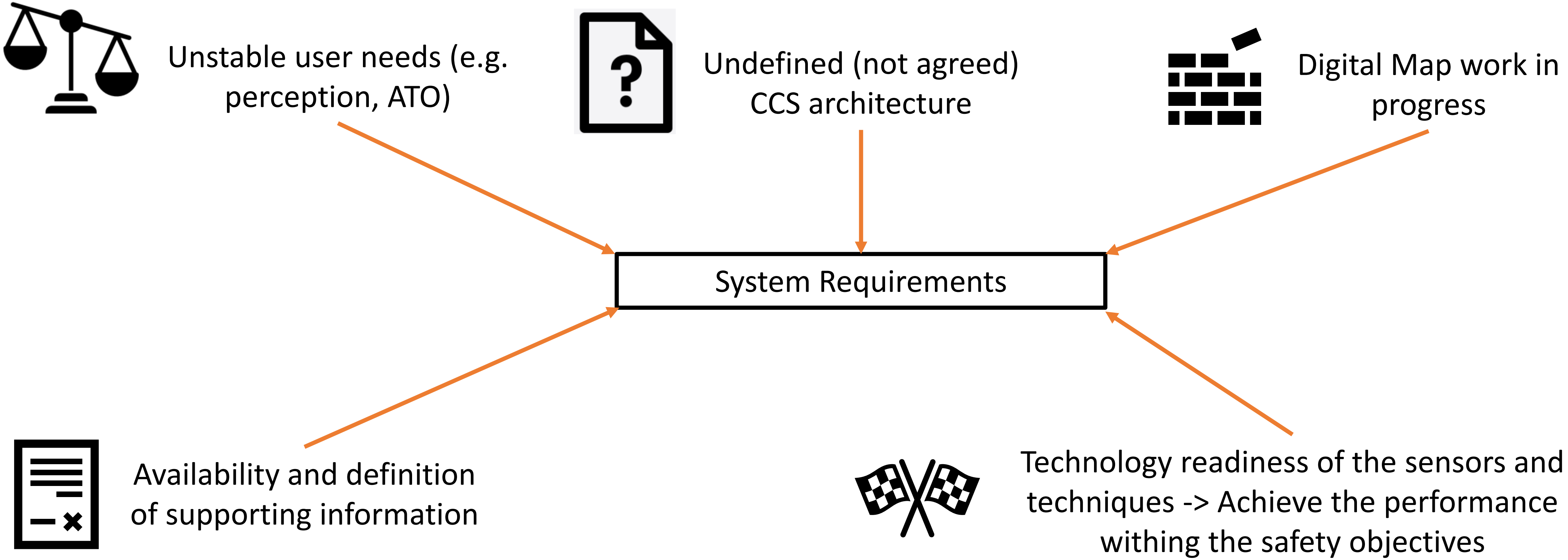
Future development of European standards

WP2.4 System requirements

Since CLUG 2.0 is a research project with uncertainties and assumptions, its current requirements are meant for a proof-of-concept and would need to be revised before use in an industrial project.



WP2.4 System requirements

DATA	Unit / resolution	Range	Safety assumption	Default invalid value
Reference location id	N/A	[0;16777214]	Safety related	16777215
Train orientation	N/A	0 Reverse 1 Nominal 2 Unknown	Safety related	Unknown
Position qualifier	N/A	0 Reverse 1 Nominal 2 Unknown	Safety related	Unknown
Estimated distance	Cm (0.01 m) / 1 cm	[0;4 294 967 294]	Safety related (used to define the max/min train safe front end)	4 294 967 295
Underestimation of the estimated distance	Cm (0.01 m) / 1 cm	[0;4 294 967 294]	Safety related	4 294 967 295
Overestimation of the estimated distance	Cm (0.01 m) / 1 cm	[0;4 294 967 294]	Safety related	4 294 967 295
Track edge id	N/A	[0;16777214]	Safety related	16777215
Validity timestamp	Depending on the selected technique (refer to SpecSysReq[034])	Depending on the selected technique (refer to SpecSysReq[034])	Safety related (safe time management)	Depending on the selected technique (refer to SpecSysReq[034])

Req ID	SpecSysReq[008]
Requirement	The 1D speed (along the track) dataset provided by LOC-OB shall include: - Movement direction - Estimated train speed - Underestimation train speed - Overestimation train speed - Validity timestamp

Req ID	SpecSysReq[072]
Requirement	If the LOC-OB is not providing data at the defined rate, the LOC-OB is considered as unavailable during this time.

- Supported the launch of a proof-of-concept campaign, with goals aligned to current performance knowledge and assumptions about localisation data safety.
- Their evaluation in WP4 and WP5 will provide valuable feedback on the feasibility of using GNSS/SBAS and IMU for safe localization, based on a subset of key WP2.4 requirements selected to demonstrate core functions and real-word potential.
- WP6 followed up with a gap analysis, contributing to other European initiatives such as R2DATO and informing future TSI definitions.
- While achieving complete requirements is a key aim, the research nature of the project means some assumptions were necessary

RAMS analysis – Activities and results

Marc SARRAT – SNCF

RAMS activities: objectives

- Specify the Reliability, Availability, Maintainability and Safety (RAMS) requirements in line with the overall SIL4 criteria of a railway embedded system to obtain a certifiable CLUG Localisation On-Board (LOC-OB) System.

- Demonstrate that the CLUG LOC-OB functional system architecture and interfaces are in line with the specified safety targets

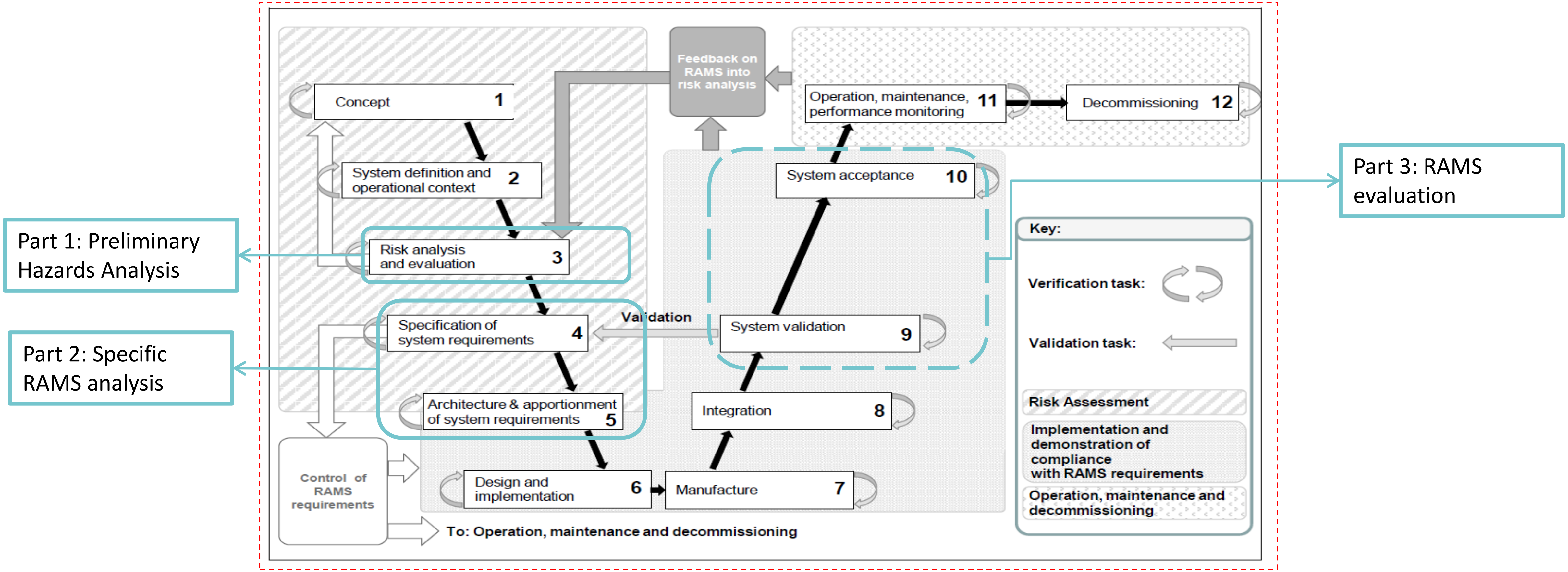
- Consolidate the remaining work to be performed to obtain a certifiable localisation unit in the future.

Description of work

Definition of work

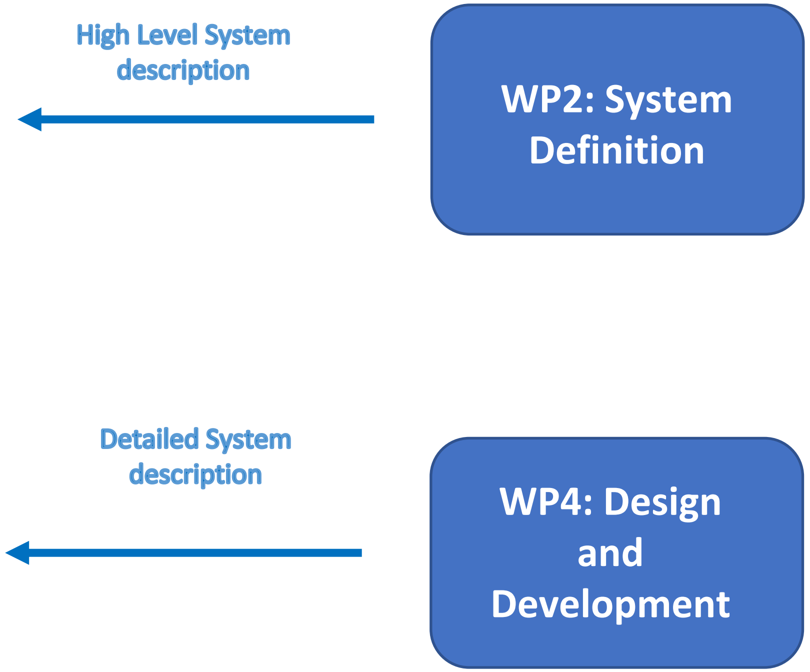
Operational context: ERTMS/ETCS with the introduction of the concept of an independent onboard vehicle localisation component

➔ RAMS activities in CLUG2 follow the recommendations of the CENELEC standards, but only partially



Definition of work

- Part 1: Preliminary Hazard Analysis
  - Identify a list of RAMS requirements on the system as a black box (from an external point of view)
- Part 2: Specific RAMS analysis
  - System Failure Modes and Effects Analysis
  - External Interface Analysis
  - System Functional Safety Analysis
  - RAM System Analysis
- Part 3: RAMS evaluation
  - Synthesis of RAMS requirements and assessment relating to WP2 and WP4
  - Way forward, remaining effort for an authorization agreement



Results

Preliminary Hazards Analysis - Results

- All functions providing 1D data shall be implemented with a SIL4 safety level
- For the functions providing 3D data, the user needs did not permit to conclude to a defined safety level.
- For several input data of the LOC-OB, a SIL4 level is expected:
  - CMD
  - BTM
  - Digital Map
  - Reference point (LRBG)

Specific RAMS Analysis – Results (1)

Architecture

- These analyses highlighted that a certifiable product based on a solution with a two chains architecture is the best solution to reach a SIL4 target for an ERTMS operational context.
- Each chain shall be designed in SIL2, using hybrid sensors. The localisation data of each chain will be then computed in a combiner
- The design of the combiner is a key point for the safety demonstrations of the system:
  - It shall be designed and validated in SIL4
  - It shall provide mechanisms to compare the results of the two chains, detecting and eliminating errors

FDE mechanisms

- The necessity of Fault Detection and Exclusion (FDE) algorithms has been highlighted to reach a high level of safety by detecting and isolating some failures on the input measurements as soon as possible.
- An exhaustive analysis of all types of failures has been performed, including proposal of detection.
- Many of these mechanisms have been implemented in the LOC-OB prototype but they need to be better characterised
- The expected THR level reached by these functions still need to be consolidated and validated

Specific RAMS Analysis – Results (2)

Need for an EGNOS for rail service

An EGNOS for Rail service is considered to improve the safety related to GNSS (considering a failure rate of 2.4 10-6 per hour).

The EGNOS service is also considered necessary to achieve the safety of FDE mechanisms on the LOC-OB system, for an architecture such as the one developed in the CLUG2 Project.

Certification of Kalman filter algorithm

The core algorithms of the CLUG2.0 demonstrator are based on fusion algorithms as Kalman filters.

SIL4 products including Kalman filter as a sub constituent already exist but the justification of such algorithm is challenging and needs to be demonstrated.

For a future industrial certifiable product, it will have to be demonstrated that the design of this function can reach a SIL2 or SIL4 level.

Specific RAMS Analysis – Results (3)

Integrity risk

A detailed quantitative analysis was performed to study if the integrity rate of the confidence interval can be reached by the combination of the results of both chains. This integrity rate is related to the size of the confidence interval, and thus the performance and accuracy of each chain.

In the architecture developed in CLUG2, the safe confidence interval provided by the combiner is the union of the confidence intervals of both chains. Thus, the probability P_safe that the train is in the output confidence interval can be deduced from those of each chain as:

P_Safe = P_Safe_A + P_Safe_B – (P_Safe_A * P_Safe_B)

It is worth noting that it is not necessary to have the same probability expected for each chain

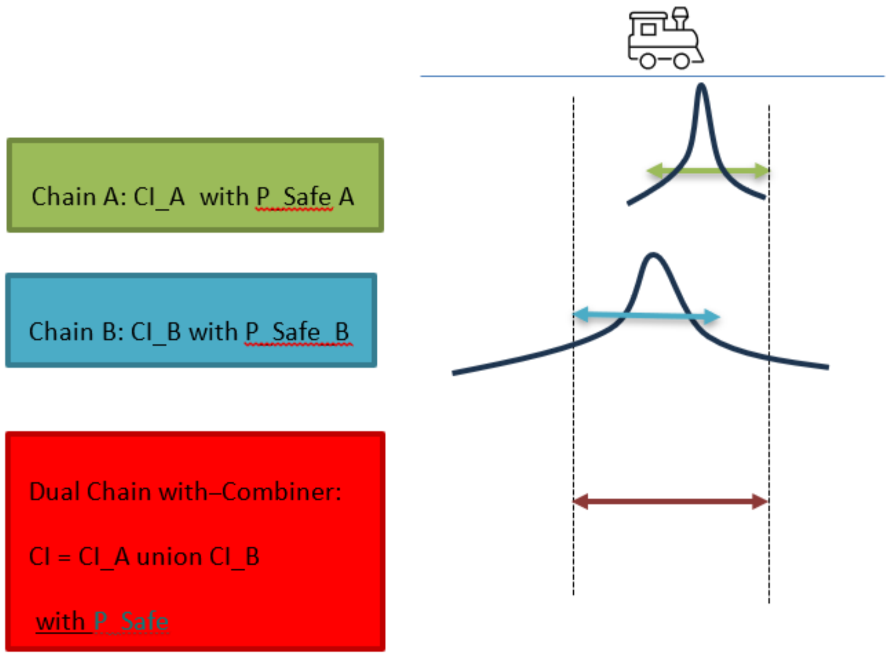


Figure 4 – Computation of the Confidence Interval for a dual chain architecture

Thus, integrity rate can be adapted for each chain to its performance to define the confidence interval.

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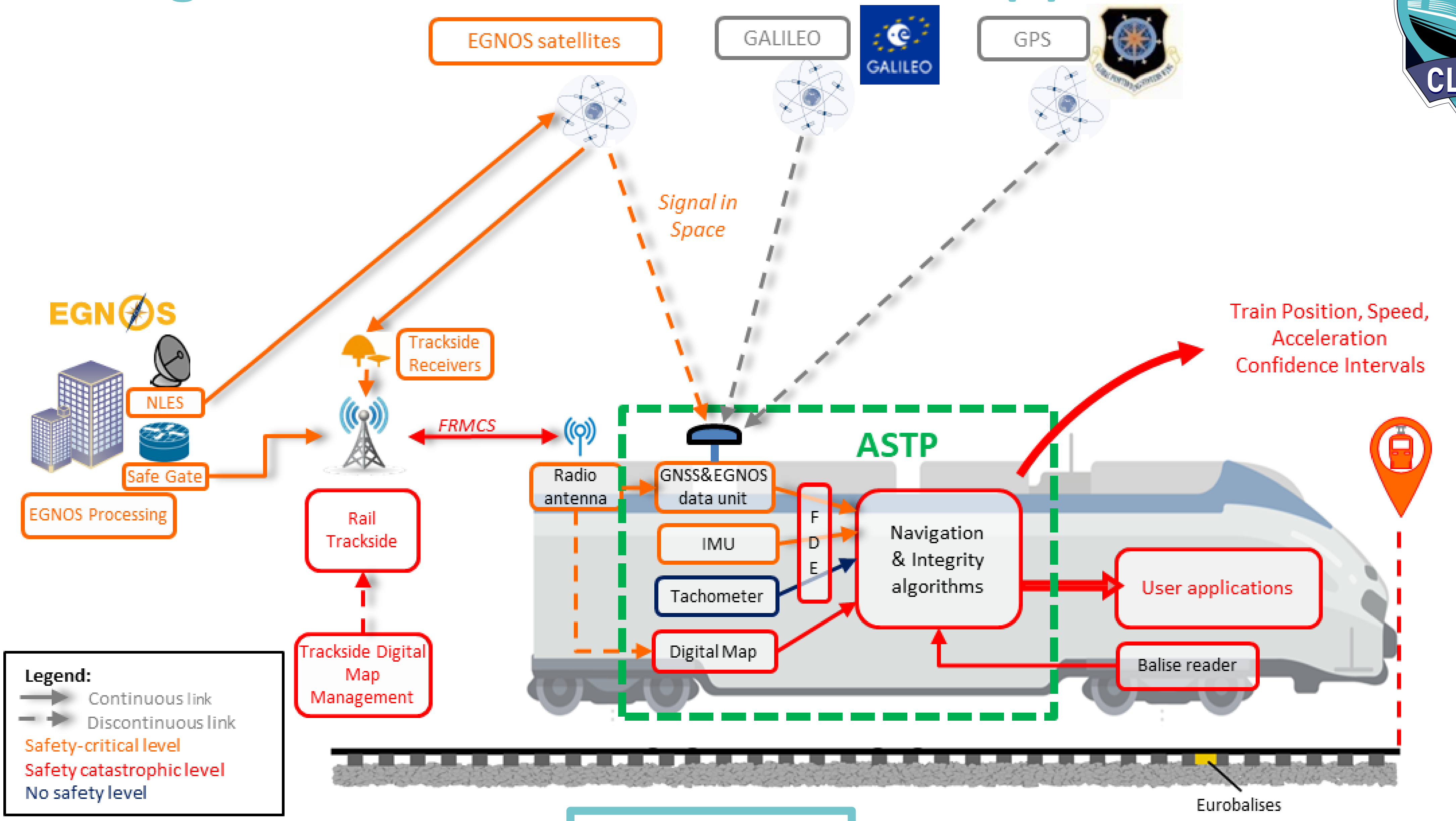
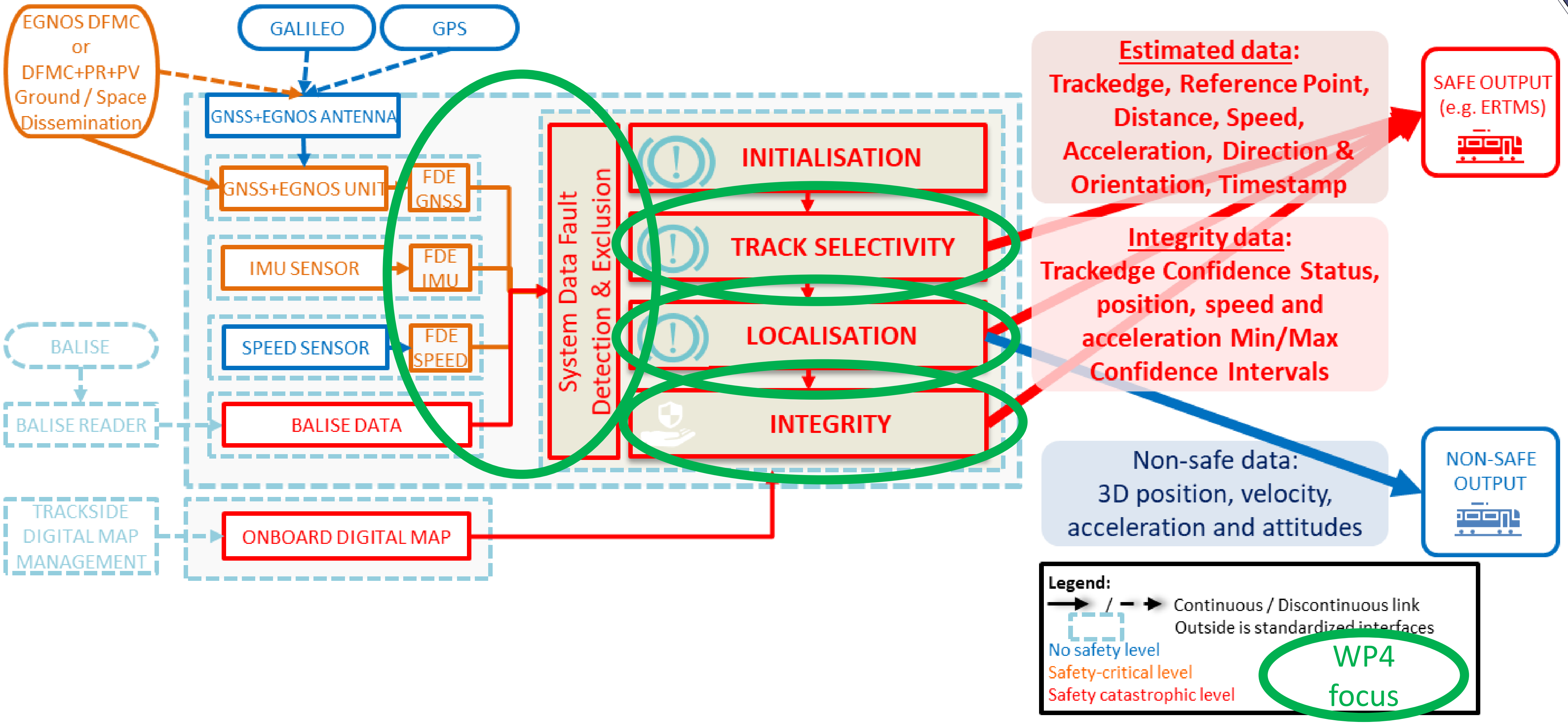
LOC-OB High level functional architecture candidates
Arnault Sfeir (Airbus)

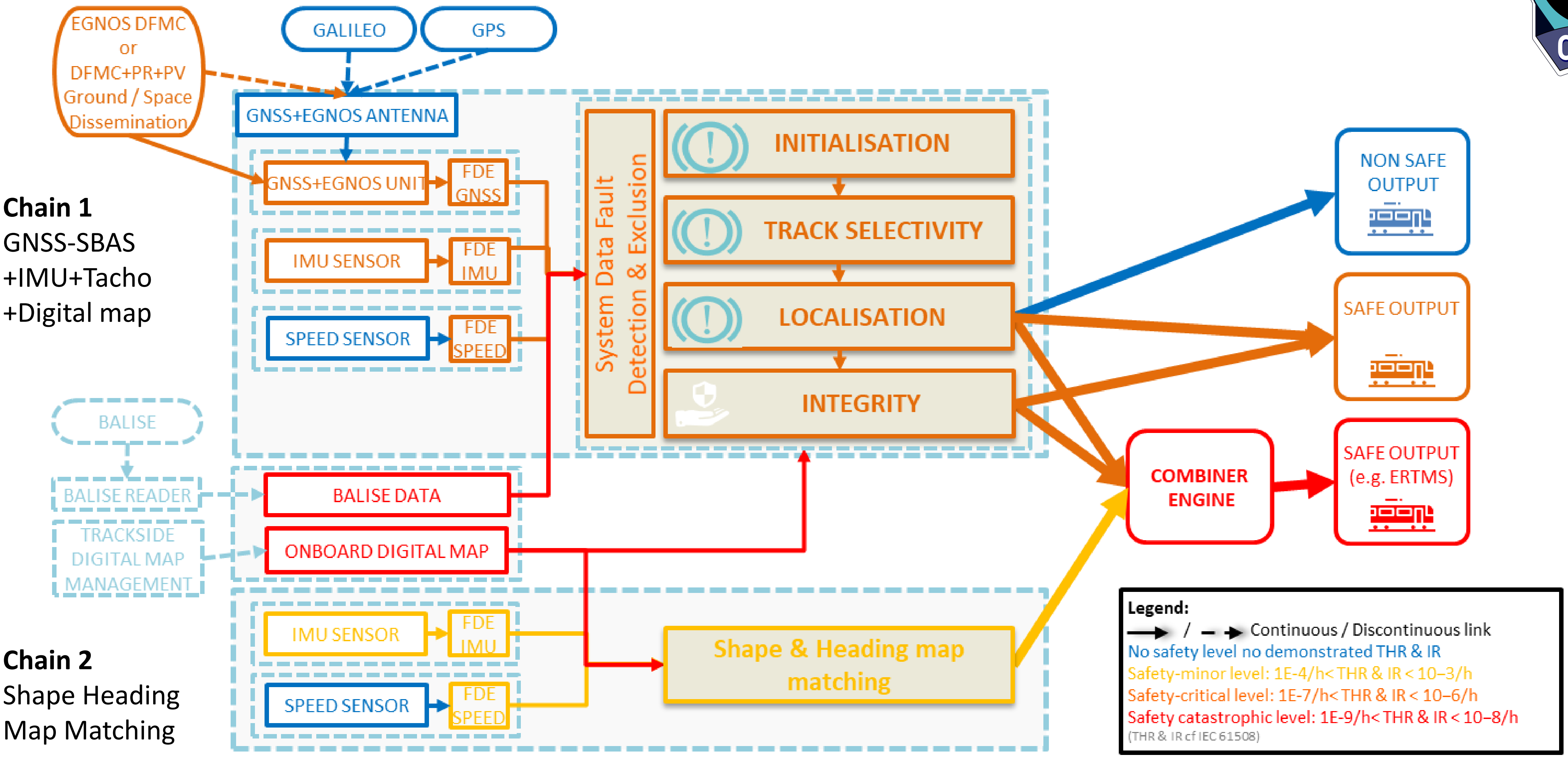
LOC-OB High level functional architecture(s)



LOC-OB single chain functional architecture



LOC-OB dual chains functional architecture



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LOC-OB single / double chain trade-off

Legend:
advantage tag: no issue preventing a product industrialization
risk tag: potential issue or warning to be monitored, deeper improved and analysed, before product industrialization
disadvantage tag: major and challenging issue preventing product industrialization

Candidates	Availability (CI<MCI)	Accuracy (estimated<x_sigma)	Computed CI Integrity Risk (Safety justification)	Industrialisation & SIL
Common to all architectures				
Digital map at SIL 4 producing outputs at IR <1E-9/h	Assumed available via initialization function	assumed accurate via periodic updates	Assumed safe: update and maintainability topic out of CLUG2 scope	Industrialisation de-risked by CLUG 2.0 prototype and experimentation; SIL 4 development: feasible as only in/out accesses to a data file (not a complex SW) and already similar maps exist in SIL 4

LOC-OB single / double chain trade-off

Candidates	Availability (CI<MCI)	Accuracy (estimated<x_sigma)	Computed CI Integrity Risk (Safety justification)	Industrialisation & SIL
Optimized single GNSS chain at SIL 4				
GNSS+SBAS sensor	When GNSS denied area, IMU high grade and/or rare balises to ensure availability	Optimum thanks to tight fusion when biases are corrected (e.g. time correlation, IMU bias…)	SBAS IR<2.4E-6/h before EKF. Absolute position IR at 1E-9/h after EKF is not yet justified: 1) 1E-3 IR gap whereas only qualitative demonstration was found on how EKF “improves” inputs’ IR; 2) to study further how IMU constrained by the map contributes to absolute position.	Industrialisation de-risked by CLUG 2.0 prototype and experimentation; SIL 2 level: Rail GNSS+SBAS unit deviations from aviation MOPS receiver (under ESA studies evaluation) + Local environment to be detected by GNSS and system FDE.
IMU sensor	Continuous outputs via hot redundancy and FDE independency	Idem, Optimum thanks to tight fusion when biases are corrected (e.g. time correlation, IMU bias…)	Outputs IR <1E-6/h already exist in aviation, not yet in rail.	Industrialisation de-risked by CLUG 2.0 prototype and experimentation; SIL 2 level: IMU IR <1E-6/h already exist in aviation, not yet in rail.
Speed sensor (Tacho, radar…)	Contributes to the IMU bias corrections	Idem, Optimum thanks to tight fusion when biases are corrected (e.g. time correlation, IMU bias…)	Outputs IR <1E-6/h to be ensured via data FDE, e.g. slip & slide data FDE for tacho…, or via redundant different speed sensor outputs	Industrialisation de-risked by CLUG 2.0 prototype and experimentation; SIL 2 level: granted by a speed sensor data FDE or granted by redundant different speed sensor
Nav. & Int. engine at SIL 4, Output IR < 1E-9/h	Optimum thanks to asynchronous tight fusion that sustains some missing sensors’ outputs	Optimum thanks to tight fusion when biases are corrected (e.g. time correlation, IMU bias…)	Challenging as asynchronous and non-deterministic data fusion → Complex qualification strategy	Industrialisation de-risked by CLUG 2.0 prototype and experimentation; SIL 4 level: challenging even EKF and all algorithms are deterministic, + SIL 4 development is a priori limited to simple functions.

LOC-OB single / double chain trade-off

Candidates	Availability (CI<MCI)	Accuracy (estimated<x_sigma)	Computed CI Integrity Risk (Safety justification)	Industrialisation & SIL
Pragmatic two independent chains at SIL 4				
GNSS chain: Nav. & Int. engine at SIL 2 producing outputs at IR <1E-6/h	Optimum thanks to asynchronous tight fusion that sustains some missing sensors' outputs	Optimum thanks to tight fusion	Feasible at IR 1E-6/h following similar certification strategy as in aviation via simulations and tests in nominal and worst cases	Industrialisation de-risked by CLUG 2.0 prototype and experimentation; SIL 2 level: feasible as EKF and all algorithms are deterministic and such type of algos have been already certified at such safety level in aviation at least
IMU Shape & Heading map matching chain: engine at SIL 2 producing outputs at IR <1E-3/h	Risk of large CIs on straight track sections, that could lower global availability, even at IR<1E-3/h; not tested in CLUG2, under experimentation in ERJU/R2DATO	Anticipated less accurate than EKF, not tested in CLUG2, under experimentation in ERJU/R2DATO	Assessed feasible at IR<1E-3/h	Industrialisation de-risked by 2 prototypes in experimentation (by CAF & by SBB); SIL 2 level: no identified issue to reach such SIL level (deterministic algorithm).
combiner at SIL 4 producing outputs at IR <1E-9/h	Risk of large CIs because of 2-chains CIs union	Expected because of mean estimates from both chains(not tested in CLUG2, under experimentation in ERJU/R2DATO)	2-chain time interpolation and CIs union are similar functions already implemented in SIL 4 odometry systems	Industrialisation de-risked by ADS prototype in experimentation for ERJU/R2DATO; SIL 4 level: Feasible algorithm as simple and deterministic: 2-chain time interpolation and CIs union

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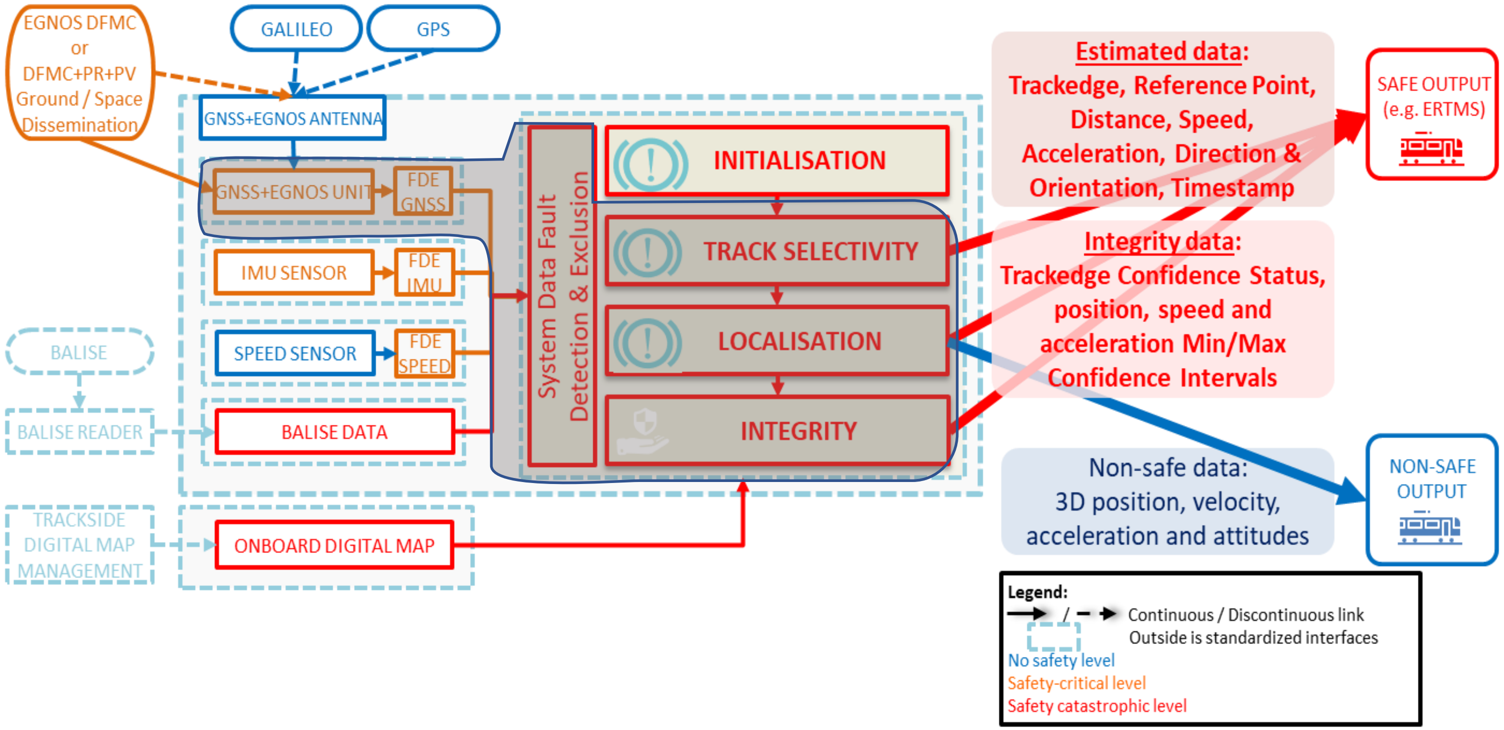
Along-track localization, FDEs, Integrity and Track Selectivity
LOC-OB sample results focusing on GNSS contributions

Gabriele Ligorio

Scope of the presentation

Part 1: Prototyped functions

Part 2: LOC-OB sample results focusing on GNSS contributions (Domino test train trip #45)



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Part 1: Prototyped functions

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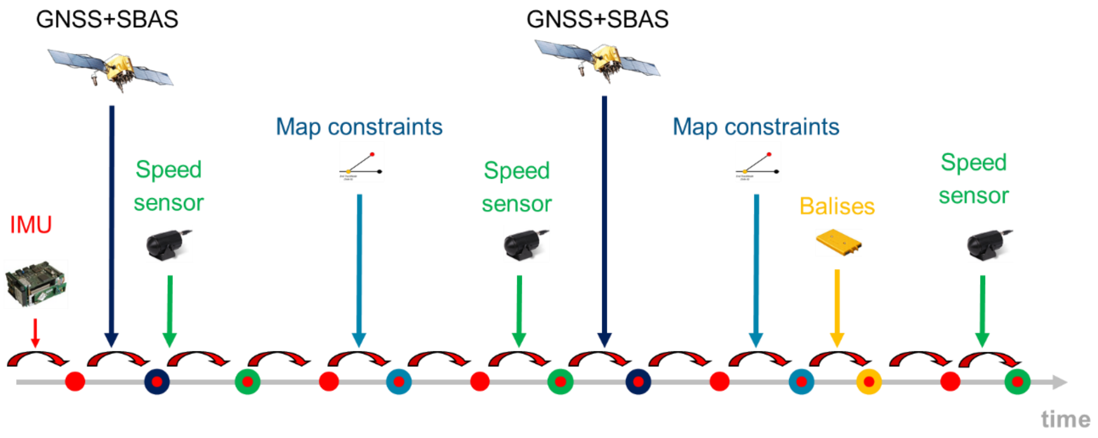
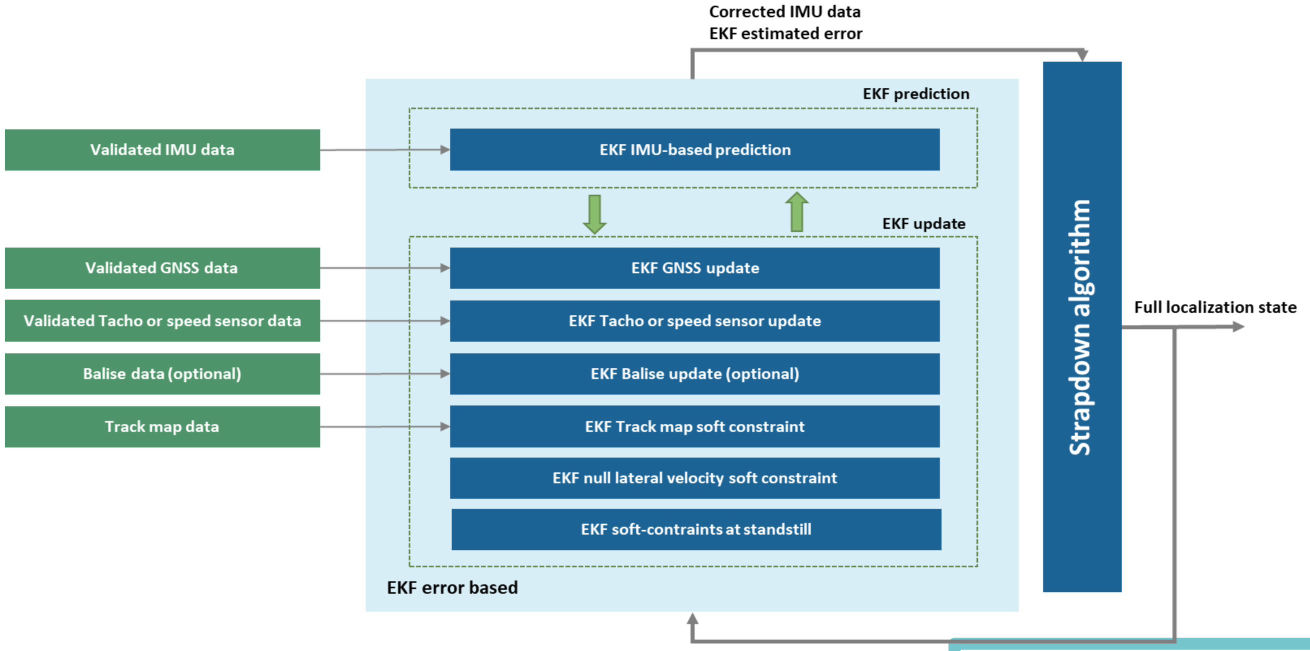
Along-track localization algorithm



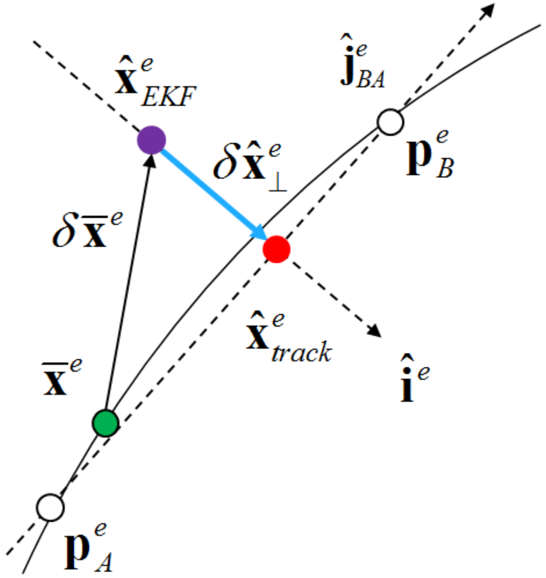


Main features

- Processing of **asynchronous flow** of heterogenous data;
- **Extended Kalman Filter** estimation framework;
- Validated GNSS, Speed sensor (e.g. tachometer), IMU input data;
- **IMU** is used for **high-rate EKF prediction**;
- **GNSS and Speed sensor** are used for **EKF update**;
- **Virtual measurements** are derived from **railways constraints** (track map, null lateral velocity, standstill)

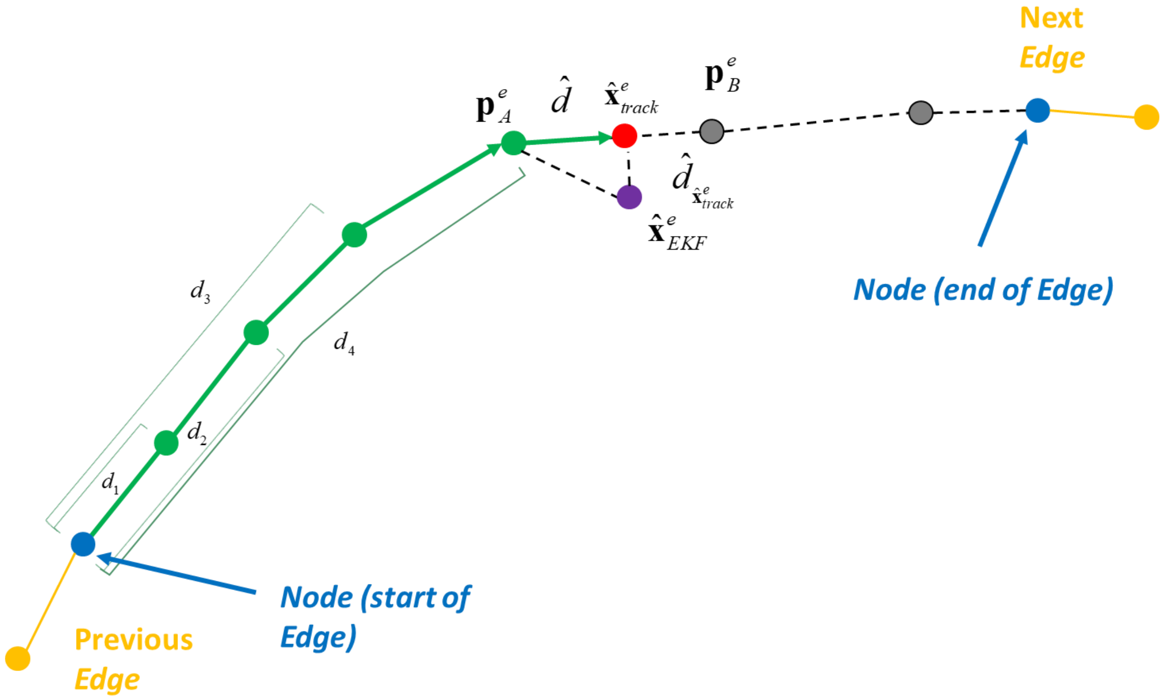
Track map exploitation

Null cross-track error constraint



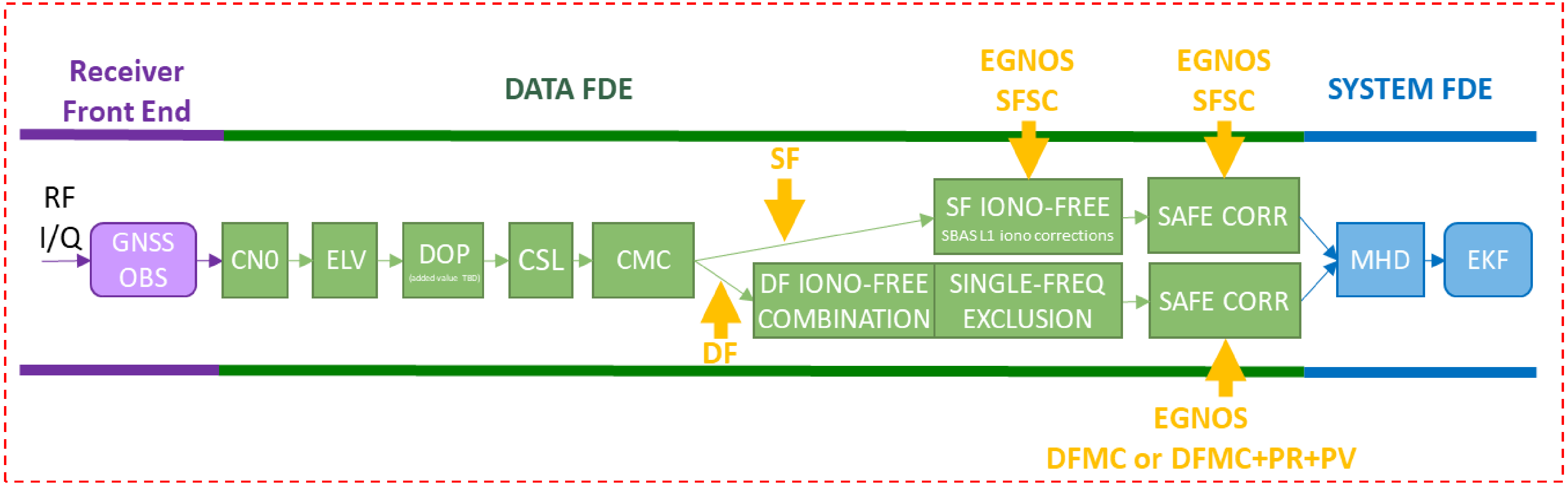
$\delta\widehat{x}^e_\perp$ can be seen as a **virtual measurement** to be used in the EKF.

From 3D localization to 1D along-track localization



The track map has a fundamental role in transforming the 3D localization output to 1D along track.

GNSS and data FDEs processing chain



- **GNSS Data FDE** acting at single line-of-sight level
  - CN0: C/N0 mask
  - ELV: Elevation mask
  - DOP: code Doppler monitoring
  - CSL: carrier cycle slip detector
  - CMC: code-minus carrier detector

- Implementation of **EGNOS SF/DFMC/DFMC+PR+PV augmentation**

- **System FDE** involving comparison with the EKF filter states.

Values of probabilities of false alarms, missdetections and thresholds set in CLUG2 are preliminary.

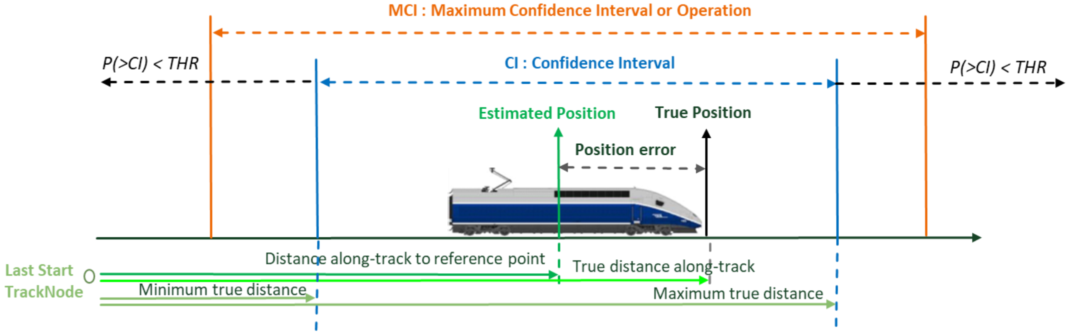
System FDE and Integrity

System FDE (GNSS/Tacho):

- **Compares expected vs observed measurements;**
- **Reject faulty** measurements based on given **Probablity of False Alarm**;
- **Provides over-bound of possible missdetections** on the distance/speed;

Confidence Interval computation

- Fault free, GNSS faults and Tacho faults are considered
- **LOC-OB output CI = max of the three CIs**
  Note: WP5 results provide fault free CI only because the GNSS and tacho faulty CIs need further analysis, development and tuning (ERJU/R2DATO)



PFA_gnss

PMD_gnss

PFA_tacho

PMD_tacho

System FDE (MHD)

If **measurement** == GNSS/Tacho

- **Update metric** for GNSS/Tacho data
- Compute **Threshold** based on **PFA**;
- **Metric > Threshold**
  - **Reject measurement;**
  - Reset metric;
- **Metric <= Threshold**
  - Update **MDF** based on **PMD**
  - Inflate slope for GNSS/Tacho

If **measurement** != GNSS Tacho

- Update (reduce) slopes for GNSS/Tacho

sigma_EKF
(from localization)

slope_gnss* MDF_gnss

Slope_tacho * MDF_tacho

Confidence Intervals (distance/speed)

CI_fault_free = k_fault_free * sigma_EKF;

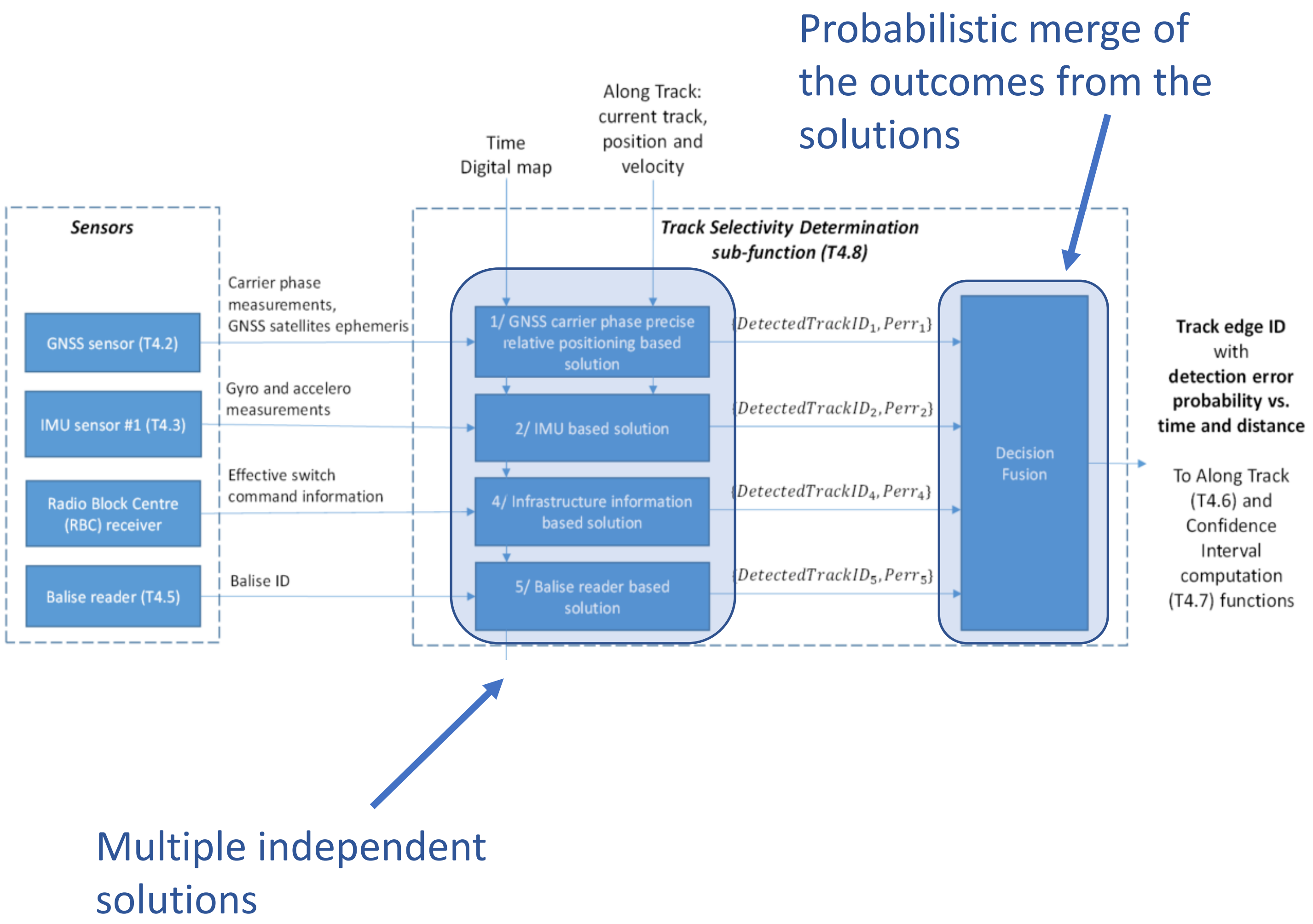
CI_fault_gnss = k_gnss * sigma_EKF + slope_gnss * MDF_gnss;

CI_fault_tacho = k_tacho * sigma_EKF + slope_tacho * MDF_tacho;

CI = max(CI_fault_free, CI_fault_gnss, CI_fault_tacho)

PFA = Prob. of false alarms
PMD = Prob. of missdetections
MDF = Minimum Detectable Fault
k_XX = inflation factor for EKF covariance, function of THR

Track selectivity



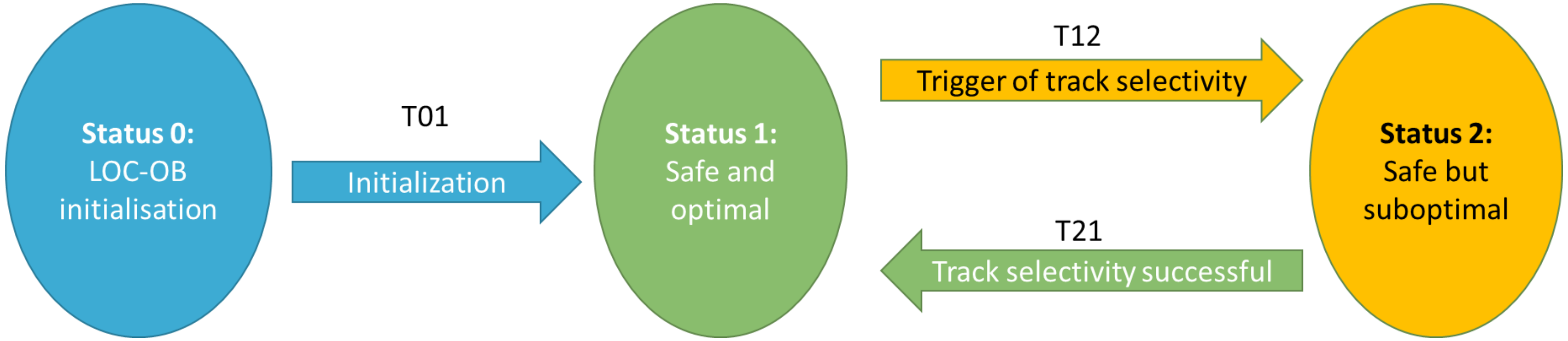
WP4

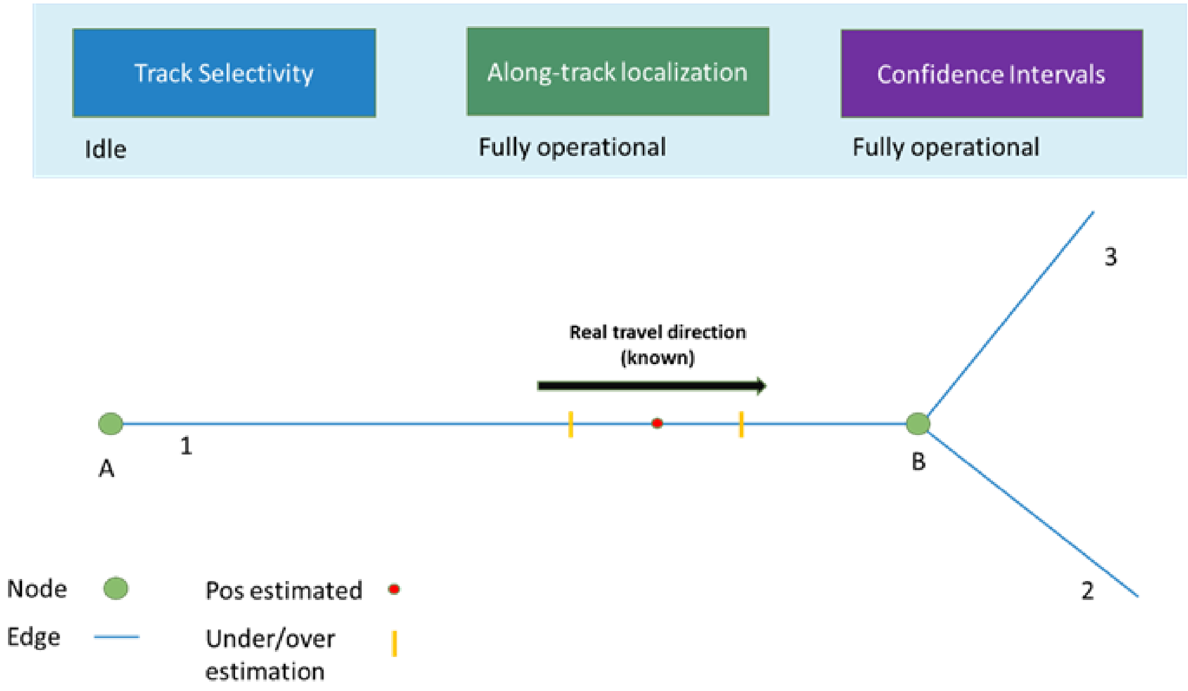
- **Solutions 1/ and 2/** fully designed and prototyped (with **Decision fusion** module)
- Solutions 1/ and 2/ estimate the new track edge by **comparing the track map with the propagated train trajectory**.
- **Architectural interactions** with along track algorithm and Integrity functions designed and prototyped

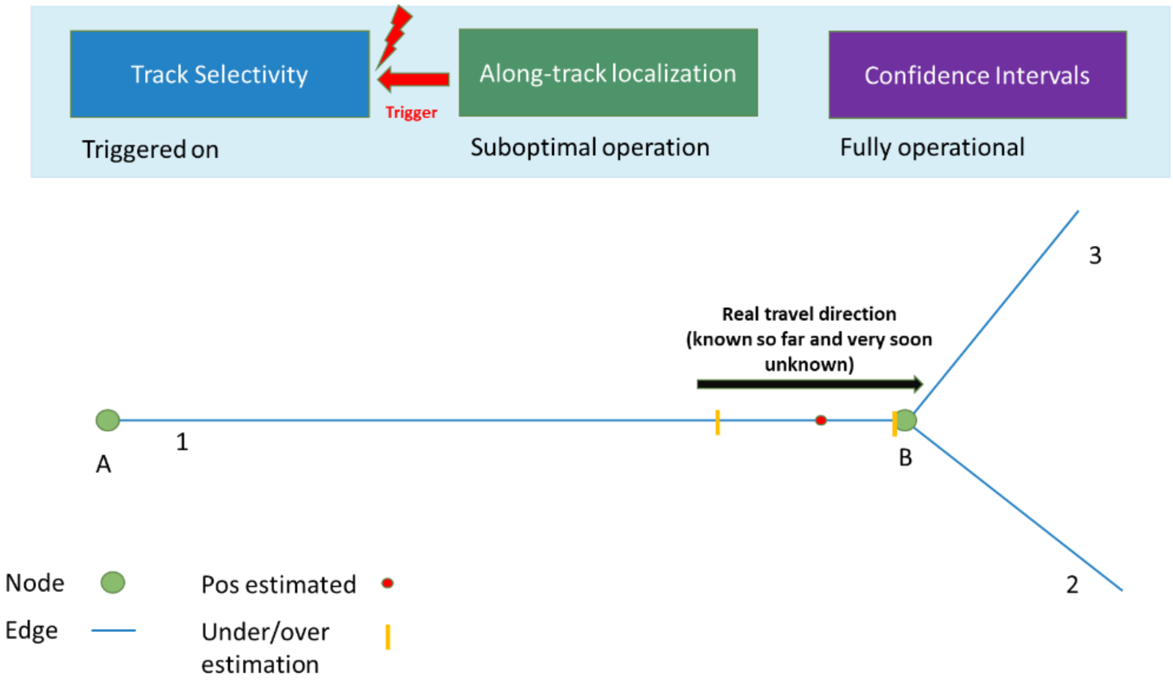
WP5

- Optional feature in CLUG2 post-processing
- Fundamental feature in CLUG2 live-demo

Track Selectivity, estimates and CIs when switching







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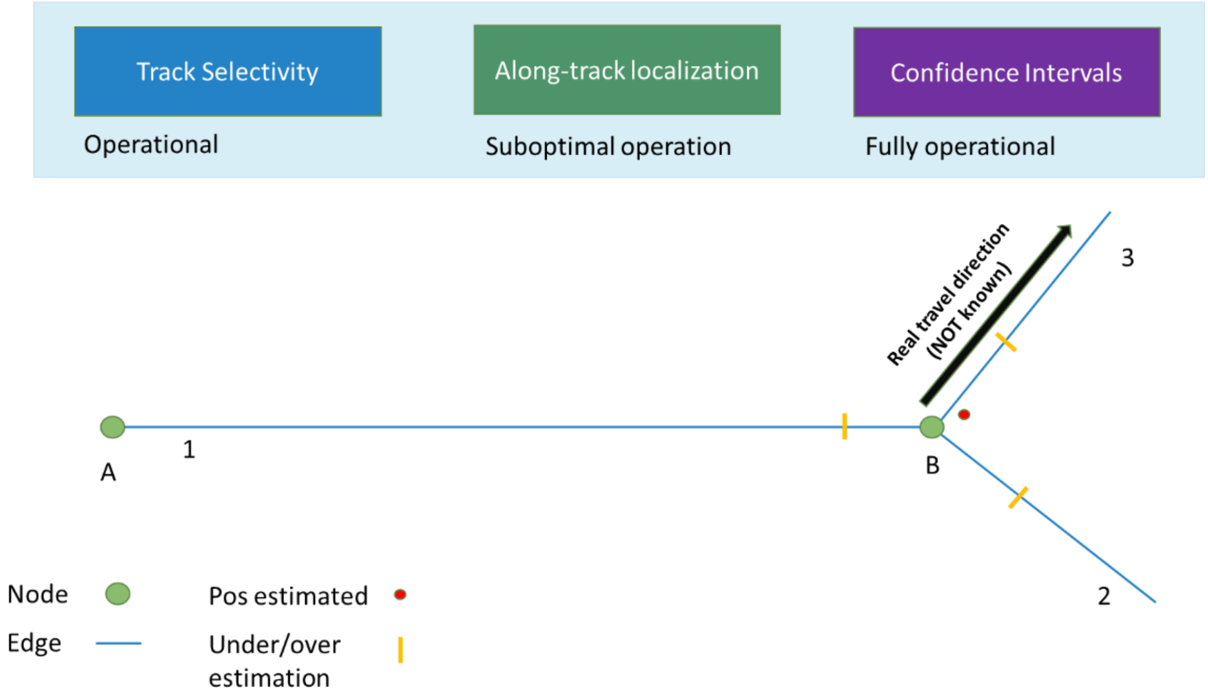
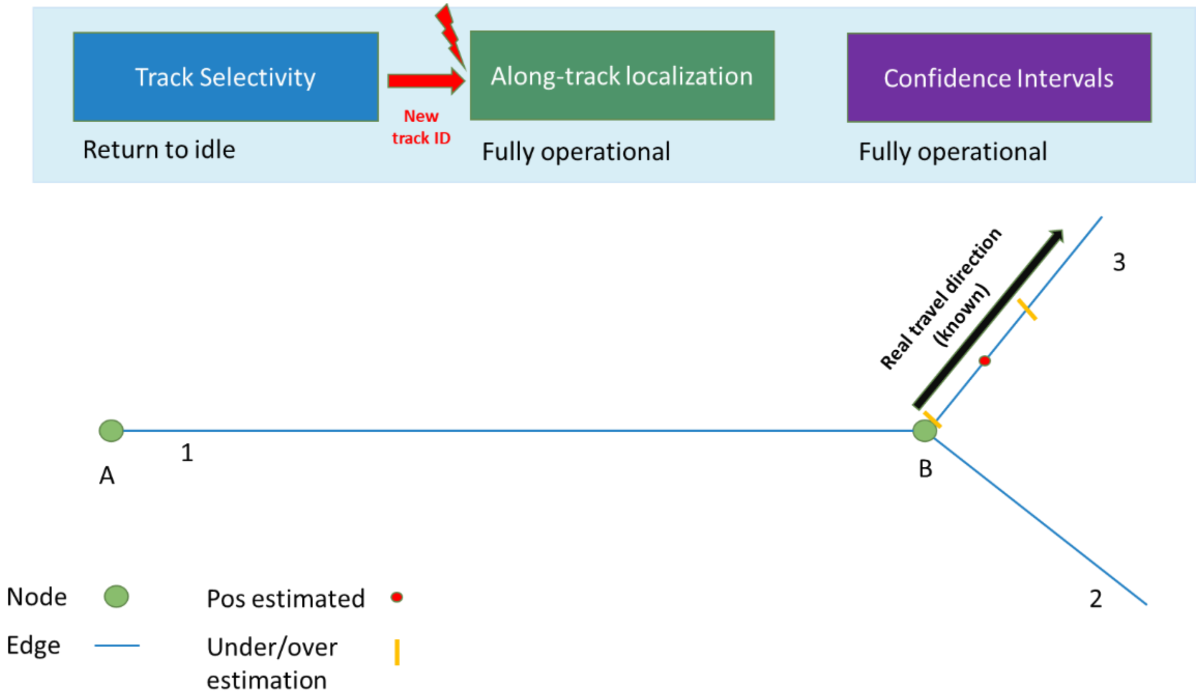
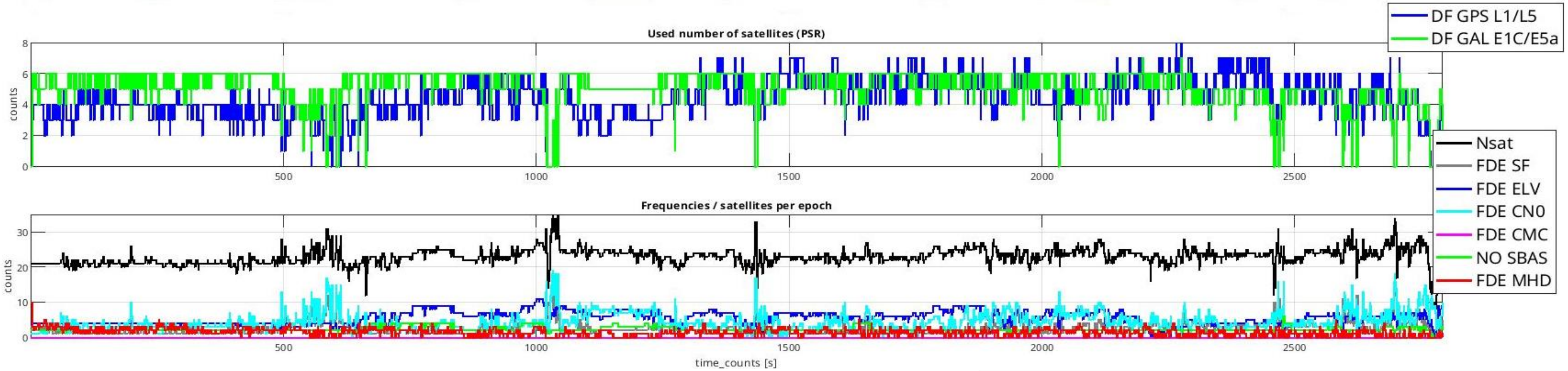
Track Selectivity, estimates and CIs when switching

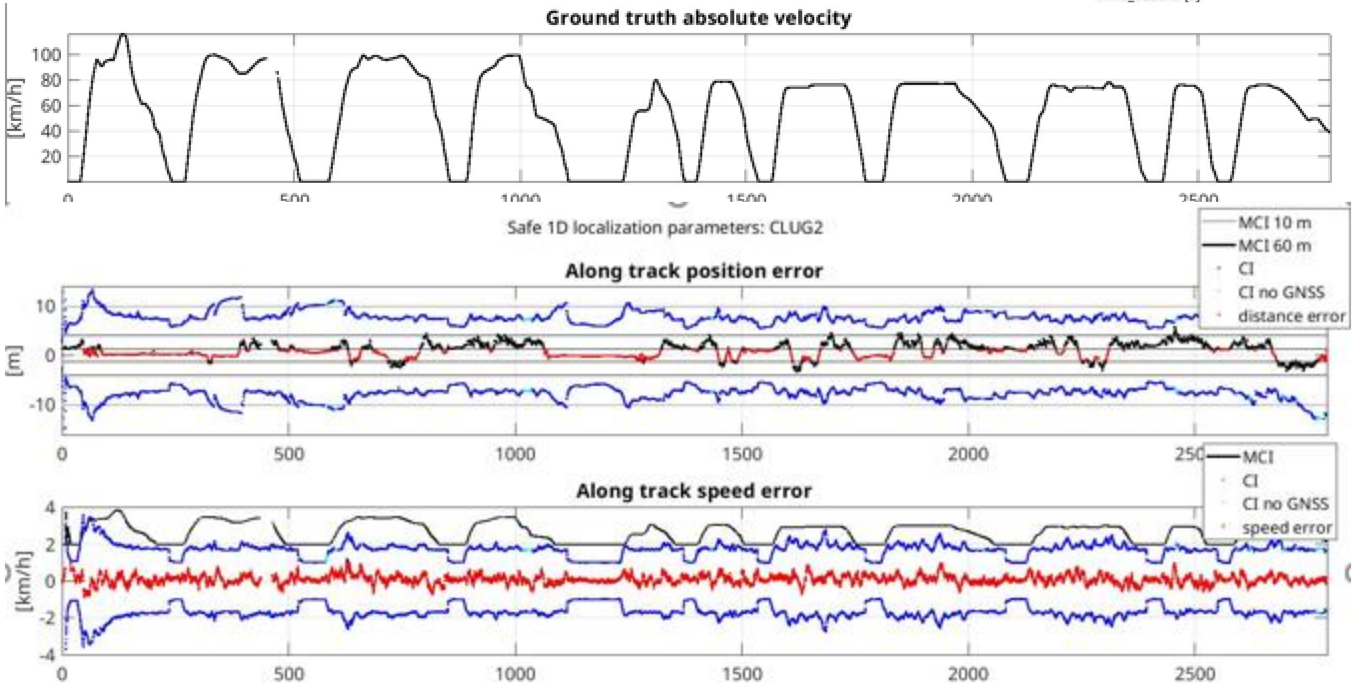




Part 2: LOC-OB sample results focusing on GNSS contributions (Domino test train trip #45)

Results on Trip#45





KPI: Safe 1D localization parameters after first 60 s	
Along track pos error mean (m)	0.93
Along track pos error 2-sigma (m)	2.98
Along track pos error inside 1.25m 95% (1s occurrences / total / %)	6651 / 13560 / 49.05
Along track pos error inside 4m 95% (1s occurrences / total / %)	13434 / 13560 / 99.07
Along track speed error mean (km/h)	0.08
Along track speed error 2-sigma (km/h)	0.48
Along track speed error inside [1 5]km/h 95% (1s occurrences / total / %)	13553 / 13560 / 99.95
Along track pos half CI mean (m)	7.88
Along track pos half CI 2-sigma (m)	2.8
Along track pos error inside CI (1s occurrences / total / %)	13560 / 13560 / 100
Along track pos CI inside 10m half-MCI 99% (1s occurrences / total / %)	12299 / 13560 / 90.7
Along track pos CI inside 60m half-MCI 99% (1s occurrences / total / %)	13560 / 13560 / 100
Along track speed half CI mean (km/h)	1.69
Along track speed half CI 2-sigma (km/h)	0.72
Along track speed error inside CI (1s occurrences / total / %)	13560 / 13560 / 100
Along track speed CI inside [2 12]km/h half-MCI 99% (1s occurrences / total / %)	13366 / 13560 / 98.57
GNSS DF GPS L1&L5 satellite (PSR) unavailability (%)	2.08
GNSS DF GAL E1&E5a satellite (PSR) unavailability (%)	2.11
Mean number of DF GPS L1&L5 satellite (PSR)	4
Standard deviation number of DF GPS L1&L5 satellite (PSR)	1
Mean number of DF GAL E1&E5a satellite (PSR)	5
Standard deviation number of DF GAL E1&E5a satellite (PSR)	1

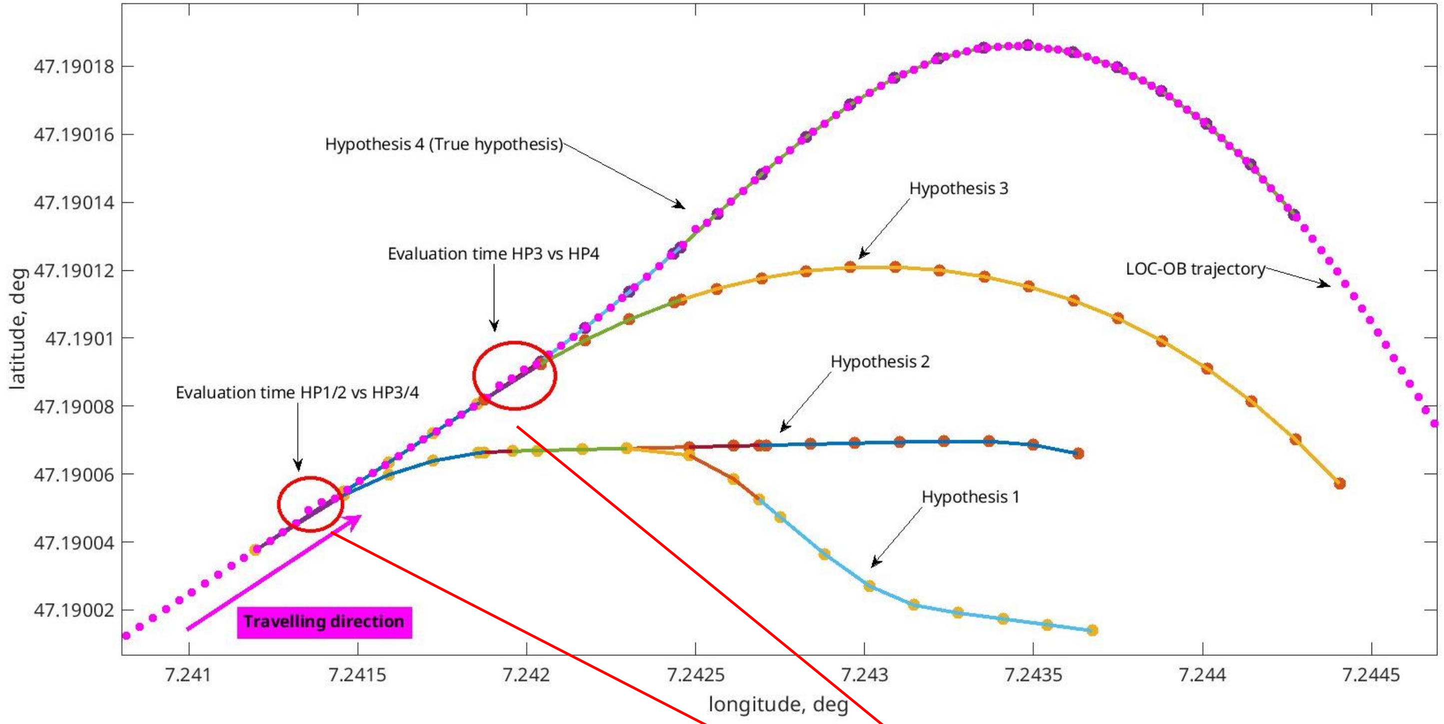
Track selectivity

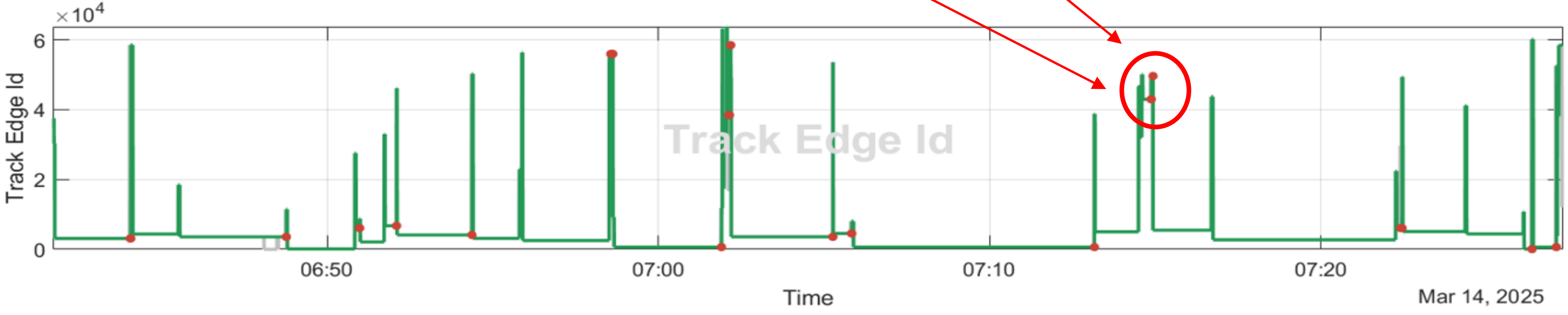
Track edge IDs **correctly selected** in the analyzed trip

Track edge decision takes usually less **than 2 seconds**

During decision phase, old track edge ID is kept for 1D report

Track edge enables successful operation of the **CLUG2 live demo, together with balise-based track edge ID initialization.**



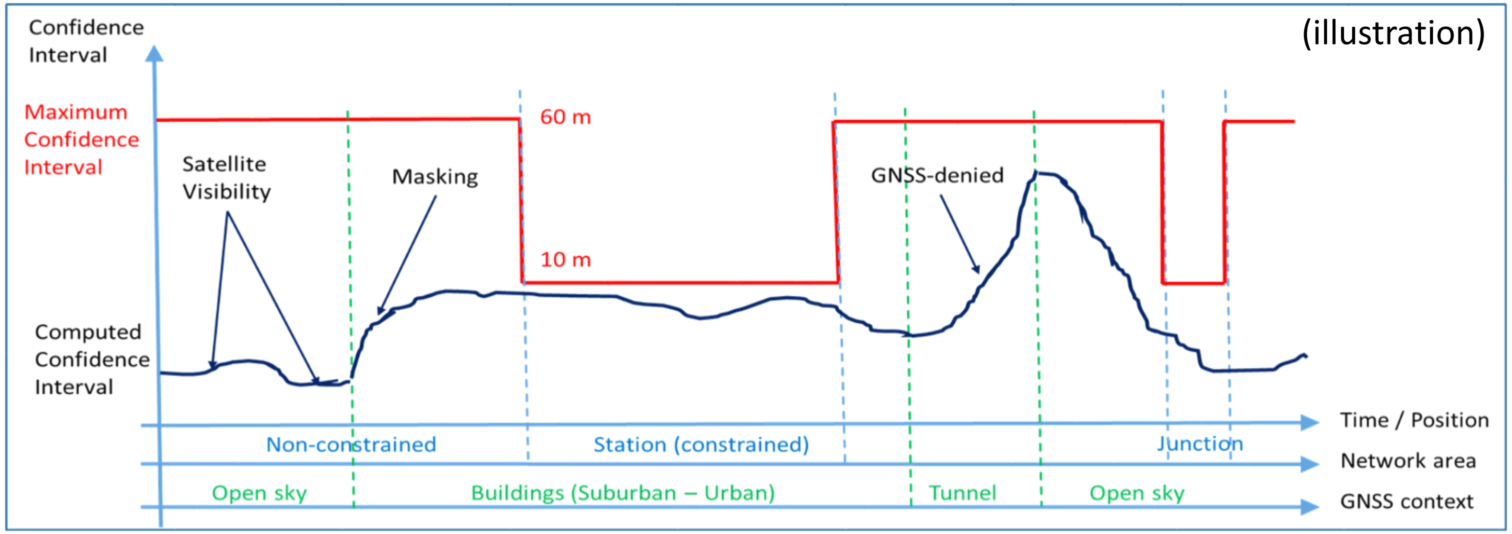


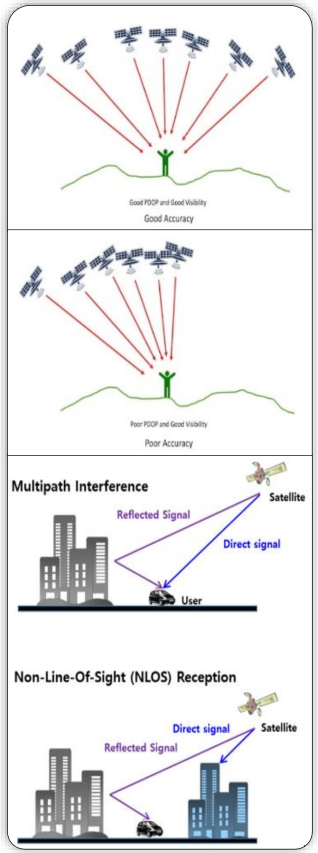
CLUG 2.0
Final Conference

T4.11 - Performance predictions in safe availability (true pos/speed/acc within computed CI and computed CI < Maximum/required CI)

A. Sfeir, P. Grandjean (Airbus)

Confidence Intervals drivers (new items CLUG 2.0)



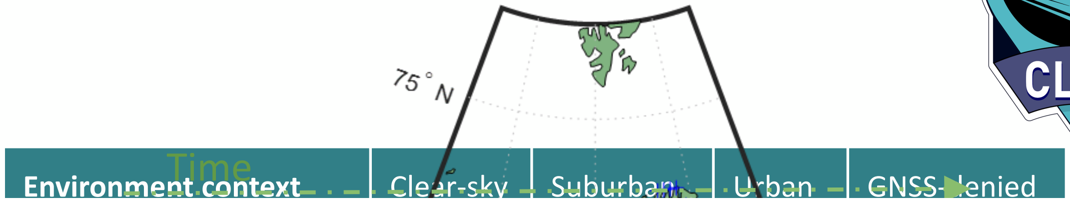


- GNSS pseudo-range measurements availability
  - Satellites visibility/geometry (number, elevation, dilution of precision)
  - Masking and Data FDE exclusion (depending on environment – Opensky, Suburban, Urban)
  - **GNSS-denied areas (specific CI model)**
- GNSS/SBAS errors and integrity models
  - GNSS system error models : GPS/Galileo, EGNOS DFMC and **+PR+PV**
  - GNSS time correlation model
  - Local error models (depending on environment - 6 categories)
- IMU, Tachometer and Track Map error models
- Management of SBAS Time-To-Alert: 6 seconds coasting

Confidence Interval algorithm

- Time correlation
- Faulty Confidence Intervals (System data FDE)
- Dual-chain / Single chain architectures
  - Combiner performance model
  - Shape Map Matching performance model

CI performance prediction (new items CLUG 2.0)



Geographical / time / track direction sampling

Simulation of satellites in train reference frame

Models of masking & exclusion by Data FDE

Available GNSS measurements

Fusion algo, all sensor Error models, Track direction projection (DFMC / +PR+PV EGNOS, Time correlation, Local errors)

Prediction of state covariance

Fault-free + Faulty scenarios (Safety factor IR + System Data FDE)

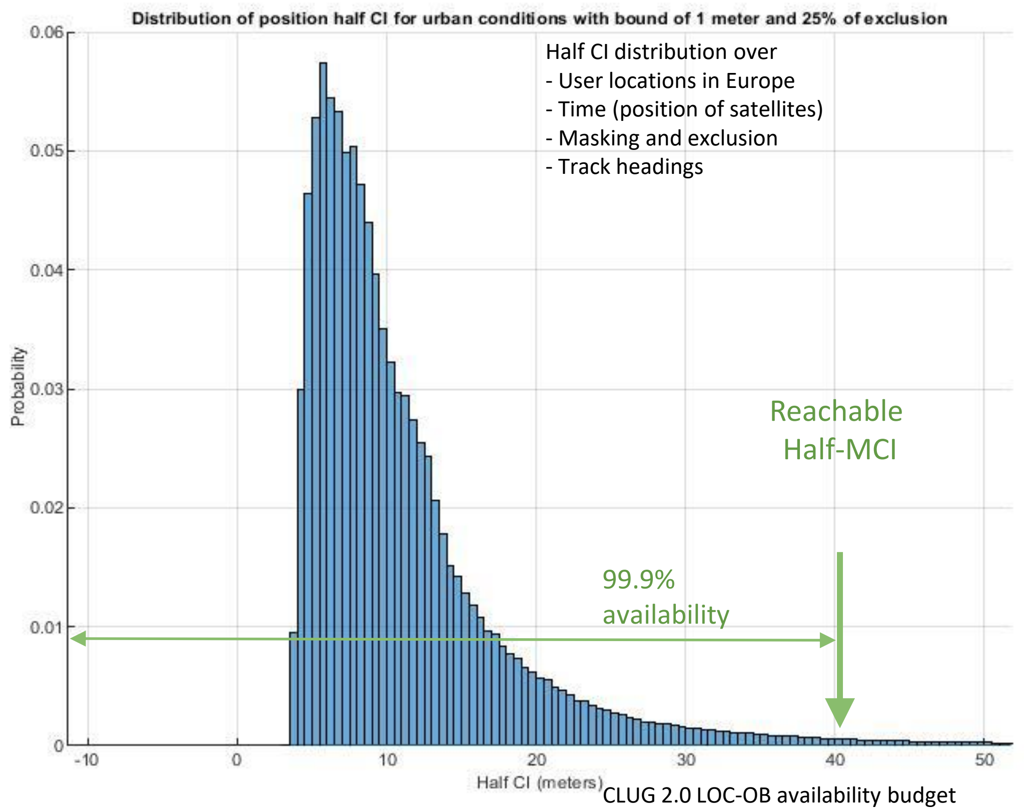
GNSS-SBAS chain Confidence Interval distributions

Shape-Map-Matching algo + Combiner model

Dual-chain CI distributions

Statistics on CI values @ THR 10^{-9}/h for 99.9% availability

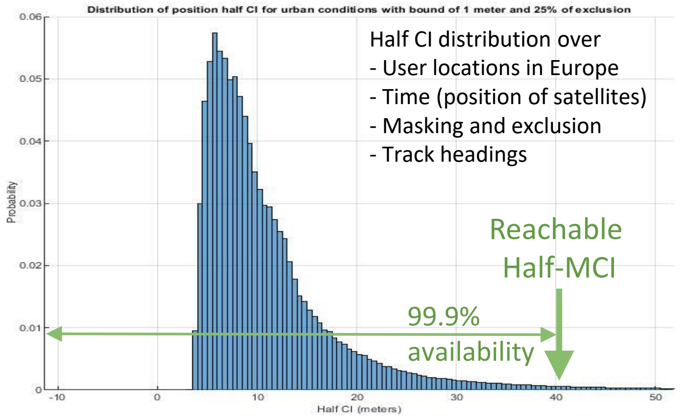
Reachable Maximum Confidence Interval



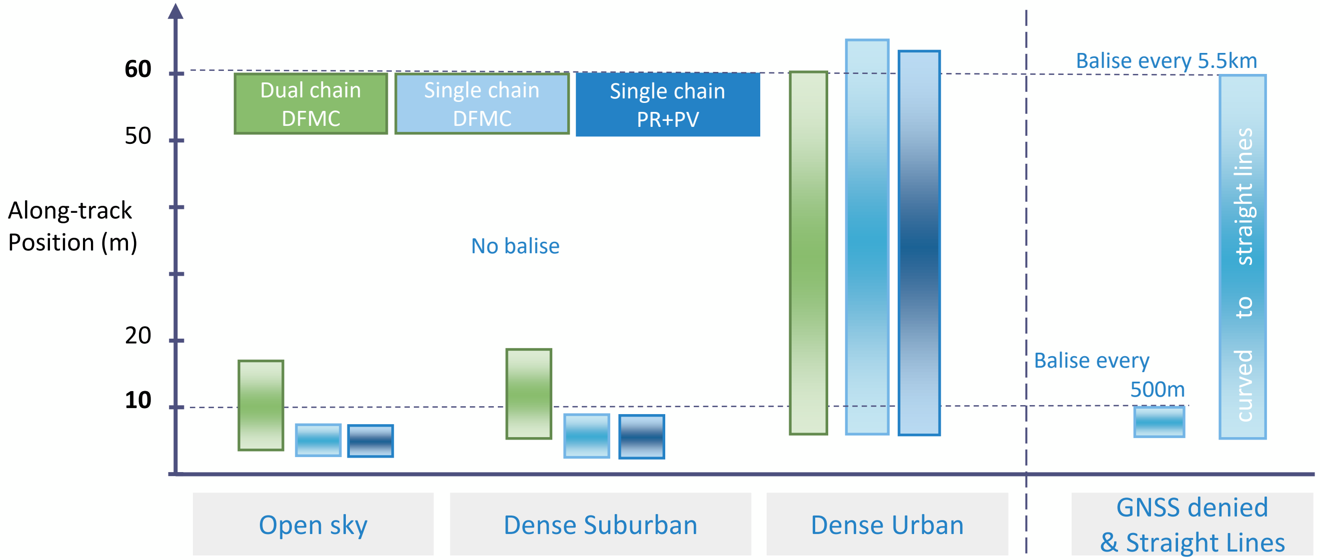
CLUG 2.0 LOC-OB availability budget is 1mn/2h i.e. ~99.2%

CI performance prediction results

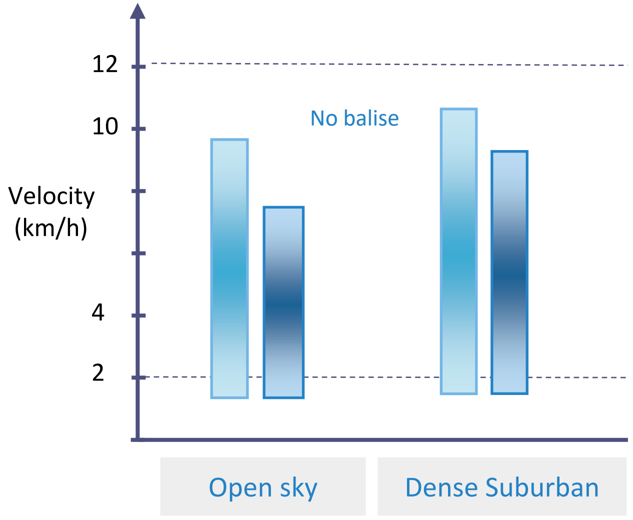
Variable	Architecture	EGNOS	Environment
Position <	Single chain <	SF GPS	Open sky <
Speed <	Dual chain <	DFMC <	Suburban
	Curvy	PR+PV <	Light
	Average <		Dense <
	Straight		Urban
			Light
			Dense <
			Canyon
			GNSS denied



Reachable Half MCI Along-track Position
@99.**9**% availability, in fault-free + faulty CI @1E-9/h



Reachable Half MCI along track Speed (at 50 km/h)
@99.**9**% availability, in fault-free + faulty CI @1E-9/h



CLUG2 Final Conference
WP5 - Integration & Testing

SIEMENS

Agenda

- Scope of WP5, Cooperation with SBB on test trains and map data, data collection, including test trips (Bernhard Stamm)
- Data Flow, Tools, Data Processing, Ground Truth (Niko Harnge)
- Data Analysis & Results (Grégory Durand)
- Demonstrator (Bernhard Stamm)

Scope of WP5, Cooperation with SBB on test trains and map data, data collection including test trips

Scope of WP5

The scope of WP5 was defined in the grant agreement as follows:

- Collection of field data from sensors using the system installed in the CLUG project on a train in Switzerland, but with upgrades and optionally using an identical system on a second train.
- Collection of map data from the network, on which the train operates.
- Generation of standardised raw data, map data and ground truth data from the collected field data.
- Fusion of that standardised raw data, using tools from CLUG with upgrades, and algorithms provided by WP4, to generate speed, position and other output data, including safe confidence intervals.
- Design, development and installation of a demonstrator on the test train, with which the data fusion algorithms provided by WP4 can be demonstrated in real time.

Scope of WP5

- Collect of field data with the site demonstrator operating in commercial services, as well as in specific test runs scheduled to perform operational test cases.
- Analyse the performance of the offline generated data, as well as the data from the site demonstrator, in regard to performance, availability and safety, considering also environment conditions, that may influence the performance.

Scope of WP5

All of these tasks have been performed, except testing of the demonstrator "in specific test runs scheduled to perform operational test cases".

This was due to the demonstrator algorithm not being mature enough at the date the test trips have been scheduled. Data for offline processing has however been collected during these tests and subsequently analysed.

On the other hand, the option of equipping a second train has been realised, which created significant benefits.

Test Trains

- SBB not only provided access to the commercially operated Domino train, which was already used in the frame of the STARS and CLUG projects, but proposed to also equip a second train, which is used in commercial operation on the S-Bahn Zurich.
- The option in the grant agreement to equip a second train was therefore realised, as a train operating on the S-Bahn Zurich allowed testing also in much more urban areas compared to where the Domino normally operates. The core of the network of the S-Bahn of Zurich consists of multiple lines crossing the city, which also include long tunnels and underground stations.
- Equipping a second train however also generated redundancy for data collection in case one of the trains would be out of service for some time for whatever reason.
- Providing the trains also included support for the installation of the equipment in maintenance depots, which not only involved staff from SBB Infrastructure, which managed the CLUG 2 project within SBB, but also from other divisions or units, which e.g. own, maintain and operate the trains.

Test Trains

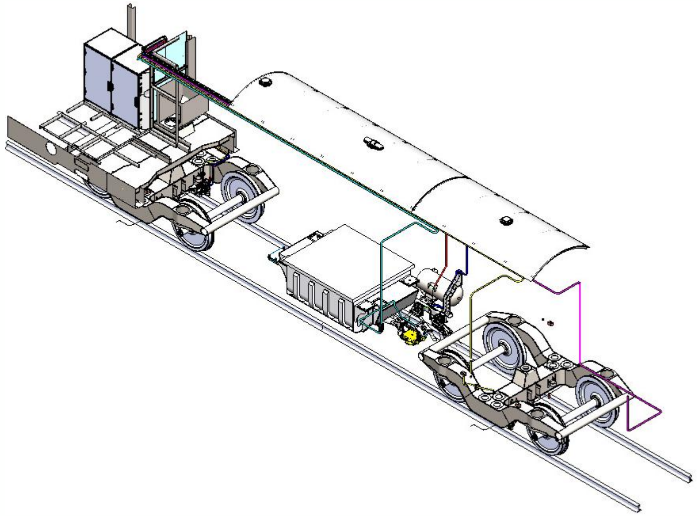
- The Domino train, which was already used for the STARS and CLUG projects, was again used in CLUG 2.
- This not only saved a lot of cost, but also allowed testing of sensors, algorithms and configurations nearly from the start of the project, and therefore also reduced project risks.
- Most updates required for CLUG 2 could be introduced into the existing installation as soon as they were available, and also during regular, scheduled maintenance slots, or even when the train was in service, with no need for re-certification.
- The only exception was the exchange of one of the broadband GNSS antennas with another type, but even this could be done during a regular maintenance slot, and the antenna was already in the approval process at SBB.

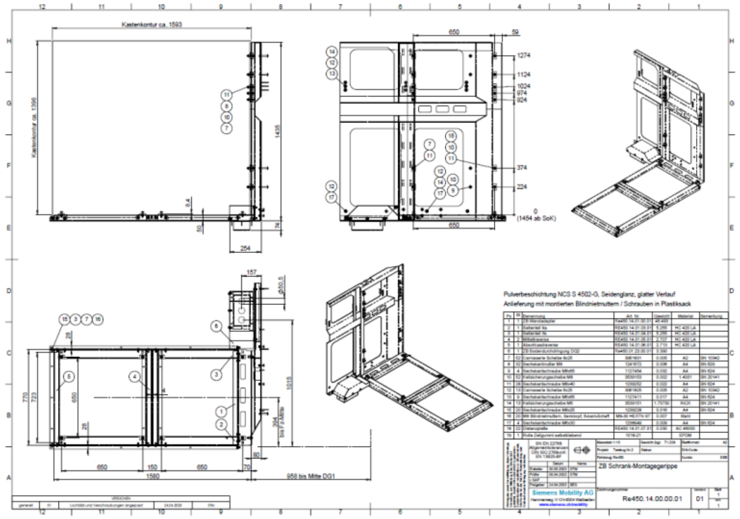
Test Trains

- The Re450 locomotive of the first-generation double decker trains of the S-Bahn Zurich was chosen as the second test vehicle, as:
  - the Re450 also has a baggage compartment, which are not used anymore in operation,
  - the Re450 is even more challenging from a traction system point of view than the Domino.

- No existing infrastructure could however be re-used from previous projects, except some spare equipment, so installation and certification was a significant effort.
- To minimise the down time caused by the installation, a locomotive was chosen which was scheduled for major maintenance, in which the necessary removal of the boogies and the roof of the locomotive was anyway planned.

Test Train Re450





Test Train Re450

Data collection with the Re450 started in November 2023, which was only 10 months after the start of the project. This is fast when considering all the work which had to be done, including design, stress calculations, manufacturing, installation, safety approval etc.

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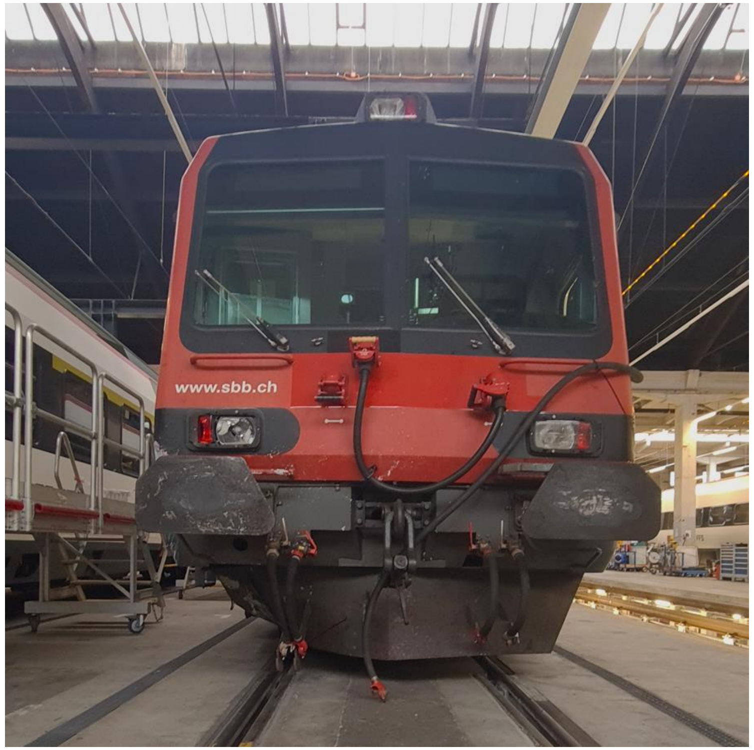
Map Data

- One of the main advantages, but also a major challenge of the CLUG 2 project was that testing was performed on commercially operated trains.
- Both trains are part of larger fleets, and are therefore operating on a large variety of lines. Where they operate could not be influenced by the CLUG 2 project and changed daily.
- SBB therefore provided map data for the full 5’000 km of the Swiss standard gauge network, including lines from other infrastructure managers.
- This data had to be processed, which included error corrections, restructuring and conversion to a format usable for the sensor fusion algorithm, and this had to be repeated with every update received during the project.

Data Collection

- Thanks to using two trains operating in commercial operation, large amounts of data could be collected in a very broad spectrum of environments.
- Using the second train has permitted data collection in commercial operation also in a more challenging, urban environment.
- Equipping a second train as fallback has unexpectedly proven useful, as the Domino train hit a car on a level crossing (nobody was hurt), which resulted in several months of down-time to perform repairs.



Test Trips

- While a lot of data could be collected during commercial operation of the trains, these are always performed within a certain envelope.
- Extreme cases, such as massive slip and slide, emergency brake applications, stopping for extended times in tunnels etc. however rarely occur in commercial operation.
- To also analyse the behaviour of the positioning system under such cases, three days of dedicated test trips outside commercial operation have been performed with the Domino train.
- The Domino train was chosen for these trips, as it is equipped with ETCS Level 2, and also has a smaller train gauge than the Re450 double decker train, allowing testing anywhere on the Swiss network.

Test Trips

- The dedicated test trips took place on the 25.-27. March 2025 and were scheduled with a focus on lines with GNSS denied areas, or areas where GNSS reception is severely impacted by the environment, such as mountainous and urban areas.
- They covered nearly 1000 km, of which around 300 km were in tunnels, including the Gotthard Base Tunnel with a length of 57 km, and two crossing of the city of Zurich, with multiple stops in underground stations.
- The trips included many test cases, including emergency stops outside, inside, or when entering tunnels, provoked slip/slide, low speed driving on canted track, including through crossovers etc.

Data Flow, Tools, Data Processing, Ground Truth

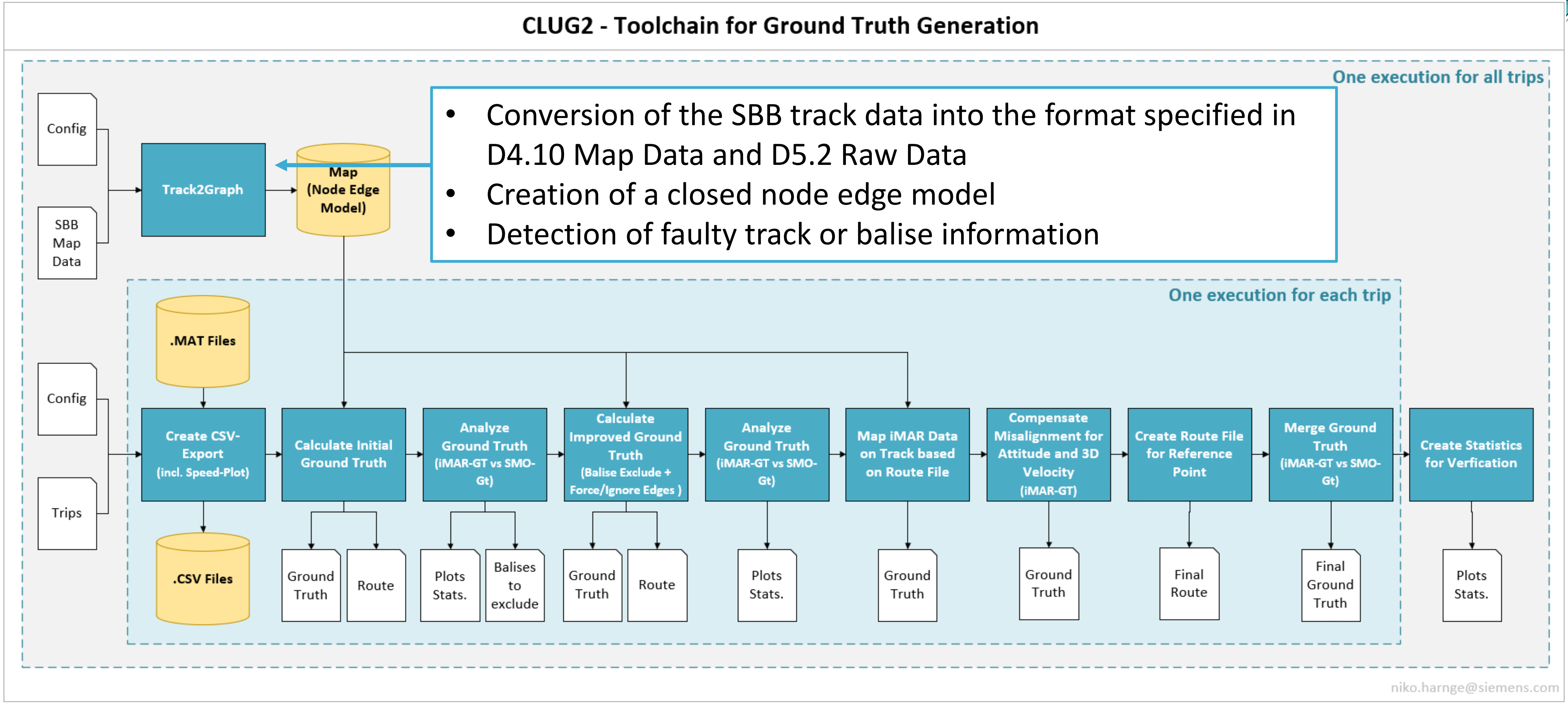
Ground Truth – Key Challenges

- High Accuracy Requirements
  - GT must be significantly more accurate than the system under test (e.g. ±0.25 m for validating ±1.25 m requirements)
- Complex Sensor Integration
  - Requires fusion of GNSS, IMU, balise data, odometry, and track maps — each with its own limitations and uncertainties
- Environmental and Operational Constraints
  - GNSS shadowing, sensor latency, map inaccuracies, and real-time availability affect GT quality and reliability

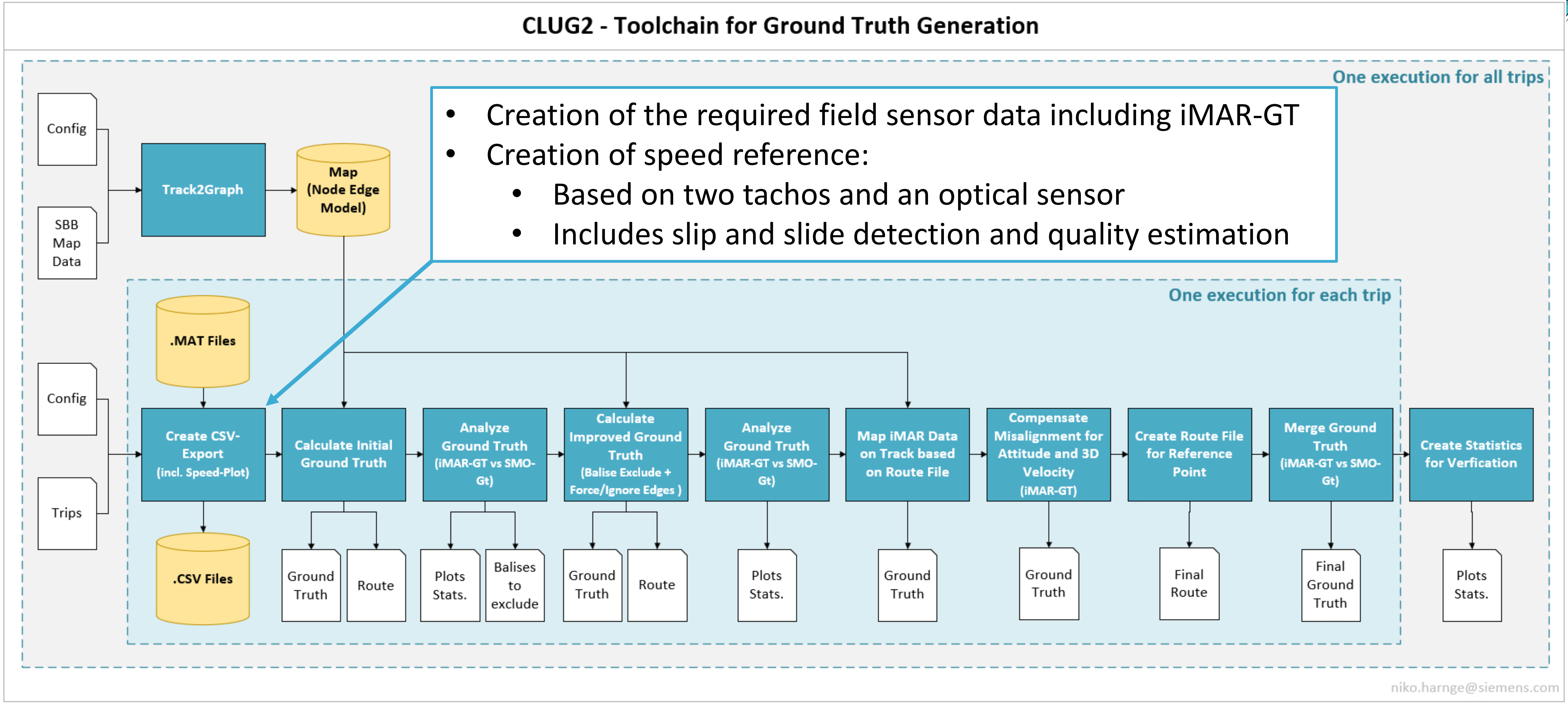
Ground Truth – Available Solutions

	iMAR-GT	SMO-GT
Data Basis	Real-time GNSS/INS with ring laser gyros and servo accelerometers	Post-processing using balises, wheel sensors, and track data
Strengths	• High-precision 3D position, velocity, and attitude • Real-time capable • Independent of track data	• Track-referenced positioning • Balise-based localization • Flexible configuration
Weaknesses	• No track reference • No distance to infrastructure points • Sensitive to GNSS shadowing	• No real-time capability • Dependent on balise and map accuracy • 3D velocity and attitude data only indirectly available

Ground Truth Generation



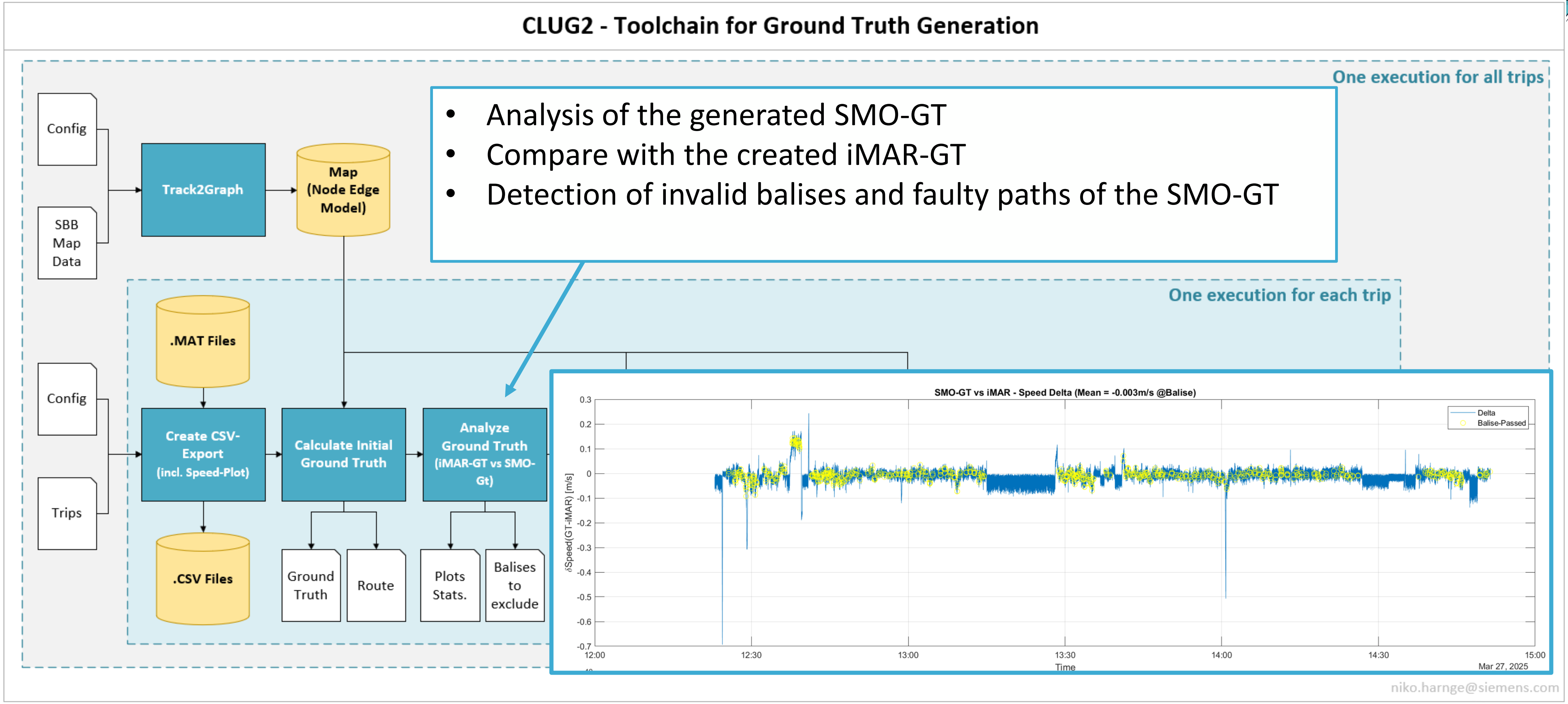
Ground Truth Generation



- Creation of the required field sensor data including iMAR-GT
- Creation of speed reference:
  - Based on two tachos and an optical sensor
  - Includes slip and slide detection and quality estimation

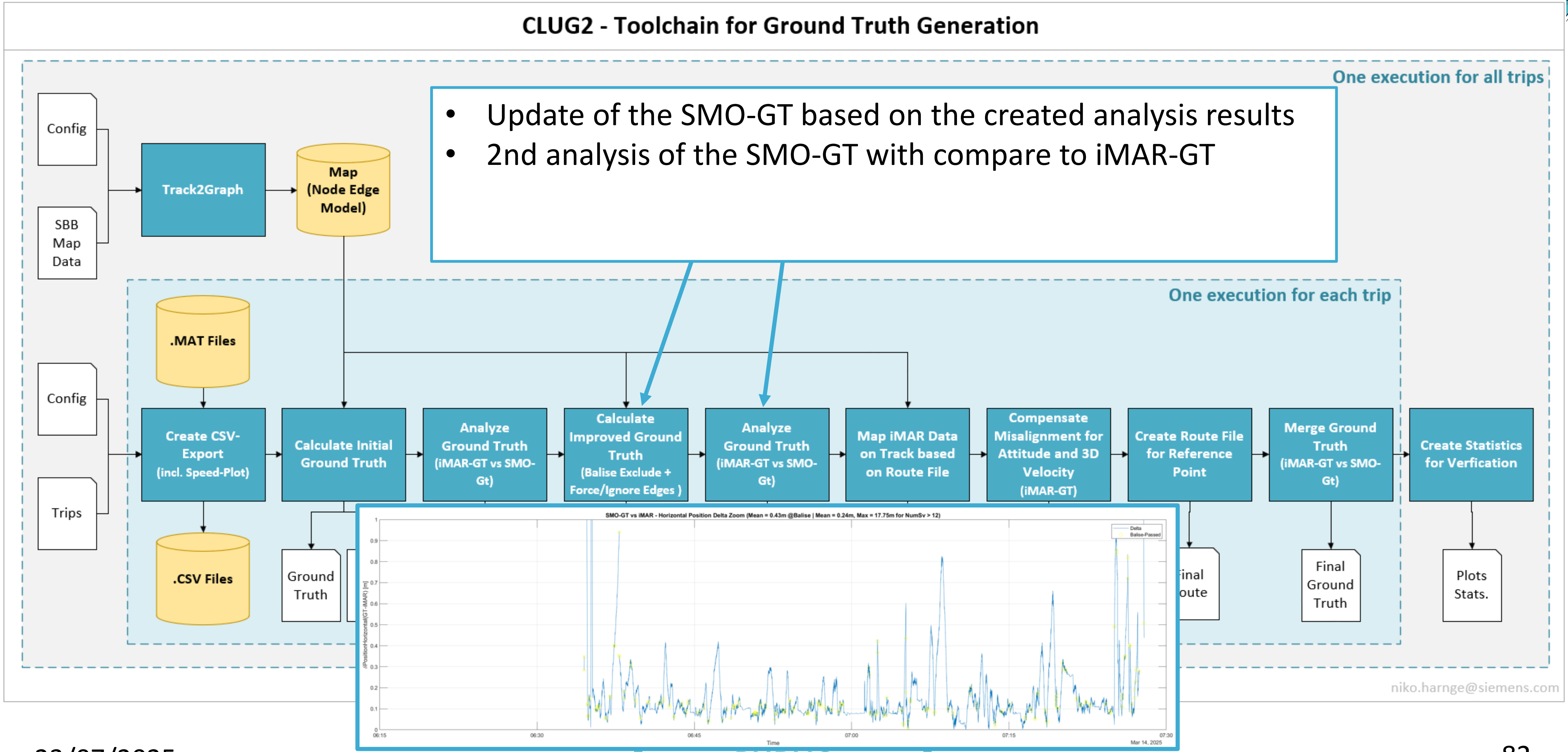
Ground Truth Generation

- Analysis of the generated SMO-GT
- Compare with the created iMAR-GT
- Detection of invalid balises and faulty paths of the SMO-GT



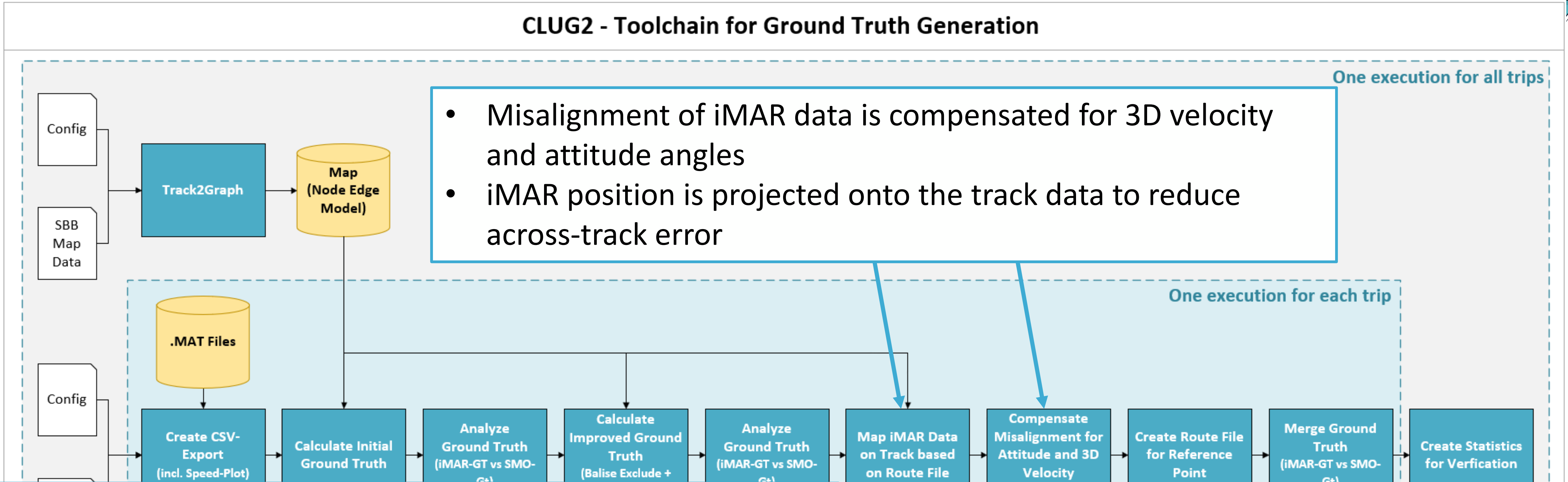
Ground Truth Generation

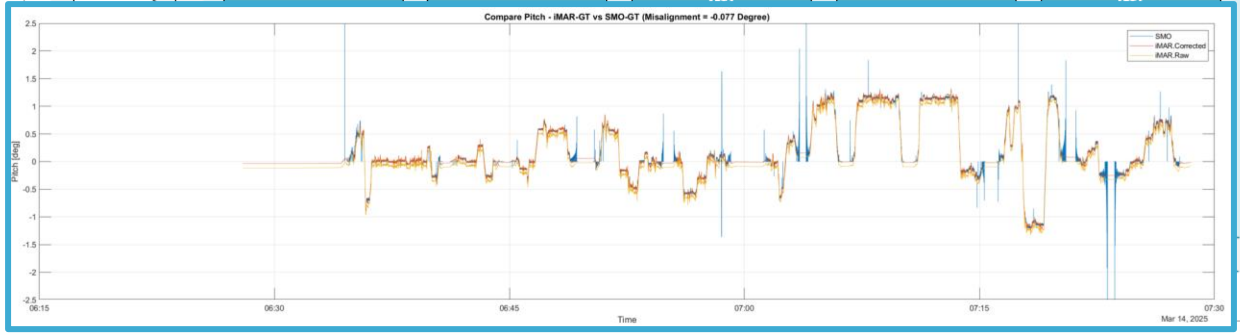
- Update of the SMO-GT based on the created analysis results
- 2nd analysis of the SMO-GT with compare to iMAR-GT



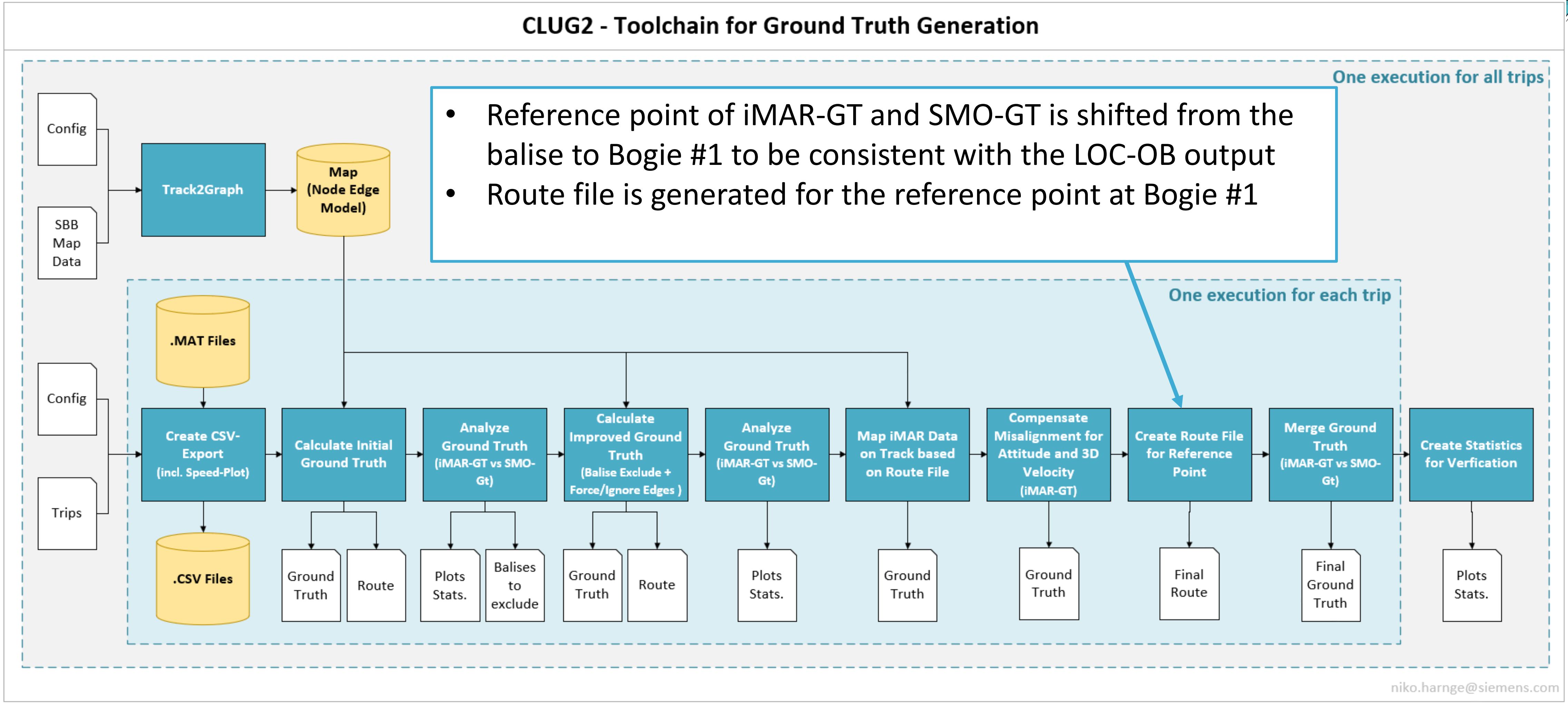
Ground Truth Generation

- Misalignment of iMAR data is compensated for 3D velocity and attitude angles
- iMAR position is projected onto the track data to reduce across-track error



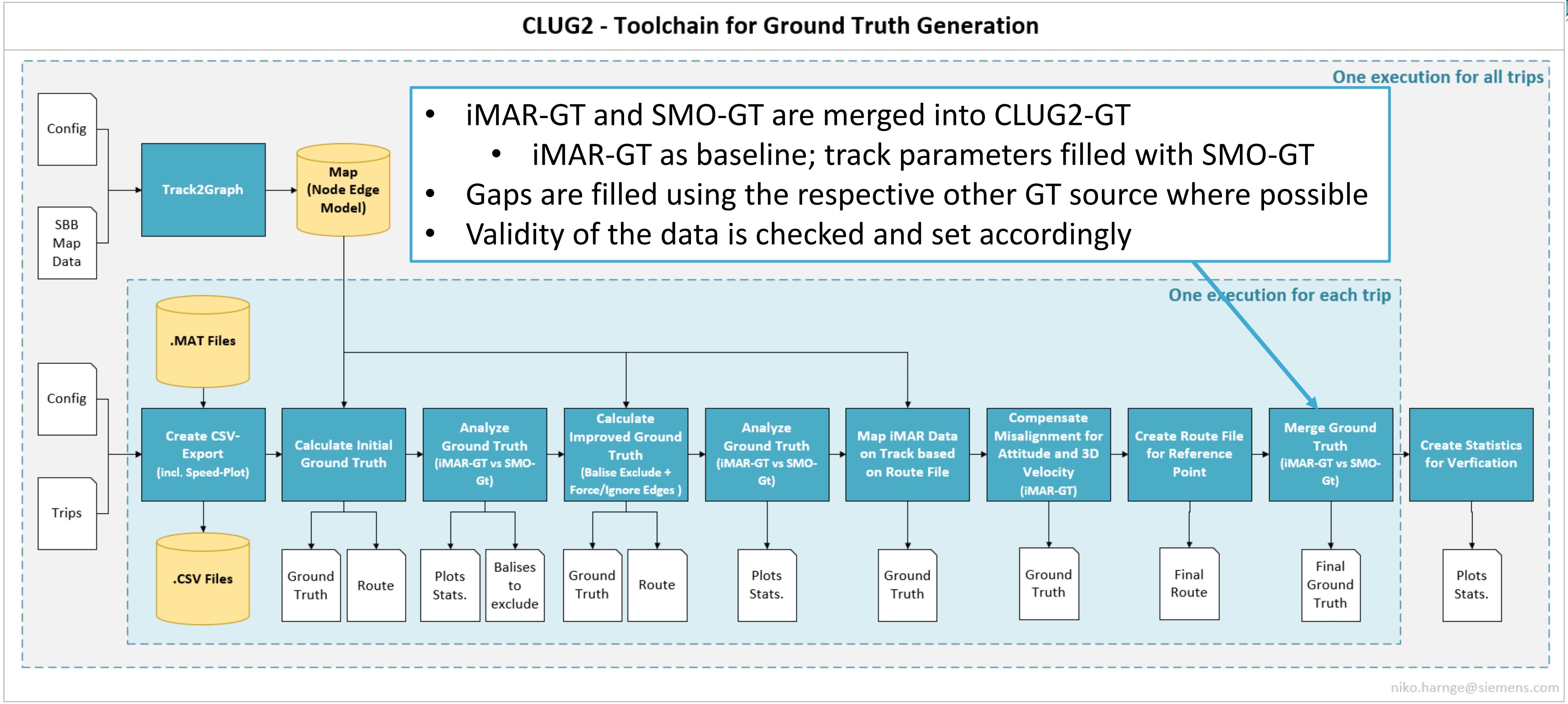


Ground Truth Generation



- Reference point of iMAR-GT and SMO-GT is shifted from the balise to Bogie #1 to be consistent with the LOC-OB output
- Route file is generated for the reference point at Bogie #1

Ground Truth Generation

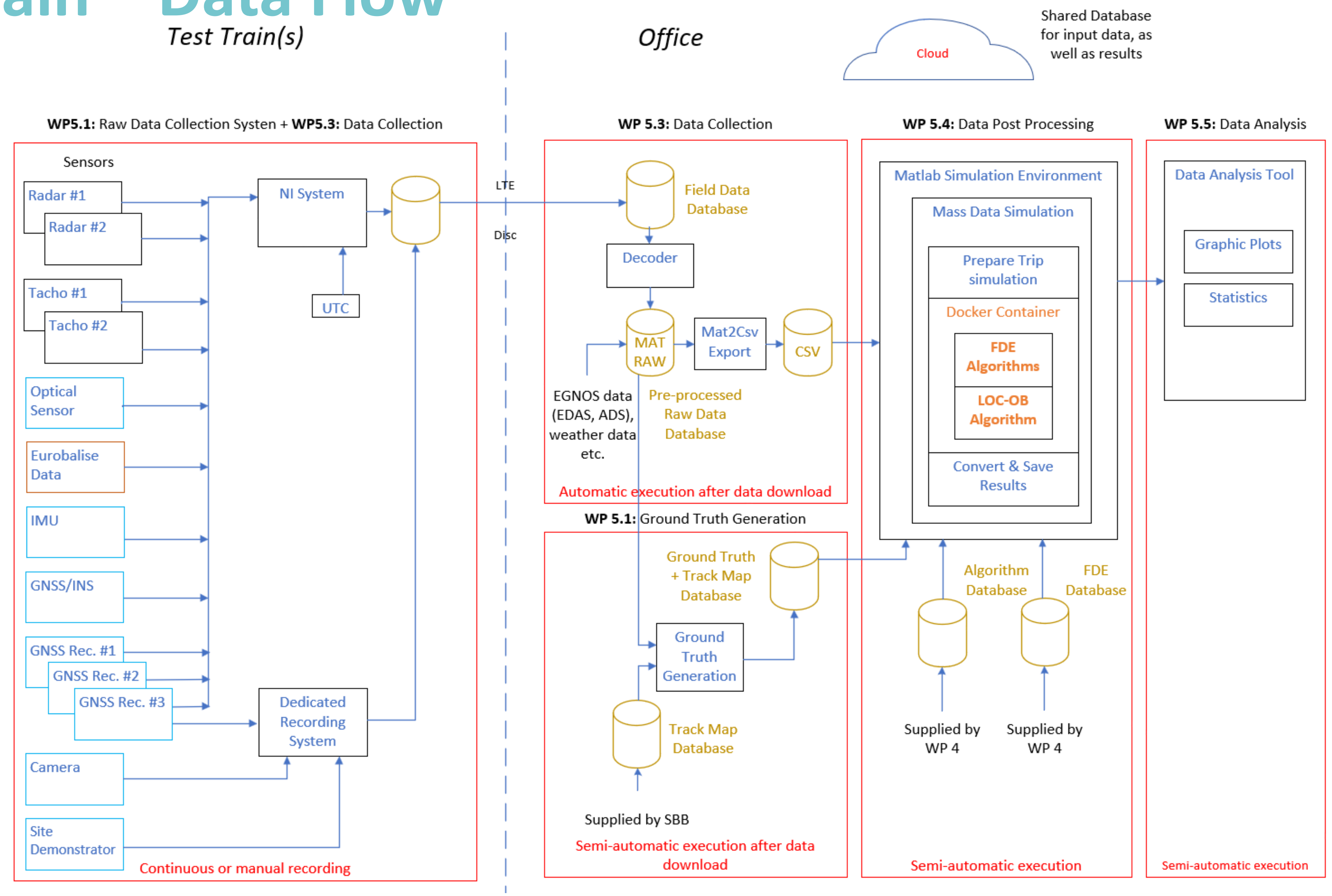


- iMAR-GT and SMO-GT are merged into CLUG2-GT
  - iMAR-GT as baseline; track parameters filled with SMO-GT
- Gaps are filled using the respective other GT source where possible
- Validity of the data is checked and set accordingly

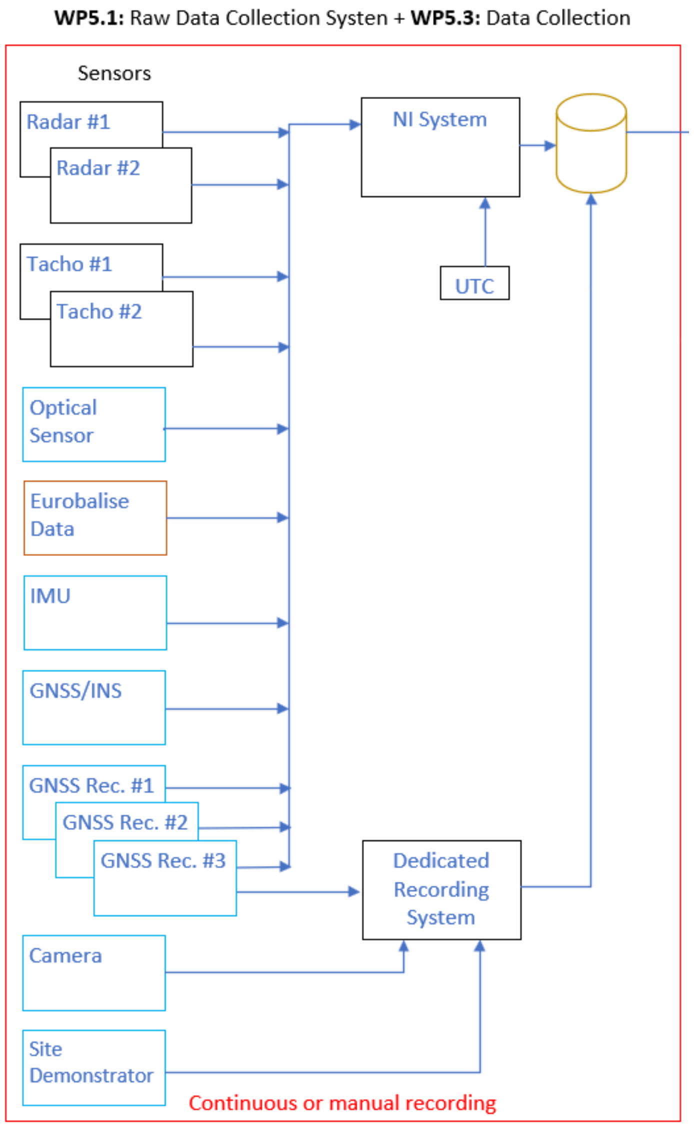
Ground Truth – CLUG2-GT

- Combines Strengths
  - Merges iMAR-GT (real-time, 3D motion) and SMO-GT (track-referenced, balise-based) for a comprehensive GT solution
- Minimizes Weaknesses
  - Compensates GNSS shadowing (iMAR) and lack of real-time data (SMO) through intelligent fusion
- Improves Accuracy and Availability
  - Reduces uncertainty through cross-validation
  - Increases availability without compromising reliability
  - Ensures consistent data quality across diverse environments

Toolchain – Data Flow

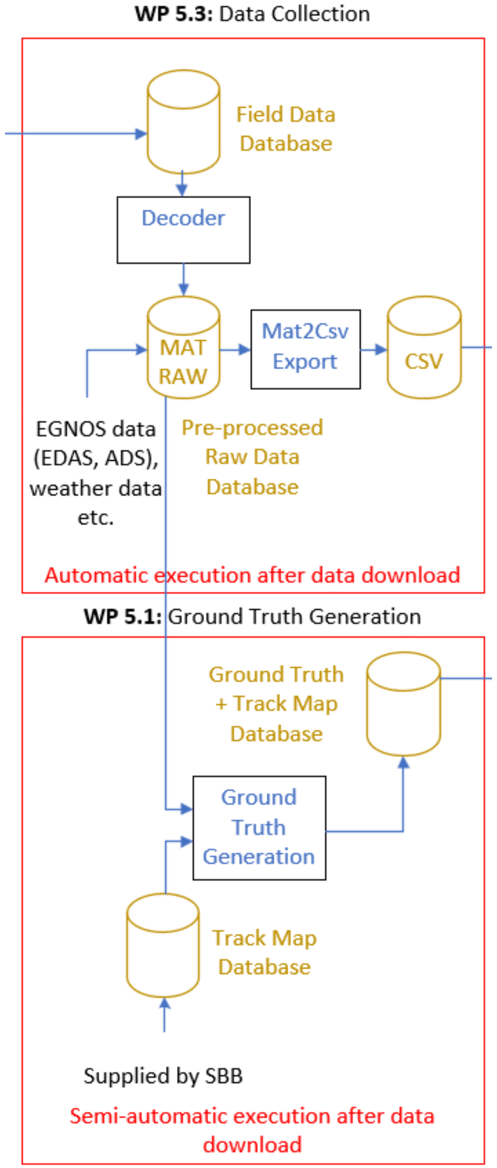


Automated Data Acquisition (RE450 & Domino)



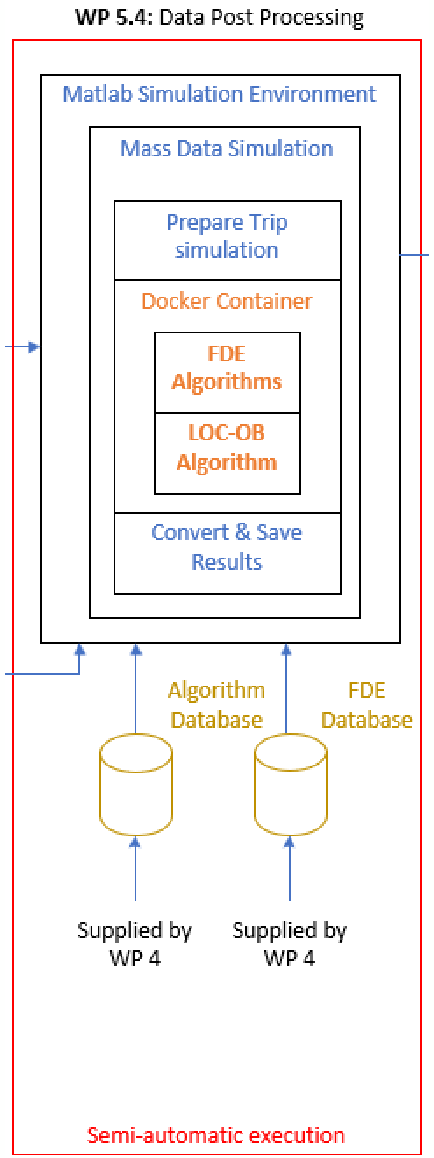
- 24/7 multi-sensor data recording on both vehicles ensures continuous data availability
- Two fully automated recording systems in operation:
  - NI system (reused from STARS + CLUG and extended)
    - Continuous acquisition of sensor data (e.g., radar, tachometer, camera, IMU, Eurobalise)
  - Dedicated recording units:
    - Focused on demonstrator data and it‘s visualization
- Objective: Provide a high-precision, synchronized data foundation for analysis, visualization, post-processing, and public demonstration

Data Pre-processing Workflow



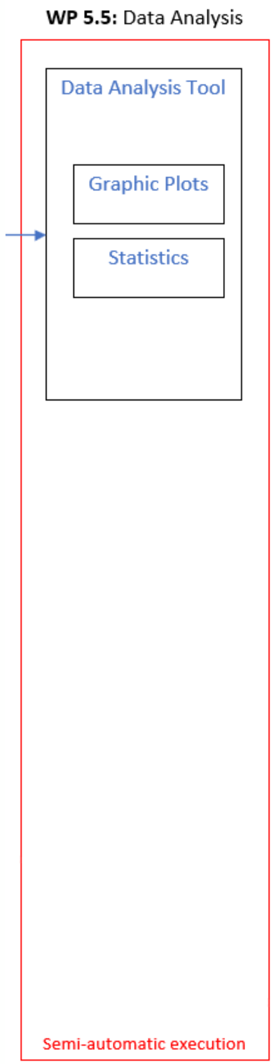
- Manual or automatic data transfer from the trains
- The decoding steps includes:
  - Extraction of field data and decoding of raw data formats,
  - Conversion into a unified data structure (MATLAB object)
  - Storage in a centralized data management system
- Enrichment with external data sources
  - EGNOS data (EDAS, ADS)
  - Weather data
  - Geolocation and site-specific information
- Generation of the ground truth
- Final output: Data is transformed into the standardized format as specified in D5.2 Raw Data

Data Preprocessing Workflow



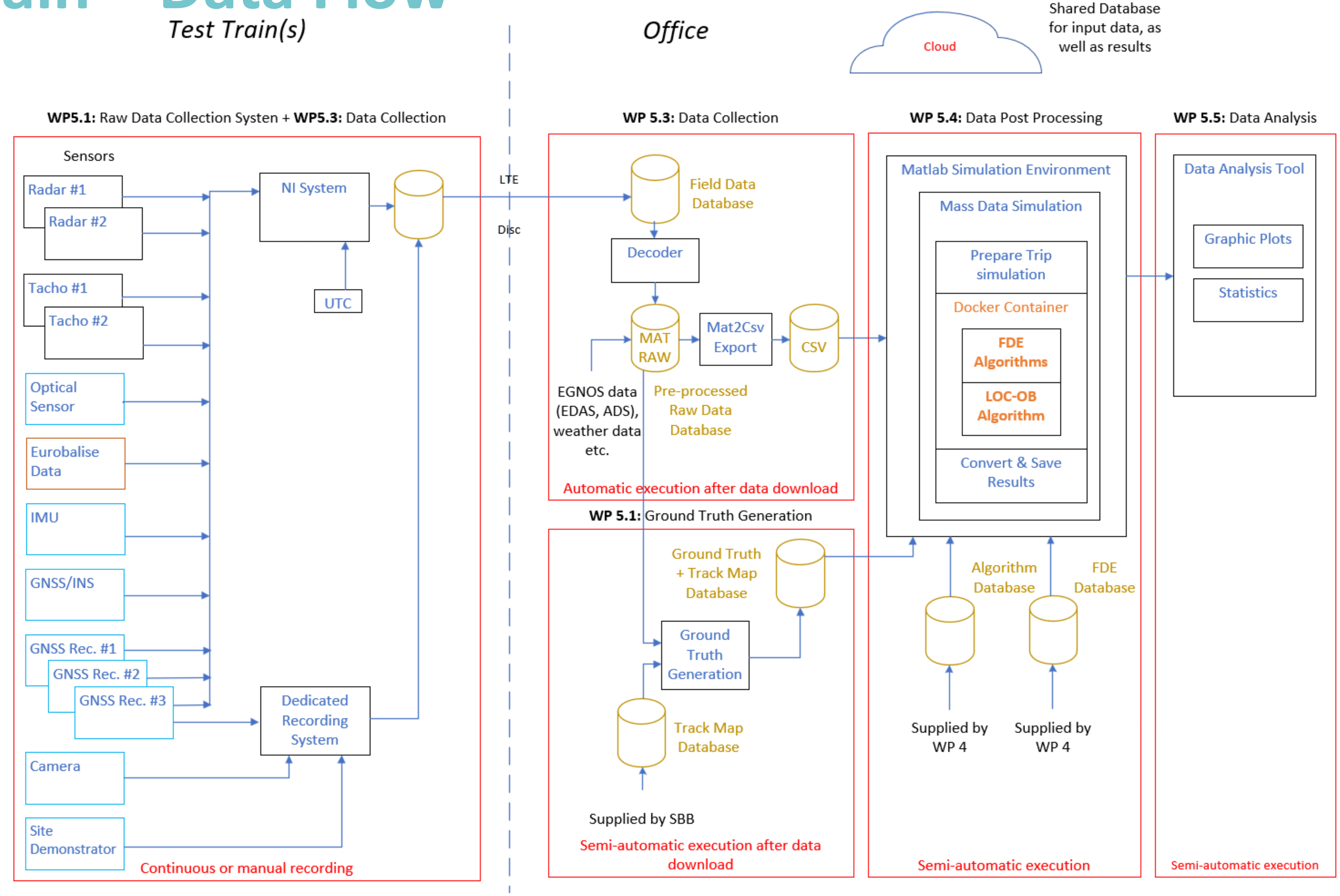
- Docker container provided by ADS
- Modular interfaces allow quick container replacement
- FDE and LOC-OB run inside Docker containers
- Trip-based execution environment supports parallel runs based on available compute resources
- Data is stored in SMO's central Data Management Platform and made available for further use
- Final output: LOC-OB navigation solution is available for the analysis and test.

Data Analysis



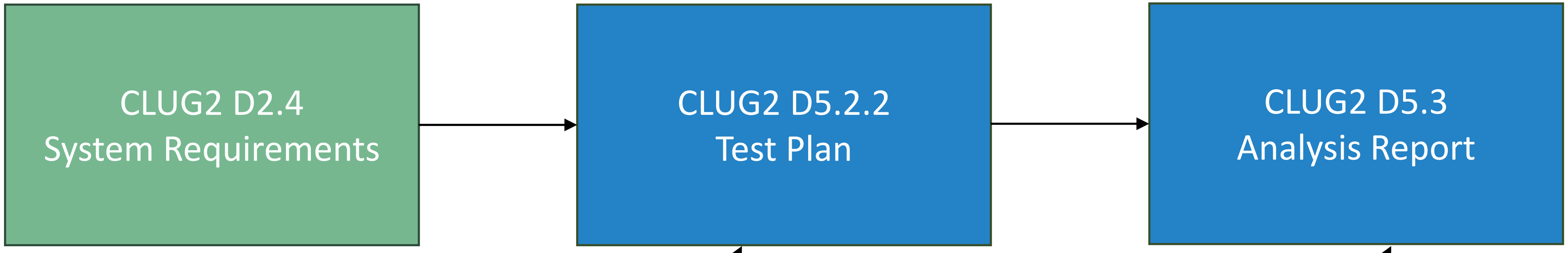
- Modular Trip Analysis
  - Toolchain consists of multiple modules analyzing trips by key LOC-OB output parameters:
  - *Speed, Distance, Position, Confidence Intervals*
- Flexible Evaluation Scope
  - Automated analysis across:
  - *Mass data, individual trips, specific events, locations, weather conditions, test criteria*
- Final Output: Comprehensive Output Generation
  - Enriched with additional statistics and visualizations for in-depth performance evaluation
  - *Plots, zoom views of events, statistical summaries, structured event lists*

Toolchain – Data Flow



Data Analysis & Results with focus on Post-processing

Methodology – Documentation flow



- Requirement coverage
- Iterative test process
- Test configurations
- Definition of the content of the analysis report

- Description of analysis tool chain
- Trip analysis overview
- Detailed analysis of specific cases
- Statistical analysis
- Requirement fulfillment

Methodology – Test configurations

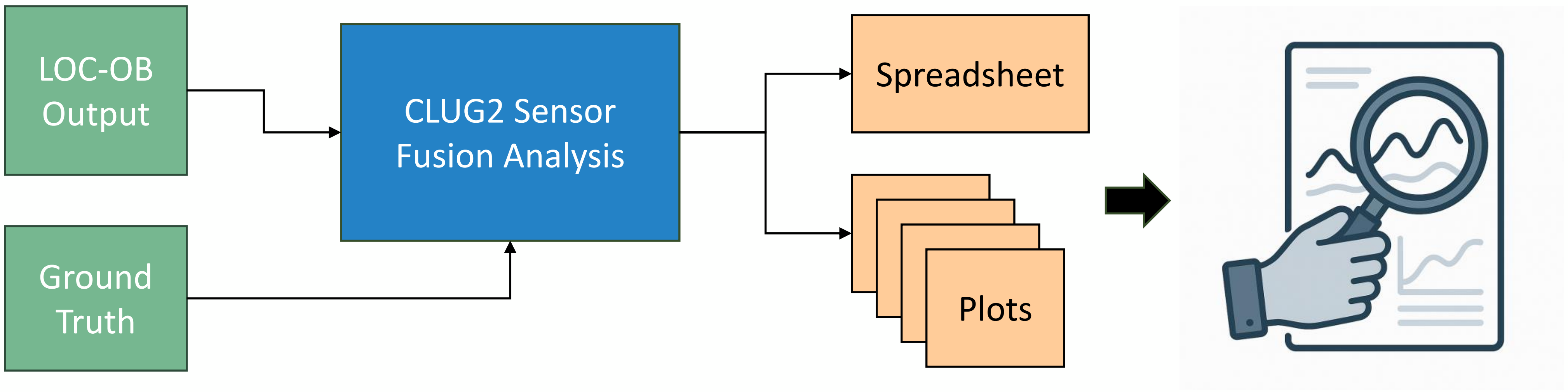
Algorithm configuration:

Test Config ID	EGNOS	Routing file / Track Selectivity
C01	DFMC	Routing file
C03	DFMC+PR+PV	Routing file
C09	DFMC	Track Selectivity

Sensor configuration:

- Speed sensor: HaslerRail odometer pulse generator, also called «wheel tachometer»
- GNSS receiver: Septentrio Mosaic-X5, supporting GPS L1, L2c, L5 and GAL E1, E5a
- IMU: ADIS 16545

Methodology – Data flow



- The spreadsheet contains performance indicators based on requirements
- Spreadsheet and plots are inputs for the manual analysis

Methodology – Selection of trips

ID	Vehicle	Date	Start UTC	End UTC	Journey	Config
45	Domino	14.03.2025	06:28:00	07:28:00	Yverdon-Fribourg	C01
						C03
						C09
46	Domino	14.03.2025	05:30:00	06:27:00	Fribourg-Yverdon	C01
47	Domino	14.03.2025	07:30:00	08:28:00	Fribourg-Yverdon	C01
58	Domino	14.03.2025	15:30:00	16:40:00	Fribourg-Lausanne	C01
49	Domino	25.03.2025	08:40:00	11:00:00	Biel-Arth-Goldau	C01
57	Domino	27.03.2025	12:15:00	15:00:00	Effretikon-Biel	C01
78	Domino	27.03.2025	09:17:00	10:20:00	Altdorf-Sihlbrugg	C01
73	Domino	25.03.2025	12:00:00	13:50:00	Arth-Goldau-Biasca	C01
						C03
77	Domino	27.03.2025	08:00:00	09:15:00	Bellinzona-Altdorf	C01
						C03
79	Domino	27.03.2025	10:22:00	11:45:00	Sihlbrugg-Effretikon	C01

4 favorable trips from regular commercial operation

3 specific CLUG2 trips with typical environmental conditions for Switzerland

3 challenging CLUG2 trips with tunnels and/or urban environment

Results from a «typical» trip: Trip 49

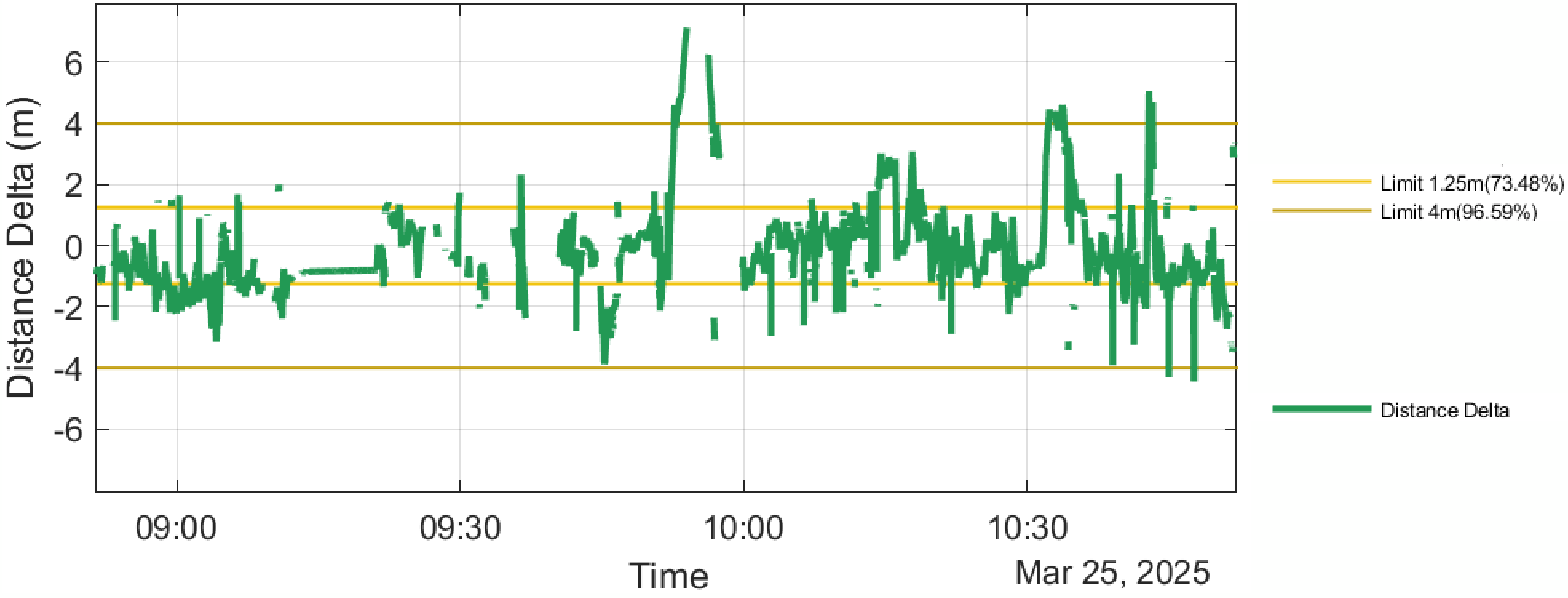
Biel/Bienne to Arth-Goldau

- **Duration:** 2:03
- **Distance:** 136 km
- **GNSS:** 2 longer tunnels along the track, few more short ones
- **Weather conditions:** dry, no snow on the rails
- **Configuration**: C01 (DFMC+Routing file)

Results – Distance 1D accuracy

1D-Distance delta between LOC-OB and GT:

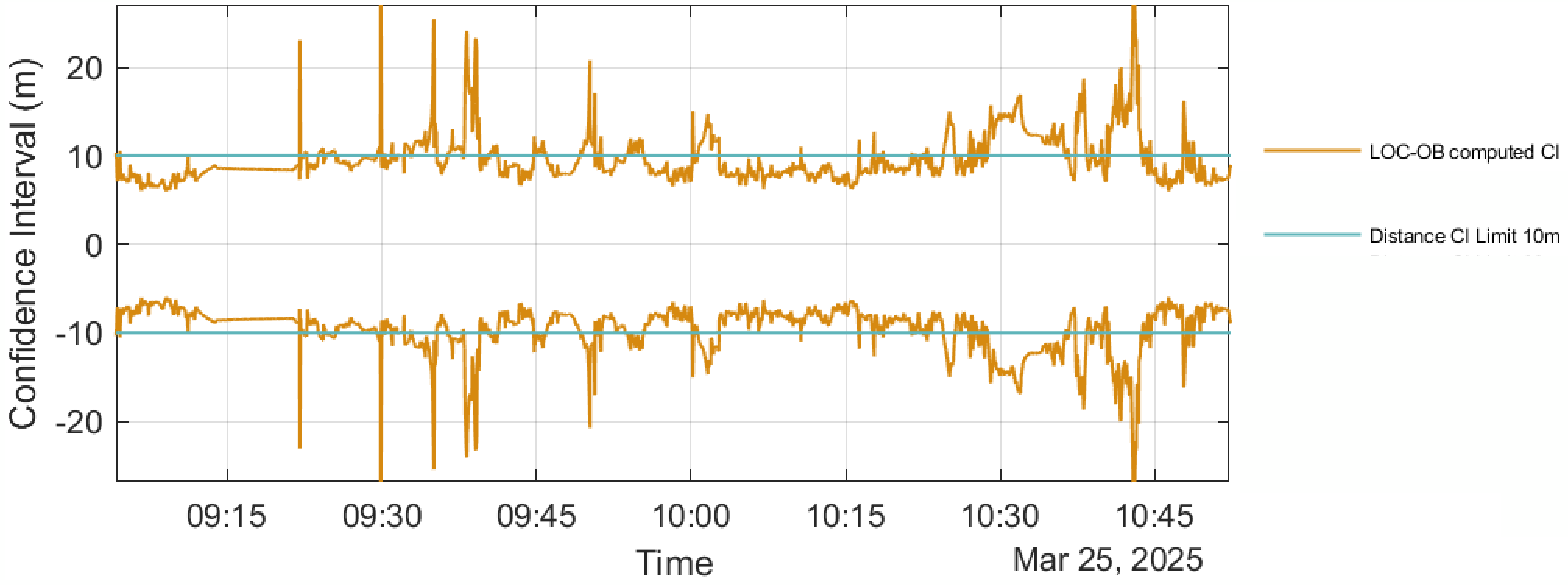
- 96.59% within the +/- 4m-limit (better than the required 95%)
- 73.48% within the +/- 1.25m-limit



Results – Distance 1D fault-free CI

Fault-free Confidence Interval for the 1D-distance:

- 100% within the 60m-limit
- 74.7% within the 10m-limit



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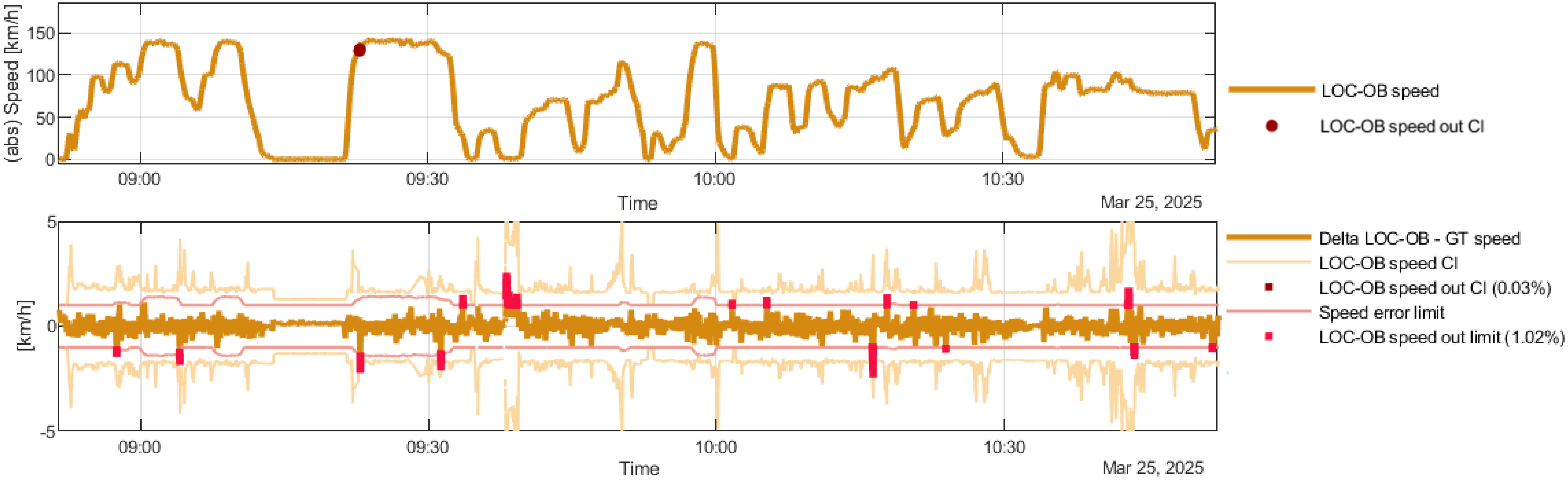
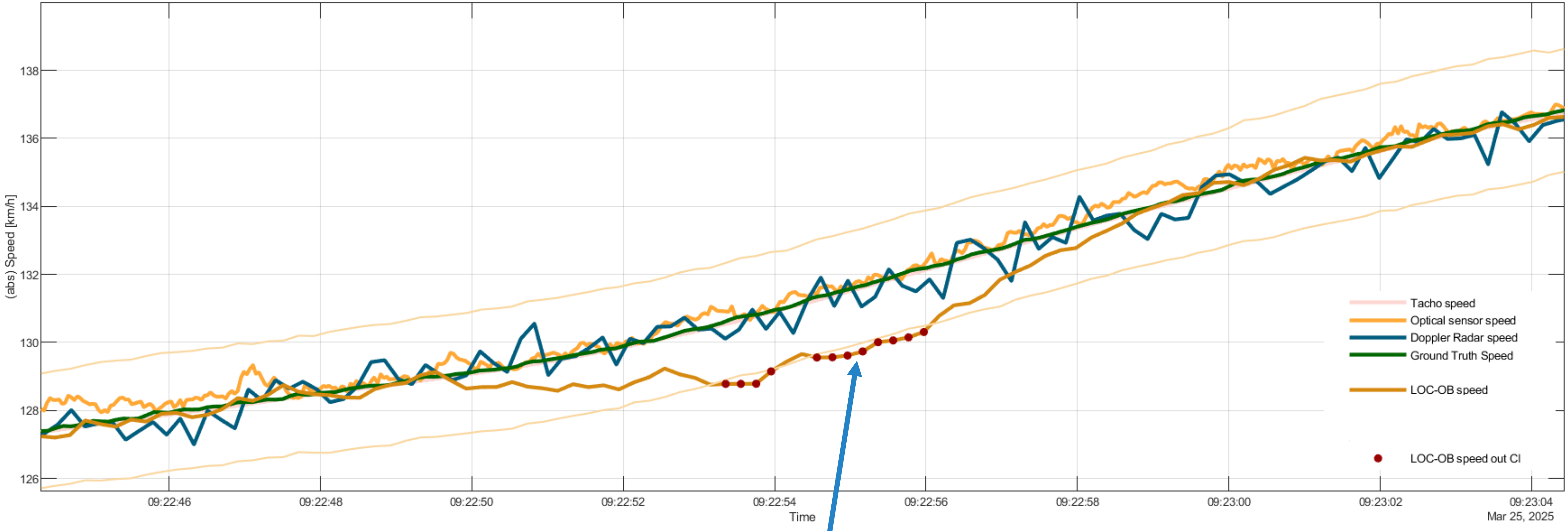
Results – 1D speed accuracy

1D-Speed delta between LOC-OB and GT:

- 98.98 % of the data points within the specified limits → better than the required 95%
- Speed error exceeds the computed CI for 0.03% of the datapoints



Results – 1D speed accuracy

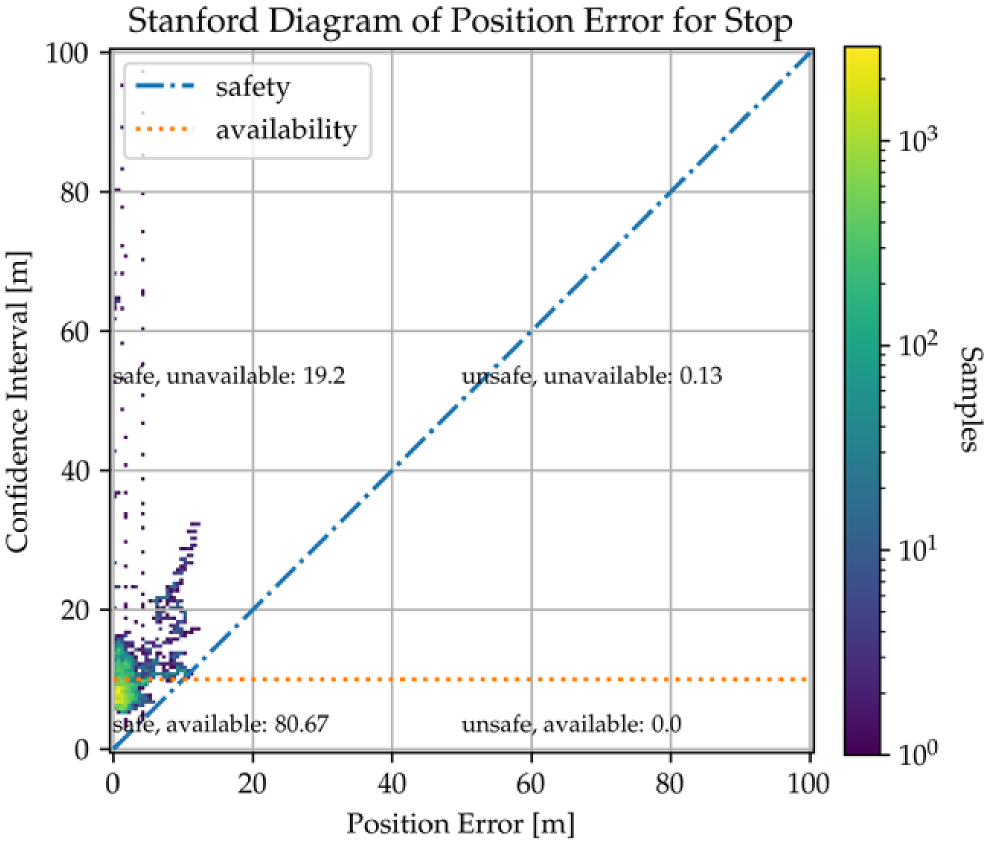


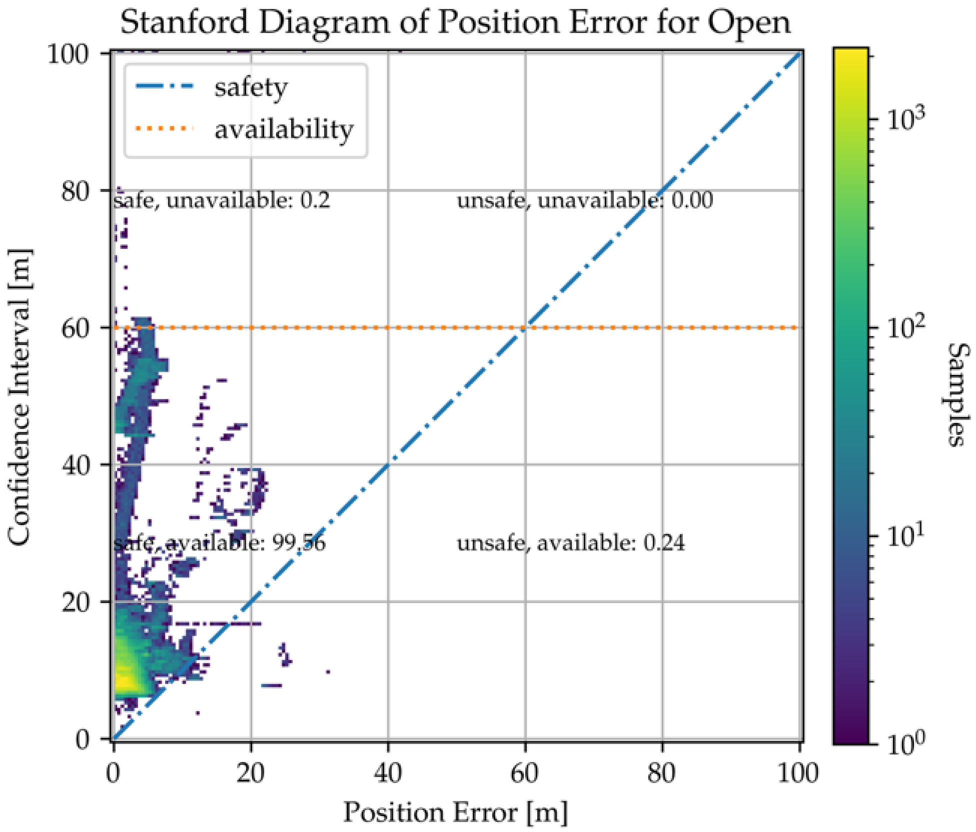
LOC-OB Speed shows a deviation of ~ 2km/h for ~ 2 seconds compared to wheel tachometers and other sensors, leading to a speed error outside the CI

Results – Statistical Analysis – Position Error

Operational surroundings:

- "Stop" for each sample within ± 500 m where the reference velocity $v < 0.1\ m/s$
- "Open" everywhere else





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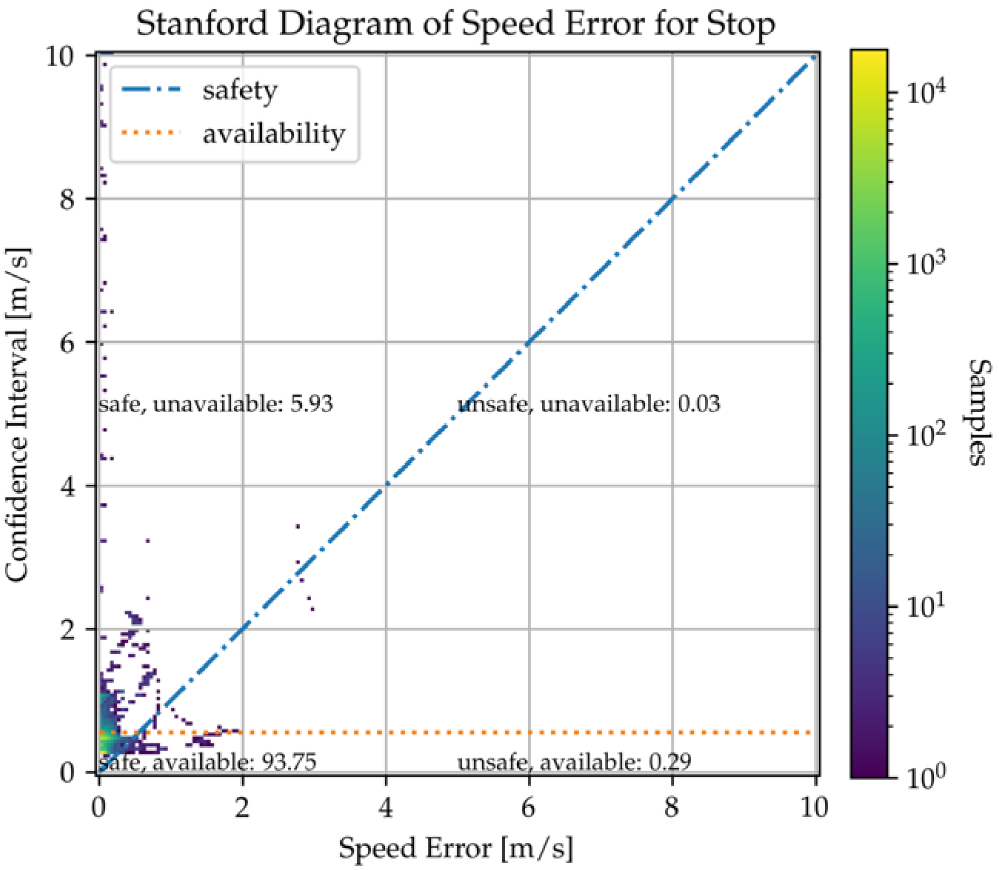
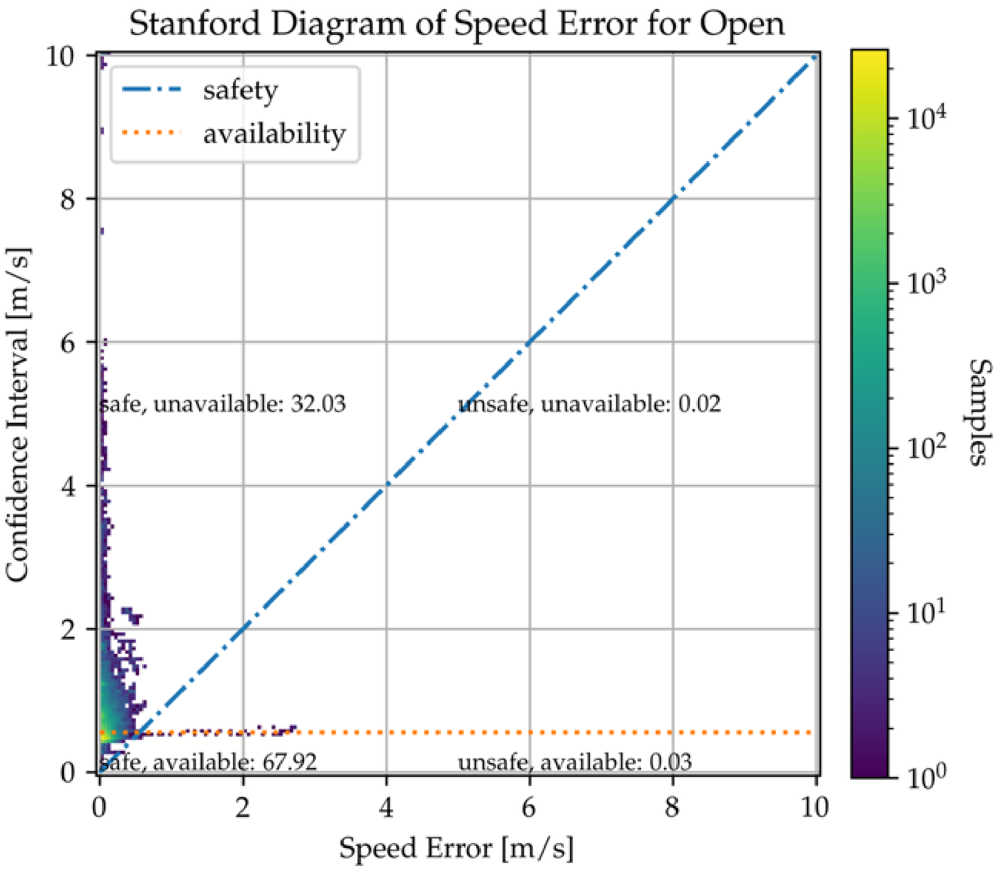
Results – Statistical Analysis – Speed Error





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Conclusion on the performance analysis results

- The LOC-OB (single chain architecture) performs adequately for its intended purpose, with most of the key requirements either fulfilled or nearing fulfillment

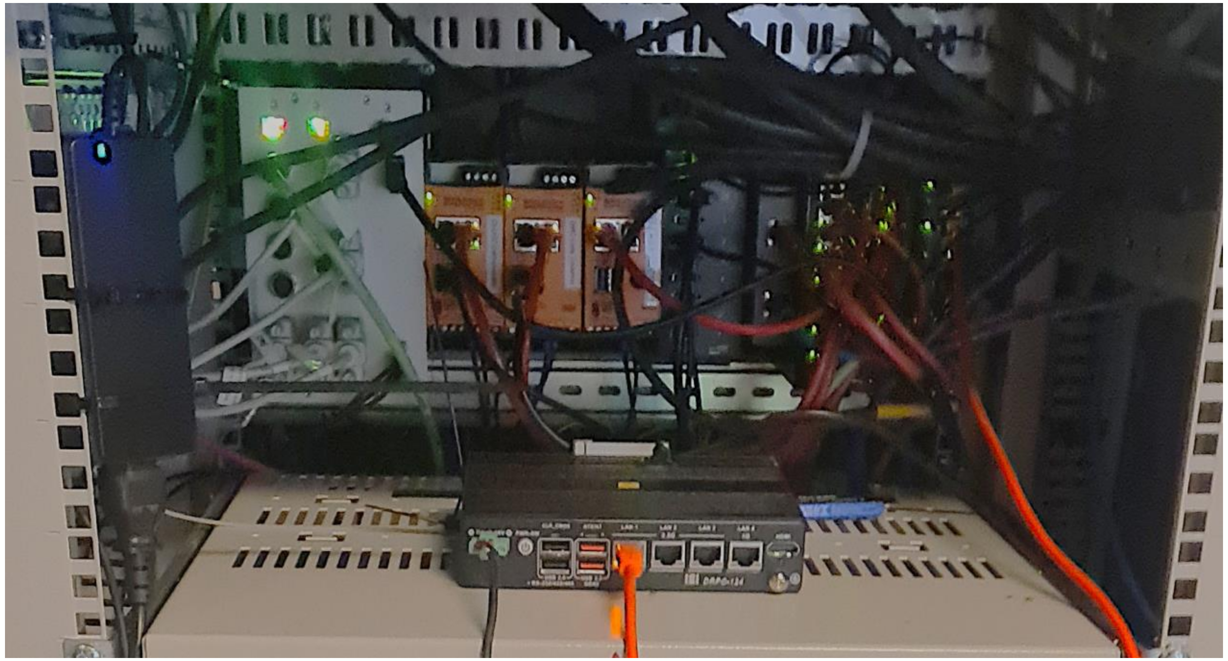
- Requirements for distance at operational surrounding «Stop» defined in CLUG2 (accuracy < 1.25m and confidence interval < 10m) remain demanding

- Even in challenging urban and mountainous environment, the LOC-OB maintains good performance in line with railway operational needs

Demonstrator

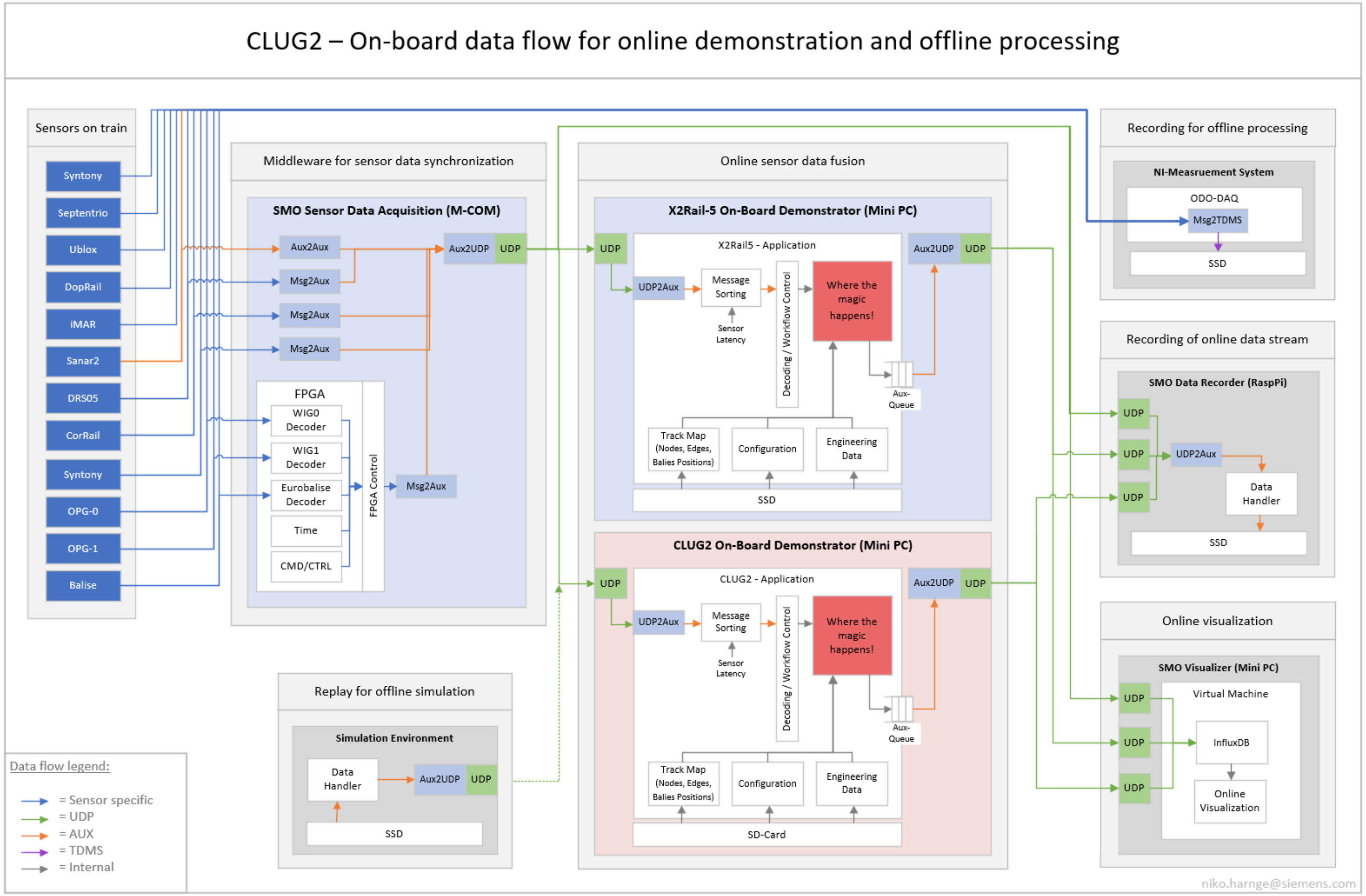
Demonstrator

- One of the major additions in CLUG 2 compared to earlier projects was the development of a real time demonstrator to be installed on one of the test trains, in addition to the offline processing of sensor fusion.
- The demonstrator was planned as functional demonstrator, and is therefore based on commercial, off the shelf components:
  - an M-COM module from the SMO rolling stock division, which is used to collect and time-stamp all sensor data,
  - a high performance, linux based embedded computer to perform the actual sensor fusion, and
  - a separate, embedded computer to collect both synchronised sensor data and sensor fusion results for later analysis.



Architecture of the CLUG2 Demonstrator

- The demonstrator is built as a modular system, permitting recording of raw and synchronised sensor data, as well as algorithm outputs.
- This even allows parallel execution of multiple algorithms, e.g. from X2-Rail 5 and CLUG 2



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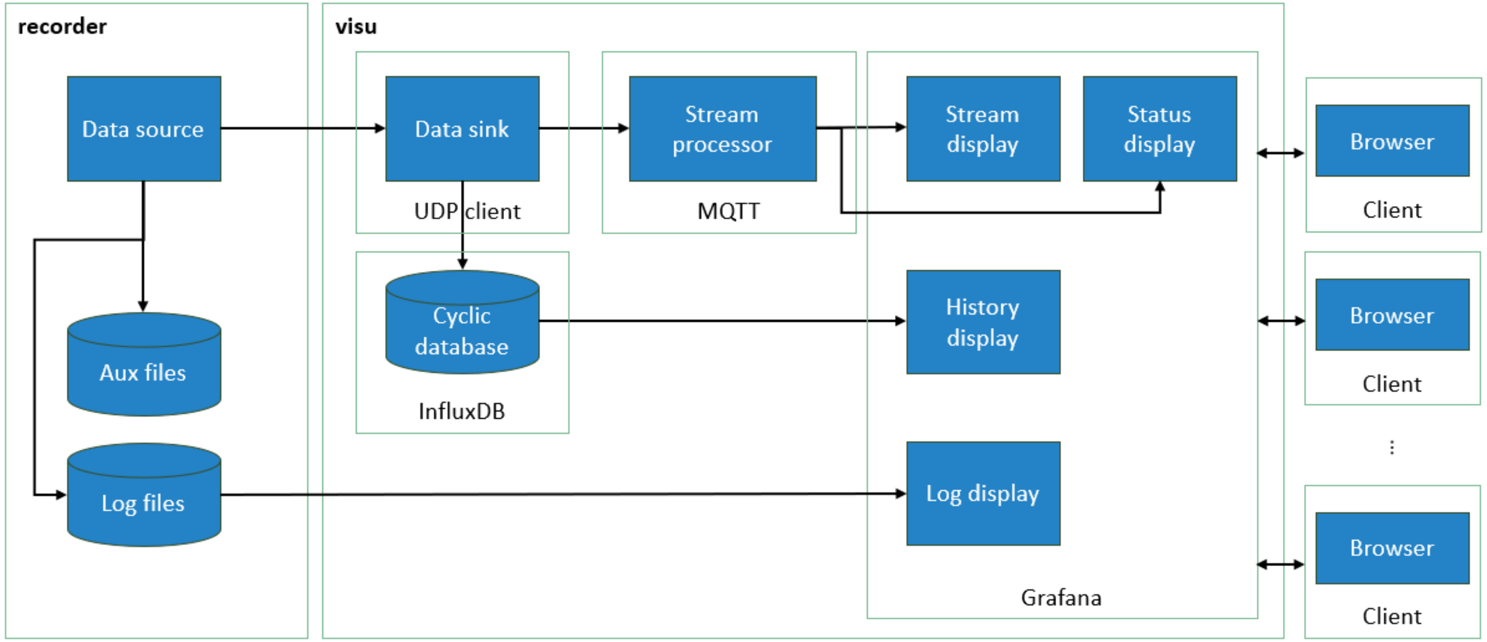
Demonstrator Live Visualization

- A tool was also developed to visualise the data generated by the demonstrator in real. This tool runs on a PC onboard the train, which is part of the data collection system, but it can also run on any other computer connected to the demonstrator via the onboard network, or even via remote.



Demonstrator Data Analysis

- Key goal of the demonstrator was to show that the fusion algorithm used for offline data processing can also be used onboard the train in real-time and shows comparable results.
- This could be confirmed, even though the algorithm used in the demonstrator did not include all elements of the offline demonstration, e.g., the use of EGNOS data for dual frequency / dual constellations, or some track selectivity elements.
- As no on-site visit of the demonstrator could be organised, we recorded the output of the visualisation tool together with a video from the cab of the train.

Link to Video 1 | Link to Video 2 | Link to Video 3

CLUG 2.0 D6.4
Cost-Benefit-Analysis

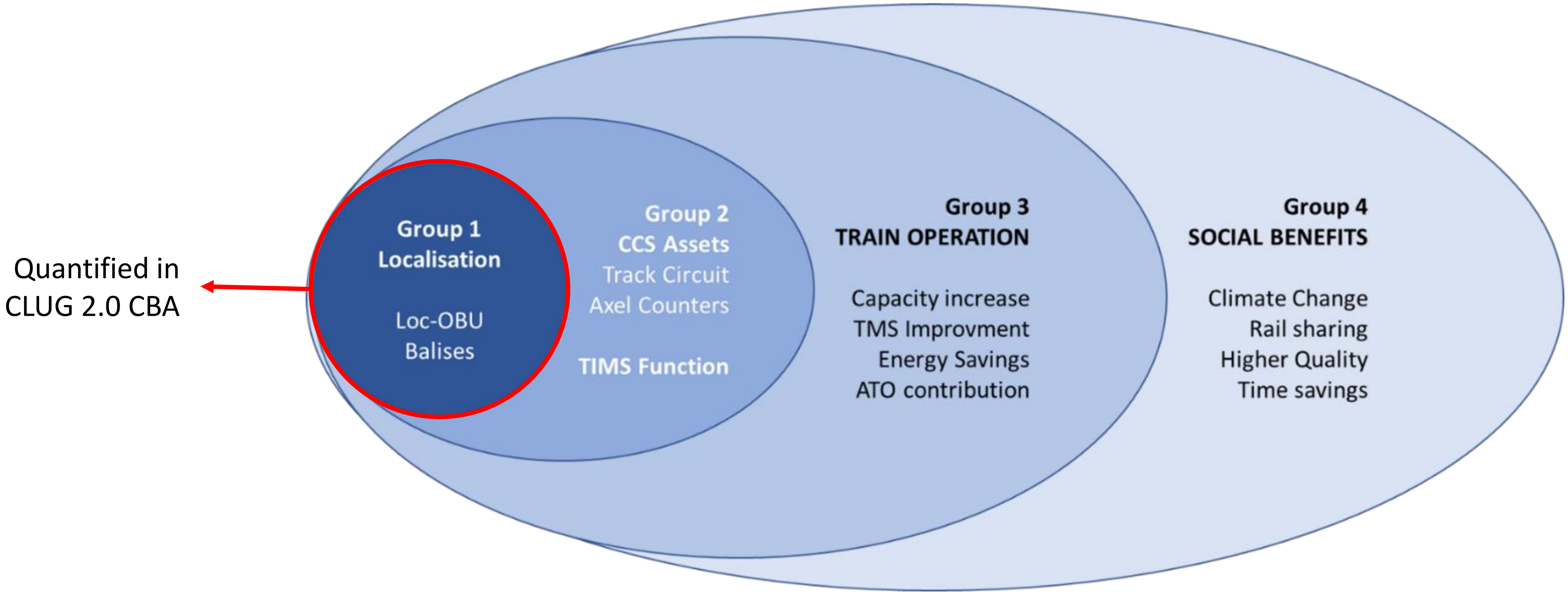
CLUG 2.0 Final Conference

Eric Ziese - DBN

Agenda

CBA scope

- CLUG 2.0 only considers safe localization solution
  →Scope of CBA is limited only to onboard localization, odometry systems & balises



General CBA mechanism

Cost transfer from trackside to onboard

Additional onboard costs

→Equipment of vehicles with LOC-OB, including:
- →Engineering costs
- →Hardware costs
- →Obsoloscence costs
- →Operation & maintenance costs

Reduced trackside costs

→No further requirement of Eurobalises only serving localisation function

→Implementation of reduced Eurobalise layout, leading to lower:
- →Hardware costs
- →Operation & maintenance costs

Profitability of LOC-OB implementation will be achieved if cost savings for reduced Eurobalise requirements outweigh additional costs for vehicle equipment

Considered business cases

	DB	SBB CFF FFS	SNCF
Scope	National	Line	National
Track type	Mixed	Mixed	Mixed
Track usage	Passengers & freight	Passengers & freight	Passengers only

Agenda

General methodological approach

- CBA model generally based on EUG TO CBA but applying more conservative approach & assumptions by:

  - Inclusion of LOC-OB engineering costs
  - Inclusion of LOC-OB obsolescence costs
  - Modelling of transition period from legacy odometry to LOC-OB
  - Sensitivity analysis for Eurobalise reduction ratio

Key cost and benefit parameters

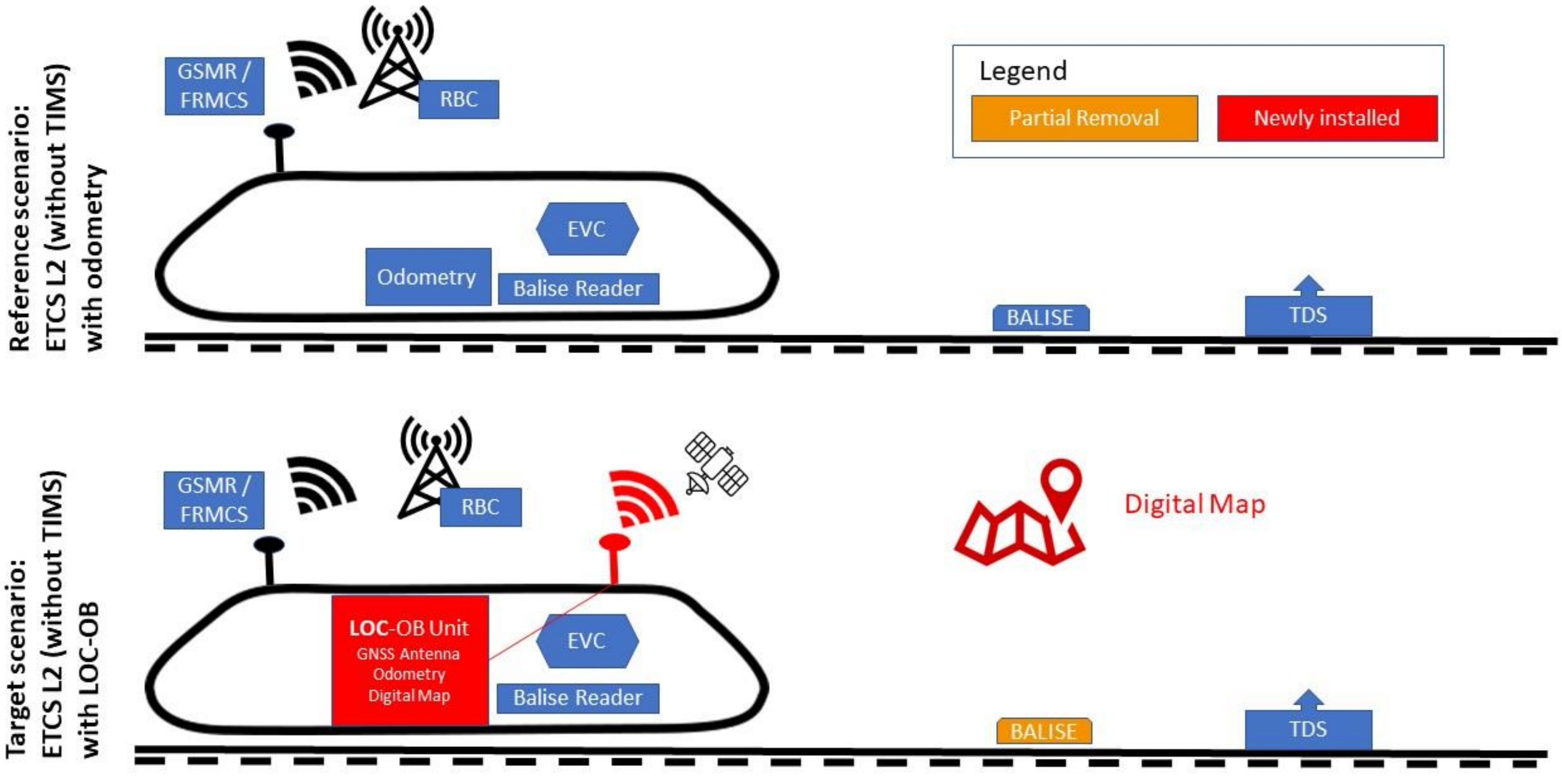
IMPACT	TYPE	ITEM	STAKEHOLDER	NATURE	
Costs	Onboard	LOC-OB unit	RU	CAPEX / OPEX	Main cost driver
	Trackside	Digital Mapping	IM	CAPEX / OPEX	
Benefits	Trackside	Eurobalise	IM	CAPEX / OPEX	Main benefit driver
	Onboard	Odometry function	RU	CAPEX / OPEX	
	Onboard	Current GNSS onboard solutions for non-safe applications	RU	CAPEX / OPEX	

Scenario overview

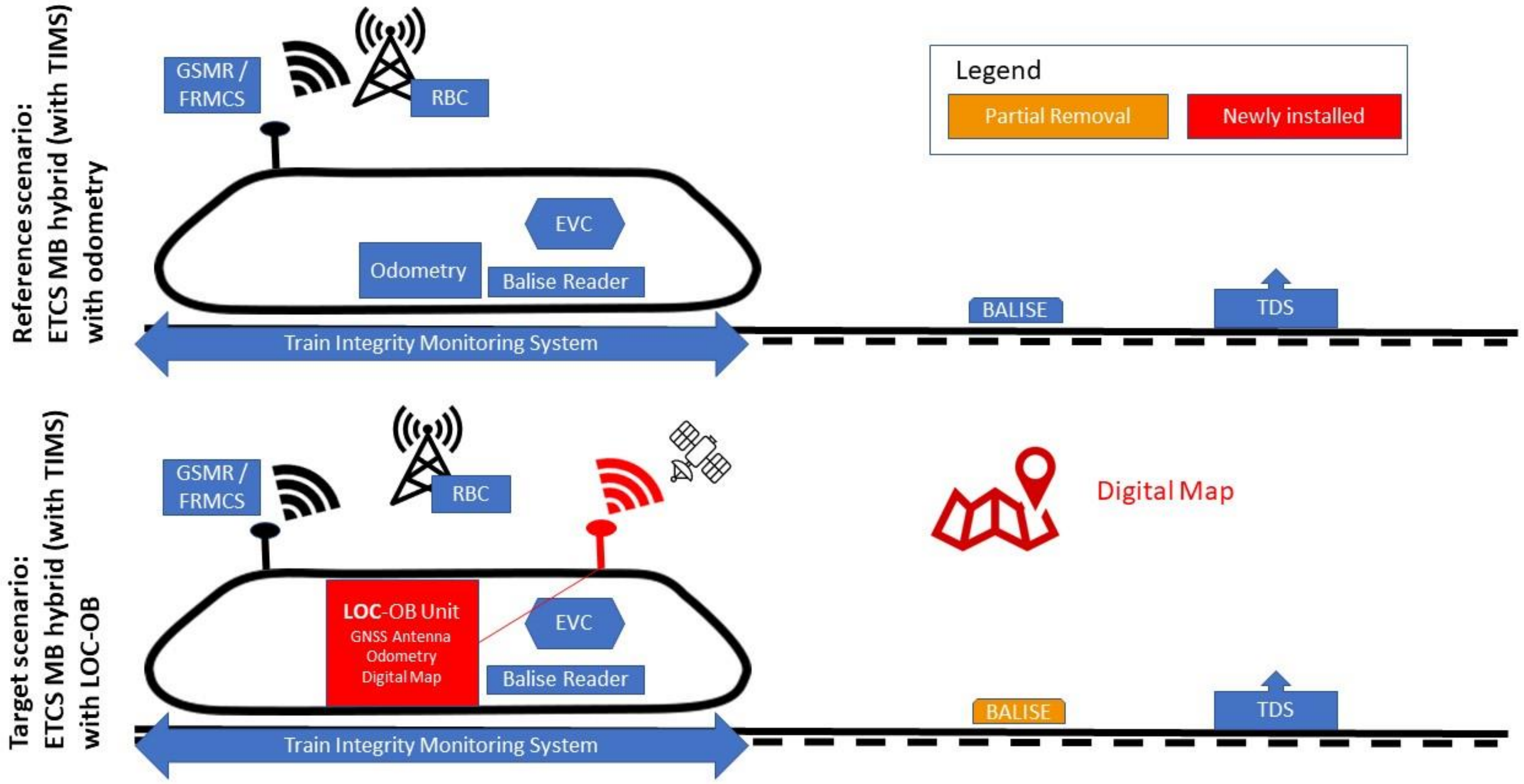
CBA conducts two scenario comparisons:

	Sub-comparison 1 (ETCS L2 fixed block)	**Sub-comparison 2 (ETCS L2 MB hybrid)**
Reference scenarios	ETCS L2 (without TIMS) with odometry	ETCS MB hybrid (with TIMS) with odometry
Target scenarios	ETCS L2 (without TIMS) with LOC-OB	ETCS MB hybrid (with TIMS) with LOC-OB

Sub-comparison 1: ETCS L2 fixed block

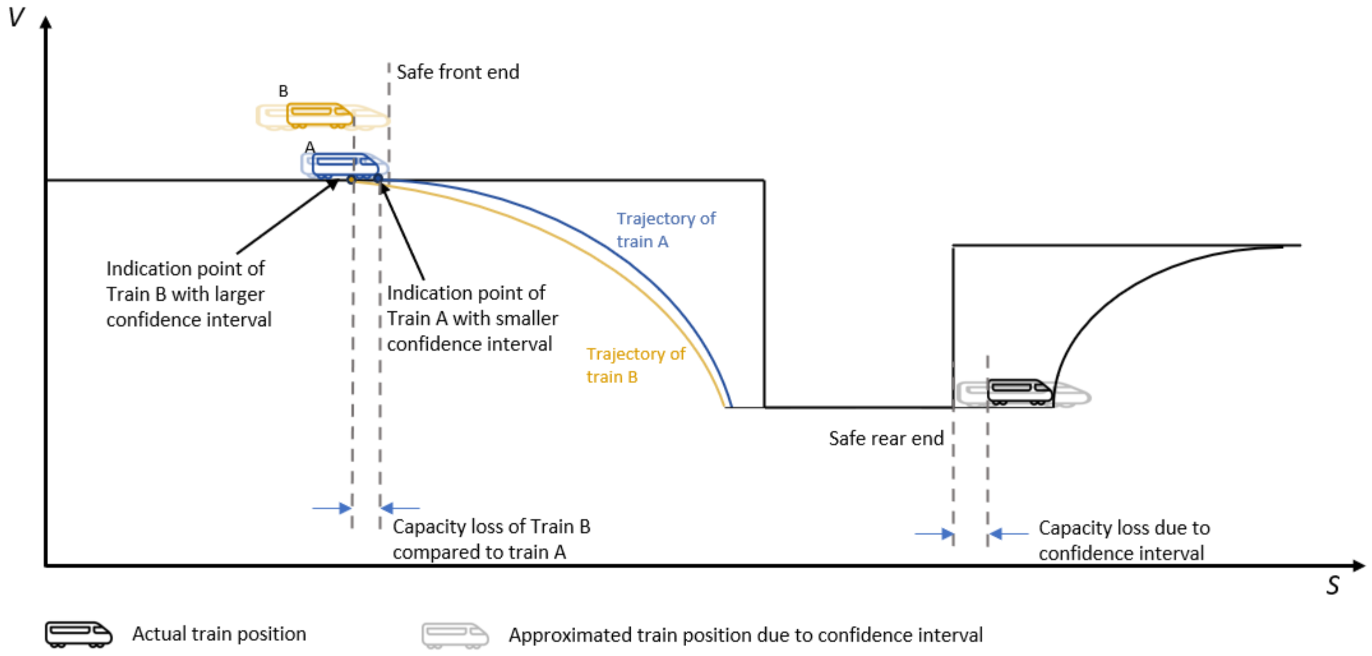


Sub-comparison 2: ETCS L2 moving block hybrid



Reasoning ETCS MB hybrid scenario

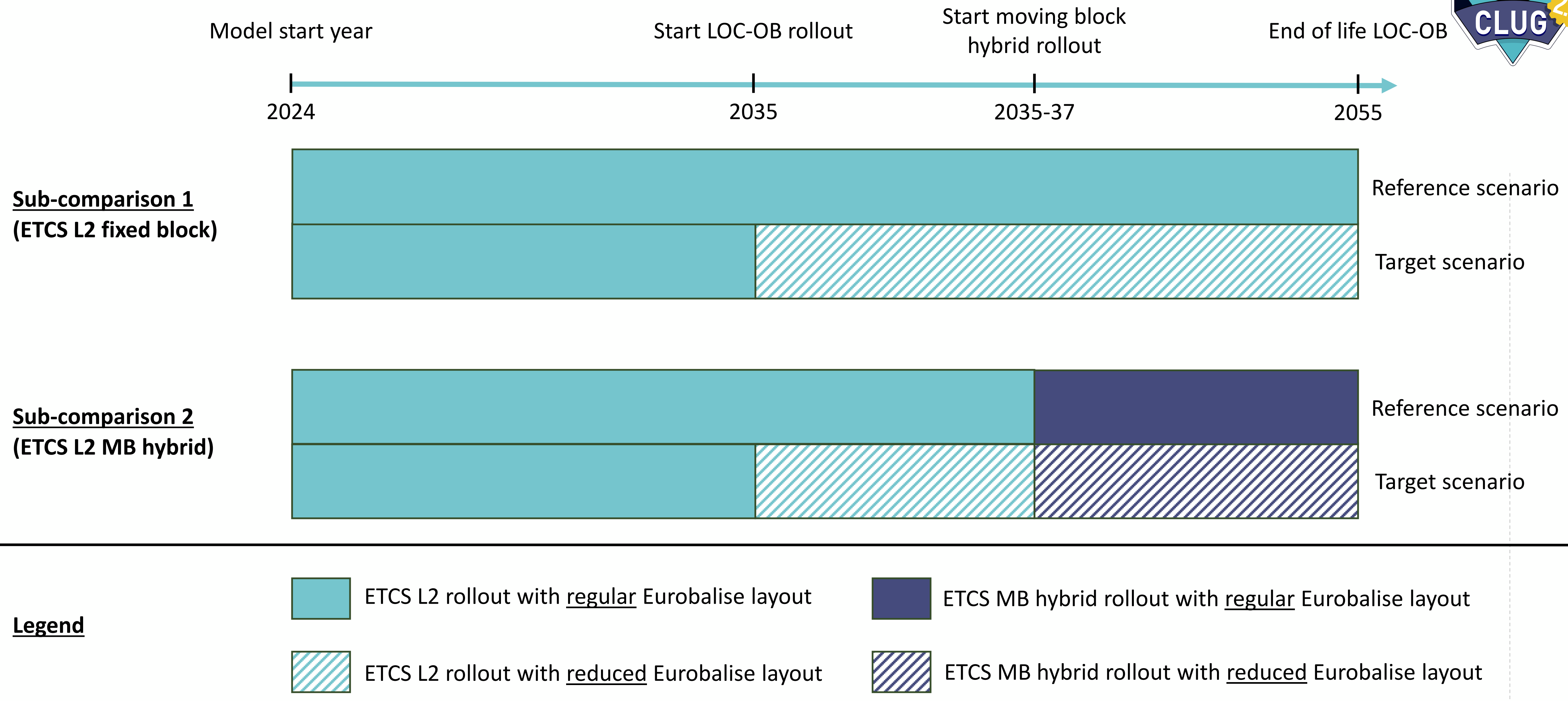
- Evaluation of MB hybrid based on additional potential for Eurobalise reduction



Mechanism:

- Continuous localisation by LOC-OB enables lower average confidence interval
- Lower confidence interval enables better operational performance under moving block hybrid
- To reach same operational performance using legacy odometry, additional balises are required

Scenario sequence modelling



CBA model limitations

- Selective vehicle equipment will incur further costs or hinder operational restrictions
- No consideration of equipment costs for new vehicles
- No consideration of costs for EGNOS transmission
- No consideration of balise reduction for existing parts of ETCS track

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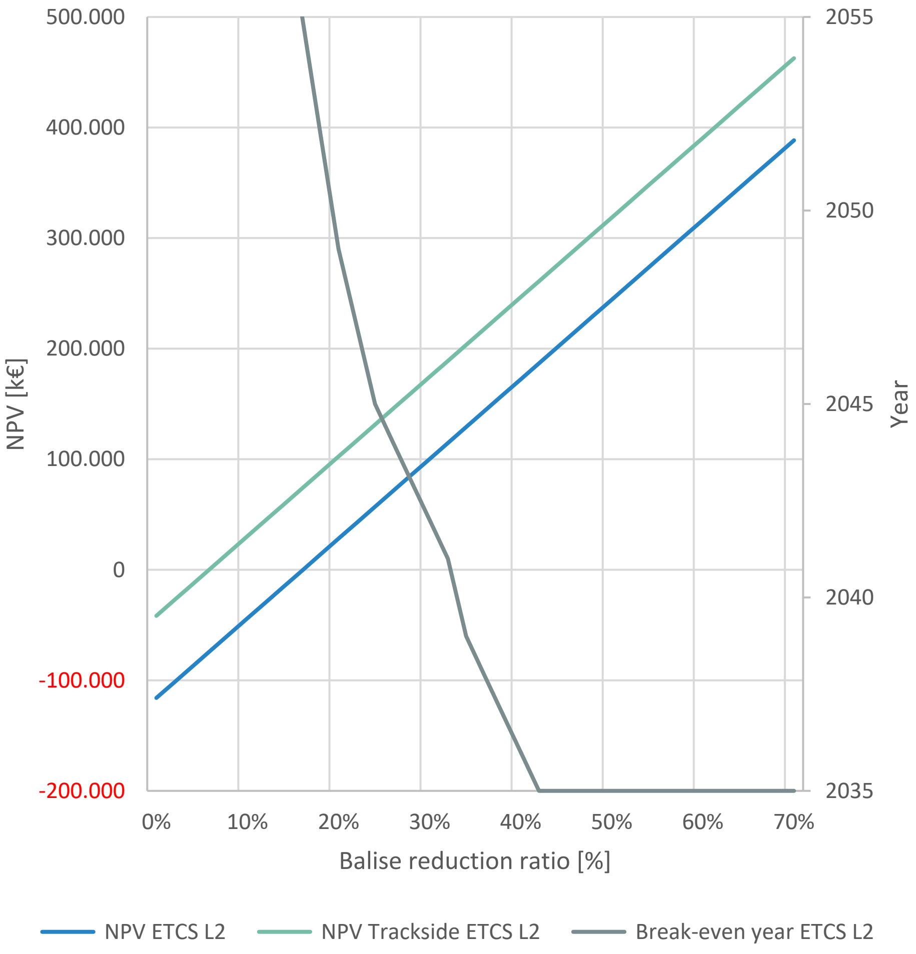
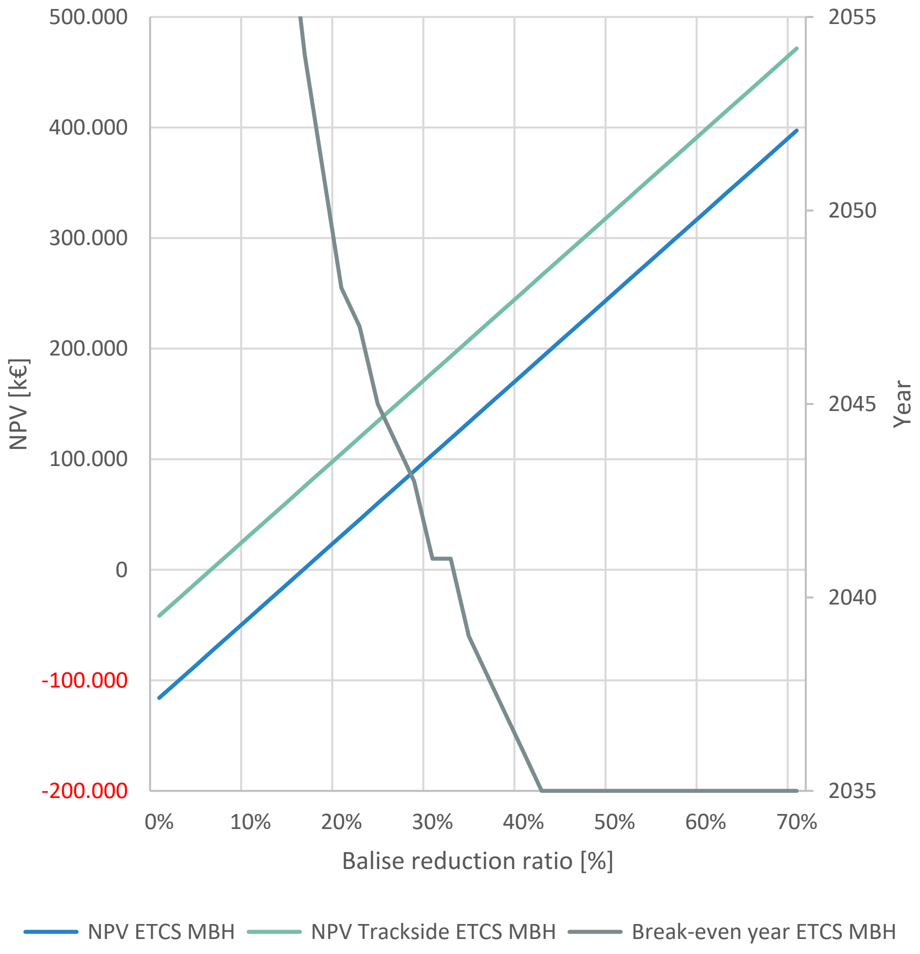
Agenda

DB: Sensitivity analysis results

Sub-comparison 1: ETCS L2

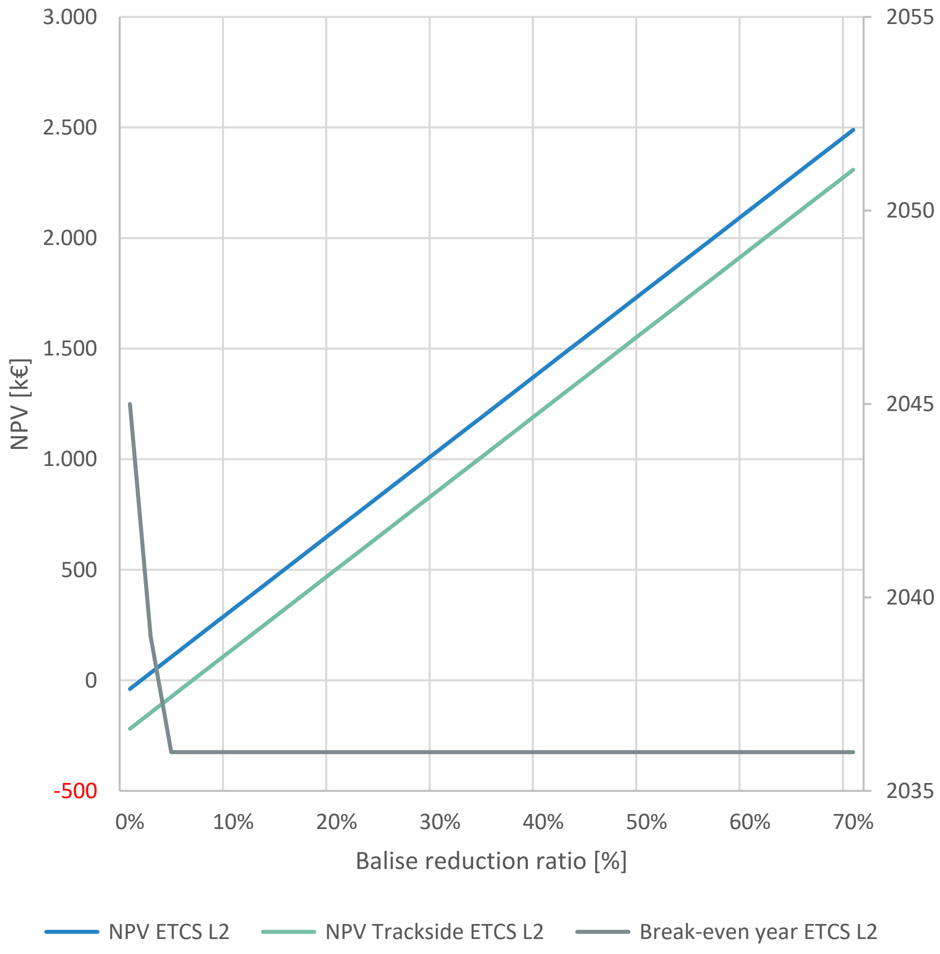


Sub-comparison 2: ETCS MB hybrid

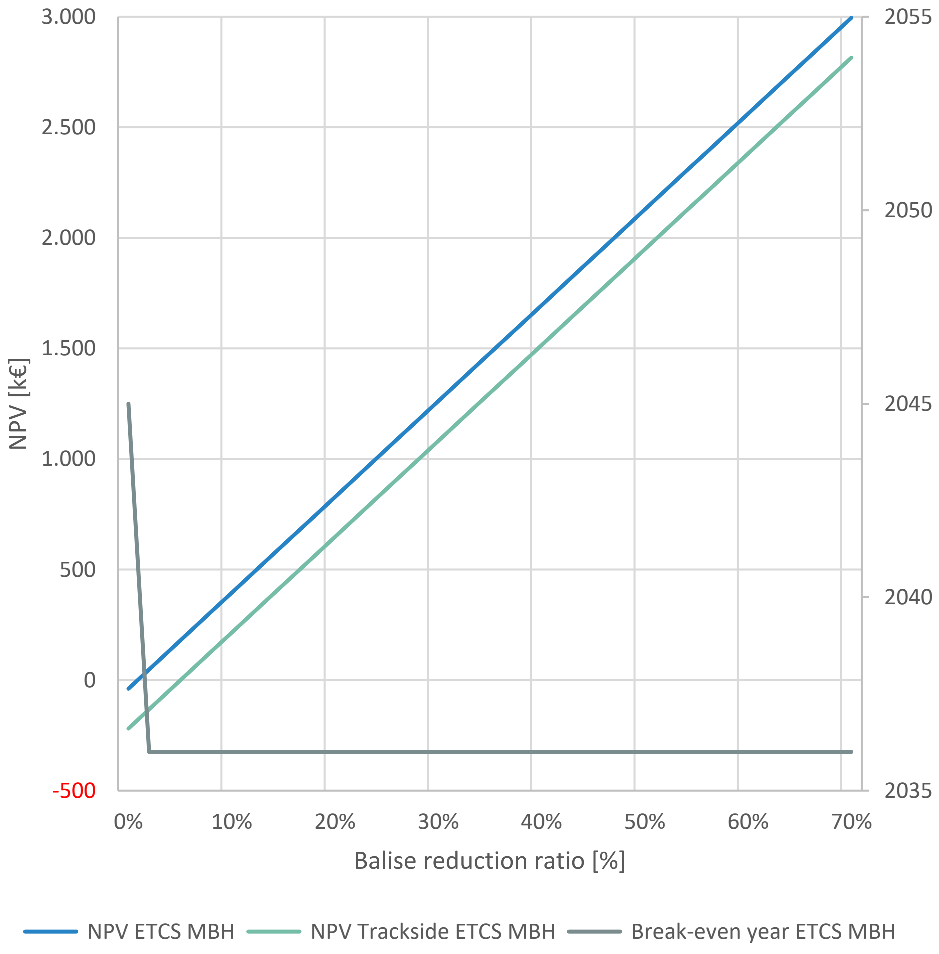


SBB: Sensitivity analysis results

Sub-comparison 1: ETCS L2

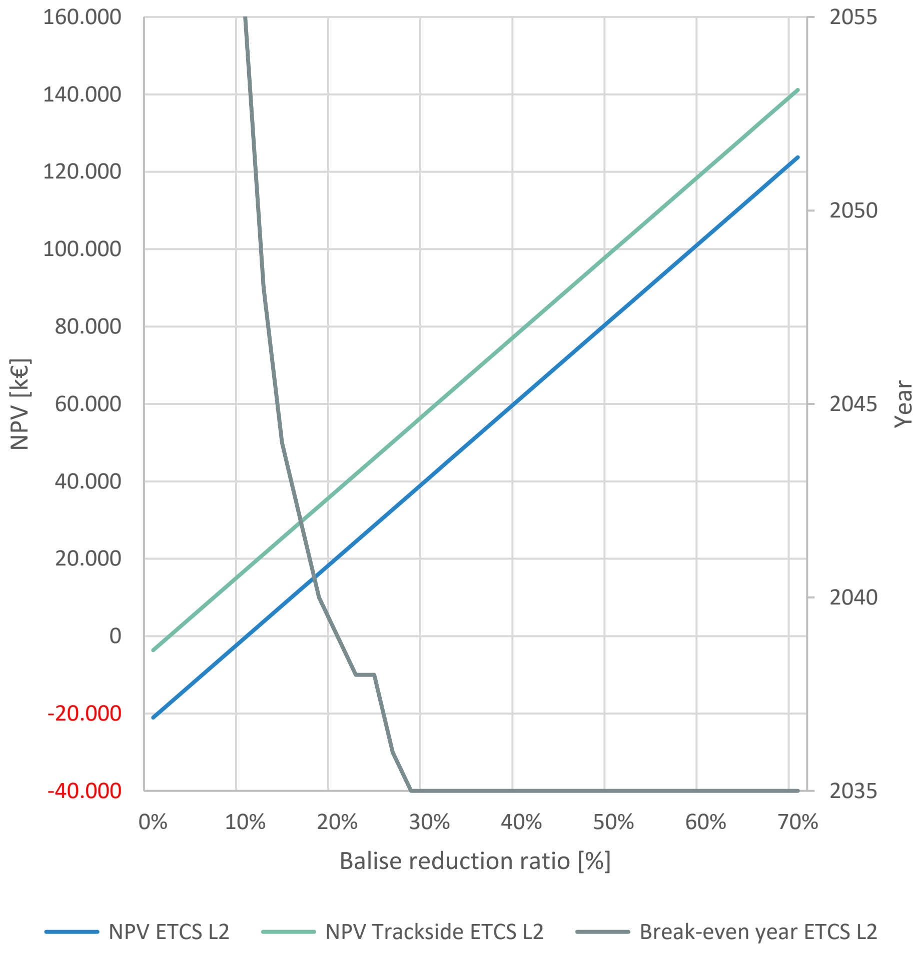


Sub-comparison 2: ETCS MB hybrid

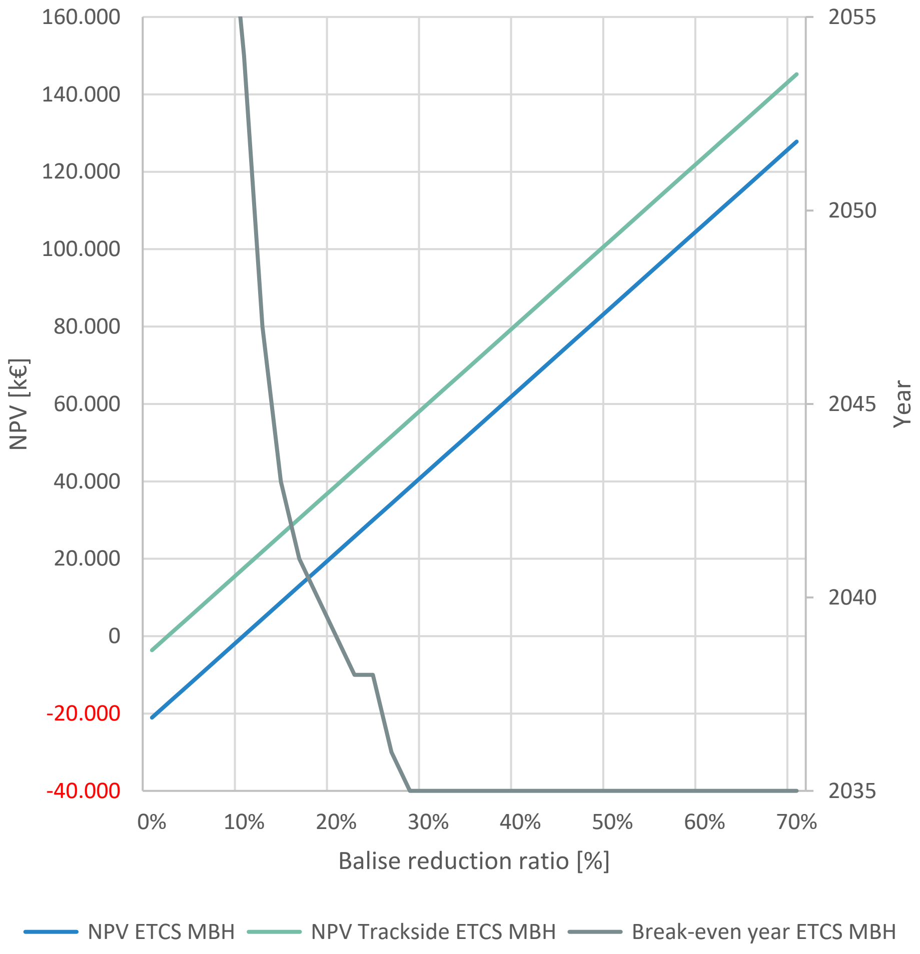


SNCF: Sensitivity analysis results

Sub-comparison 1: ETCS L2



Sub-comparison 2: ETCS MB hybrid



Agenda

Main CBA takeaways

- LOC-OB shows potential for profitability even for Eurobalise reduction ratios <50%
- Larger scale implementation yields overall better results
- Delay in LOC-OB availability diminishes benefits as ETCS rollout advances
- LOC-OB implementation results in cost shift from trackside to onboard

CLUG 2.0 GAP ANALYSIS

Adrien Gharios (SNCF)

Reminder of CLUG 2.0 interaction with other ongoing initiatives (definitions alignment)

- System Pillar : train CS domain
  - LOC-OB = Full ASTP.
  - Basic ASTP is not tackled on in the scope of CLUG2.0.

- Innovation pillar : FP2 WP21/WP22
  - LOC-OB = ASTP.
  - Basic ASTP is not tackled on in the scope of WP21/22.

Reminder of CLUG 2.0 Gap Analysis

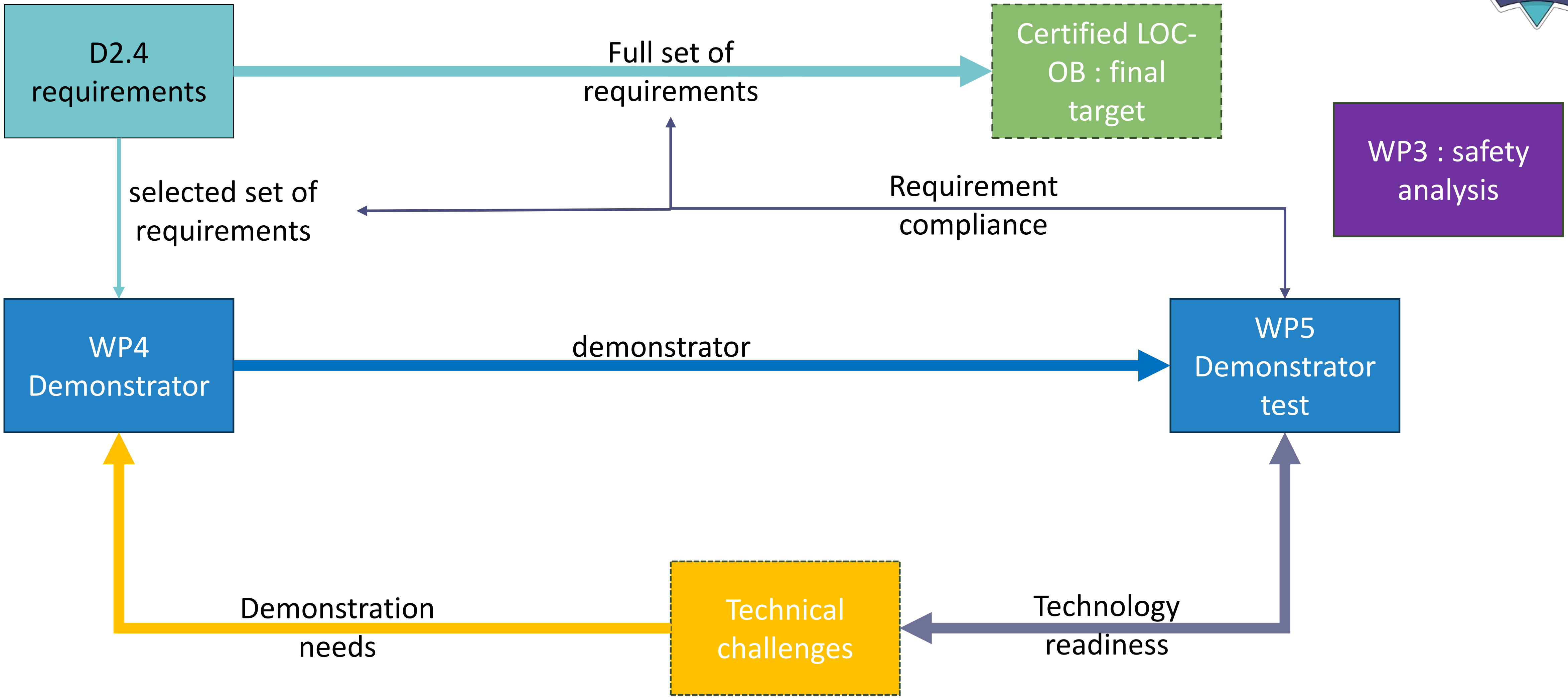
CLUG2.0 Gap Analysis is divided in three main tasks :

1. Re-evaluation of the system requirements
2. ETCS gap analysis
3. Overall Gap analysis

The results of the CLUG2.0 gap analysis are formalised in D6.6 publicly available.

Re-evaluation of the system requirements

Re-valuation of the system requirement : overview



Re-valuation of the system requirement : main facts

- Performance requirements where not consider since test results are not yet available.

- Most of identified discrepancies are related to the unavailability of a CCS onboard architecture and unclear functional allocation between the CCS-Onboard constituents.

- Significant effort is still needed from the sector. Most of the needed clarifications are not purely technical and require the sector to take decisions.

ETCS gap analysis

Reminder of the subsets

Objectives :

- Interoperability
- European harmonisation
- "High-level" specifications where only the critical points for interoperability are defined

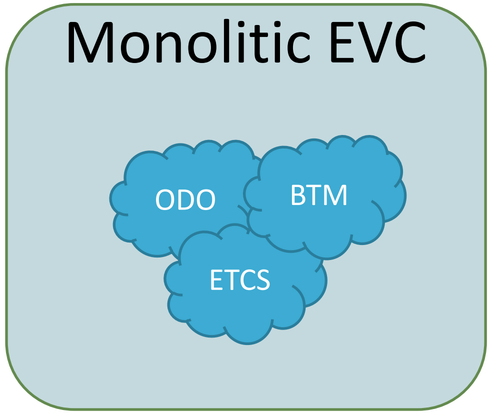
Facts :

- Interpretability
- Top-down but also bottom-up approach
- ETCS / EVC seen as a monolithic component

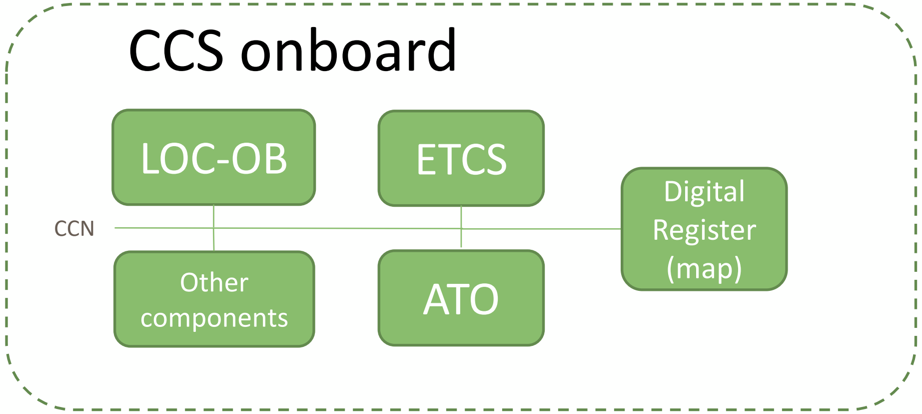
Introduction of LOC-OB, main disruptions :

Architecture, functional allocation and interfaces

Today's architecture
(simplified view)



Future targeted architecture, LOC-OB replacing the odometry constituent



ODO : odometry
BTM : Balise Transmission Module
ETCS : European Train Control System
ATO : Automatic Train Operation
CCS : Control Command and Signalling

Introduction of LOC-OB, main disruptions :
Architecture, functional allocation and interfaces

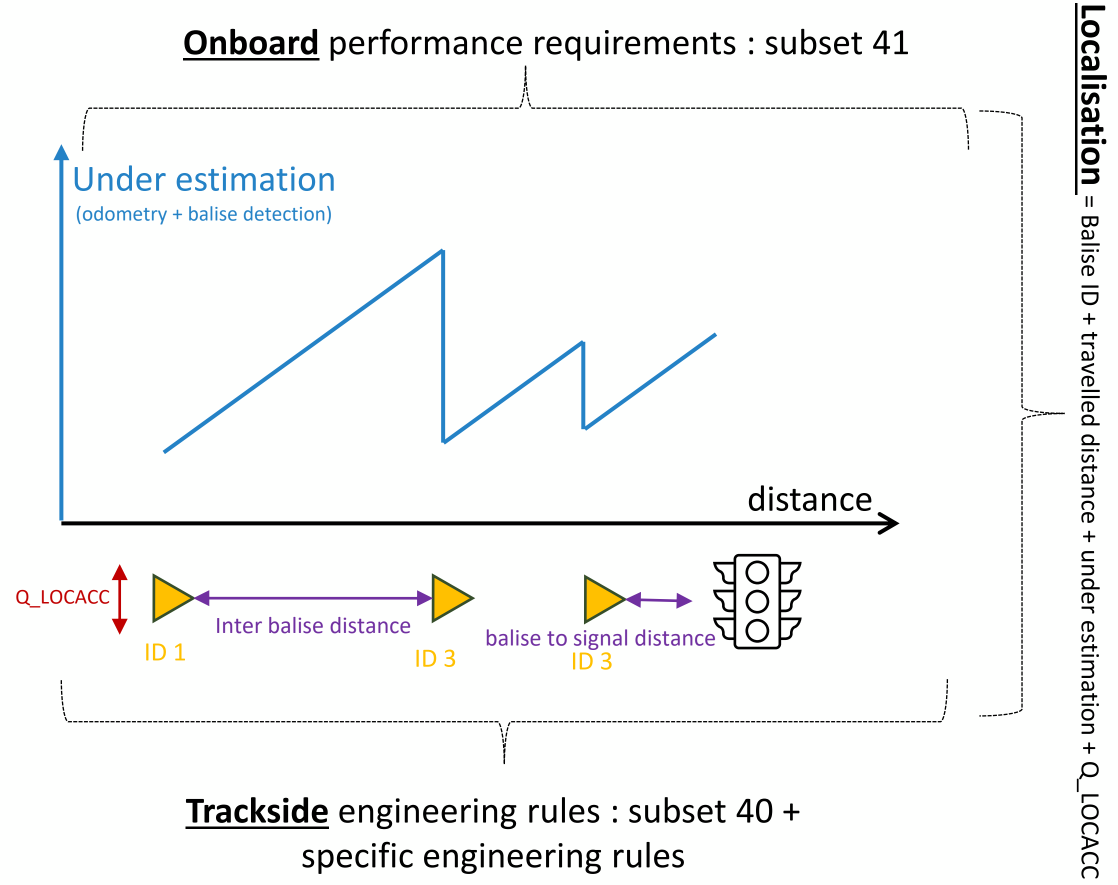
- Agreement on functional allocation (for illustration, which component translate the LOC-OB localisation to the train front end position)

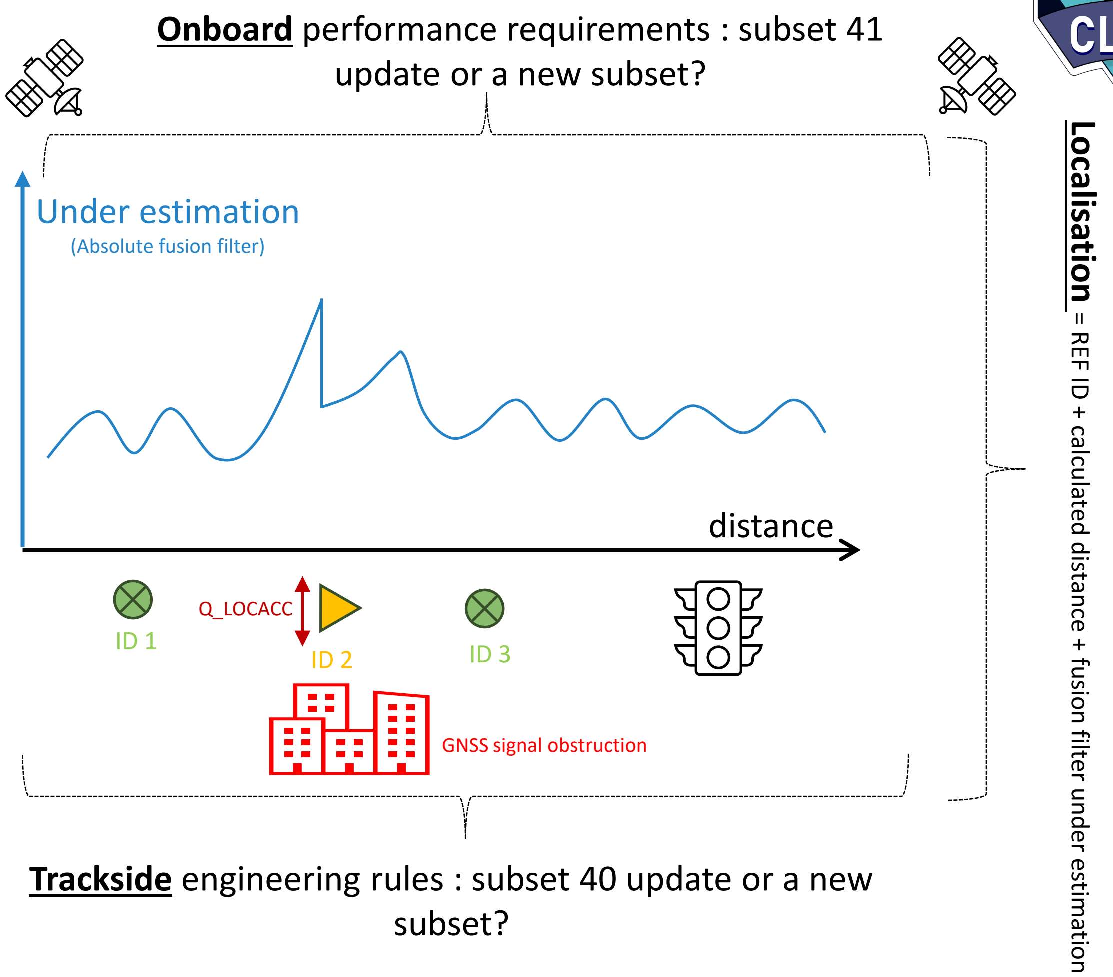
- Definition of standardised interfaces : LOC-OB to users
  - Definition of standardised application data depending on the functions allocated to LOC-OB
  - Definition of the FFFIS

- Definition of standardised interfaces : LOC-OB supporting information
  - Identification of the mandatory supporting information
  - Definition of standardised application data
  - Definition of the FFFIS

Introduction of LOC-OB, main disruptions :

From Odometry / Balise technology to GNSS based technology





Physical eurobalise

Virtual reference location (map)

Introduction of LOC-OB, main disruptions :

From Odometry / Balise technology to GNSS based technology

- EUROBALISE concept is a corner stone of ETCS :
  - Can we reduce the number of physical balises without impacting safety and performance?
  - How to handle physical balises and Virtual reference locations in parallel?
- New model of accuracy :
  - What is the real impact on ETCS if over estimation and underestimation is not following the “sawtooth” model?
- Specific exported constraints to trackside :
  - How to handle exported constraints to trackside (tunnels, Multipath areas, etc)?
- What about retro compatibility :
  - LOC-OB onboard on a line without a map?
  - ODO / Balise onboard on a line with reduced number of balises?

Introduction of LOC-OB, main disruptions :

illustration on the subsets impact

SUBSET	Impacted by the LOC-OB introduction
Subset 026: System requirement specification (V4.0.0)	Major impact, general description and mechanisms, modification of the model of accuracy, extension of Balise Group to any type of reference location.
Subset 034: Train interface FIS (V4.0.0)	Introduction of LOC-OB to train interface.
Subset 040: Dimensioning and Engineering rules (V4.0.0)	Major impact related to the balise removal and the introduction of new rules related to areas where GNSS may struggle.
Subset 041: Performance requirements for interoperability (V4.0.0)	Major impact related to the model of accuracy and performances.
Subset 088: ETCS Application Levels 1 & 2 - Safety Analysis (V3.7.0)	Major impact related to the balise removal.
Subset 091: Safety Requirements for the Technical Interoperability of ETCS in Levels 1 & 2 (V4.0.0)	Major impact related to the balise removal.
Subset 119: Train Interface FFFIS (V4.0.0)	Introduction of LOC-OB to train interface.
Subset 125: ERTMS/ATO: System Requirements Specification (V1.0.0)	ATO receive the train localisation through ETCS. The introduction of LOC-OB can impact this principle.

Overall Gap analysis

Overall Gap analysis : main conclusions

- Technology readiness : Positive results from CLUG2.0, TRL still need to be improved to trigger a change request.

- Safety demonstration : No blocking points identified but several demonstrations are still to be consolidated and can be considered as risks.

- Impact on ETCS : Still numerous questions to be tackled. Depending on the sector decision, impacts on the subsets can be consequent.

Follow up activities

- System Pillar Train CS
  - Focus on the introduction of ASTP into the TSI
  - Two step approach
    - Basic ASTP = Enhanced odometry
    - Full ASTP = LOC-OB

- Innovation Pillar R2DATO FP2 (WP21/WP22)
  - Focus on the technology readiness
  - Basic ASTP is not in the scope on the project

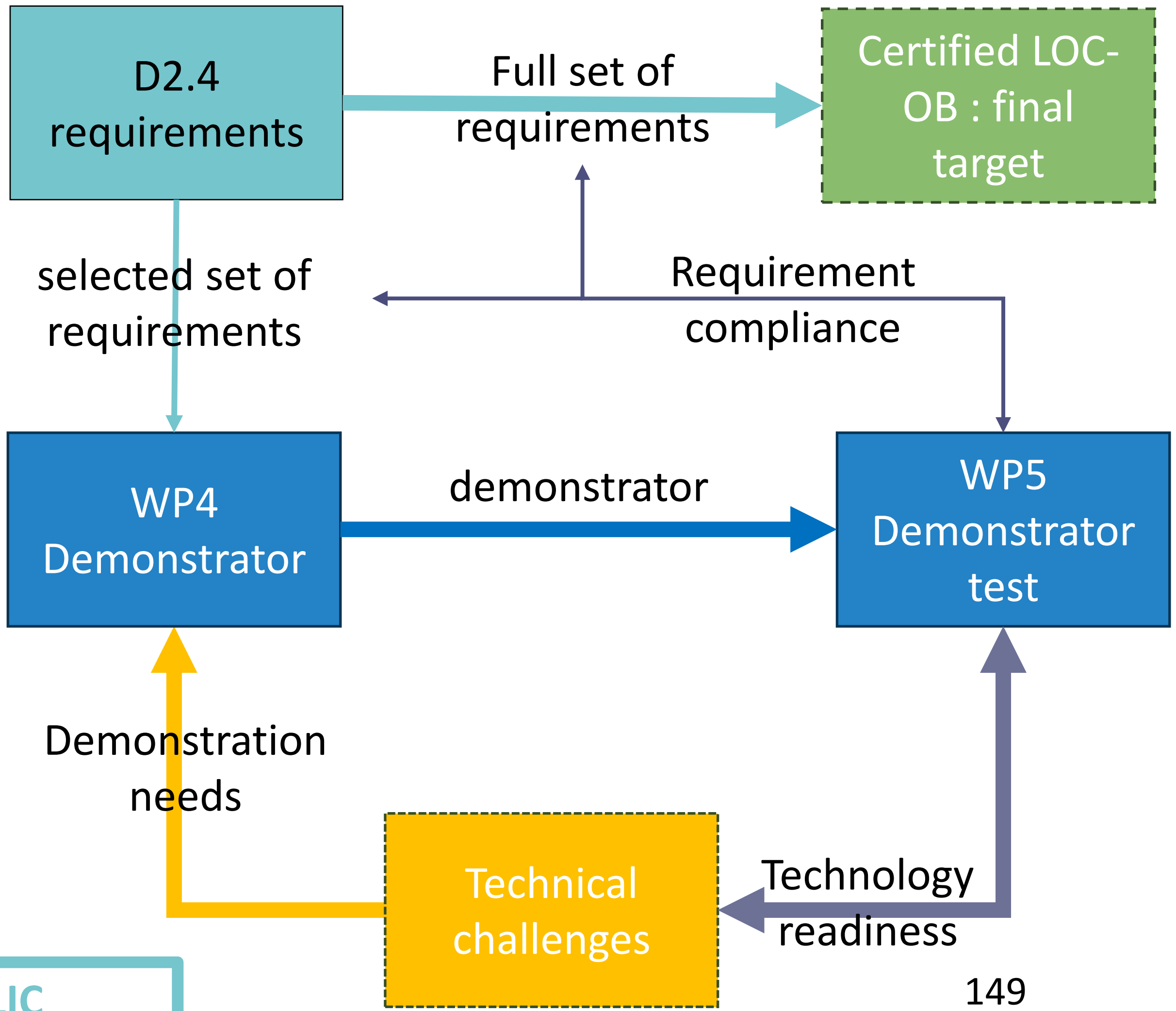
Project Results, achievements and future activities

Adrien Gharios – SNCF
On behalf of CLUG 2.0 project technical coordinator

Project results

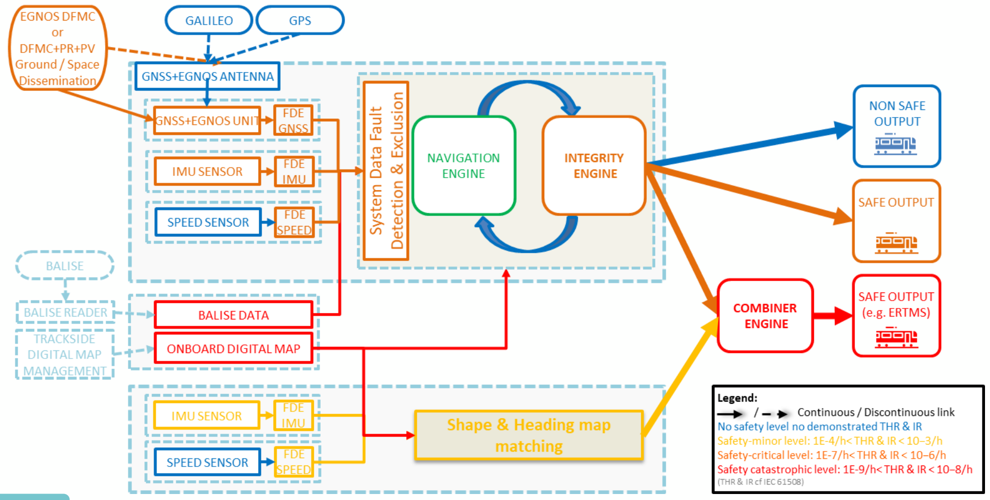
Requirements

- WP2 provided a set of requirements focusing on an assumption of the “certified final product”.
- Most of identified discrepancies are related to the unavailability of a CCS onboard architecture and unclear functional allocation between the CCS-Onboard constituents.
- Significant effort is still needed from the sector. Most of the needed clarifications are not purely technical and require the sector to take decisions that cannot be taken by CLUG 2.0 consortium.



Architecture & safety concept

- Consolidation of localization system architecture and of the associated safety concept and RAMS analysis focusing on two variants:
  - 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 :
    - The GNSS/INS solution using EGNOS corrections chain
    - An additional INS/Carto Shape map-matching chain
    - With a SIL4 combiner



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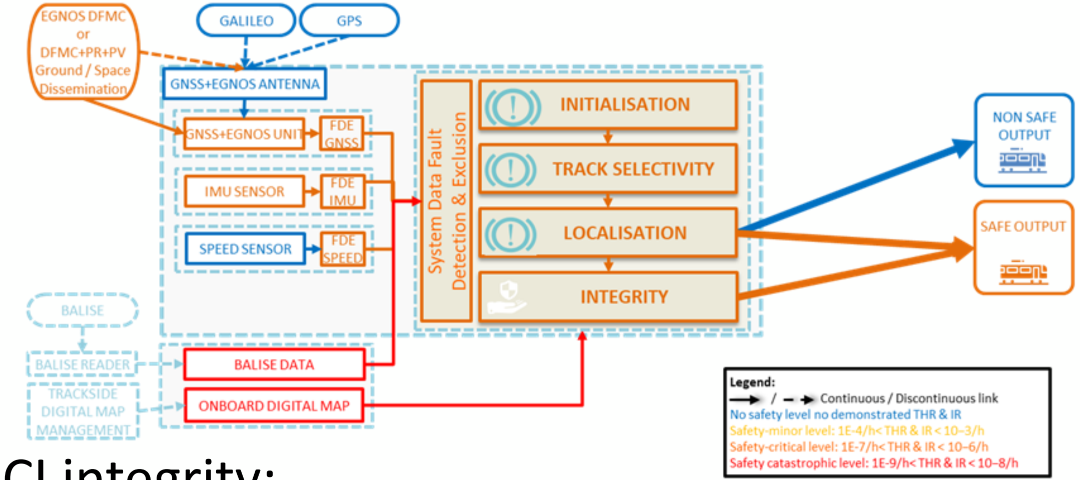
Architecture & prototyping

- Development :
  - Focus made on the GNSS/INS chain using EGNOS
  - Targeting the prototyping of the main components
    - Along-Track algorithm robustification
    - Track Selectivity module
    - Sensor and system levels FDE algorithms
    - Confidence Intervals computation
    - Emulator of DFMC corrections (PR and PR+PV)



- Considerations of potential sensor's faulty data in CI integrity:
  - « All satellites and speed sensor Faulty » CI → unrealistic and pessimistic scenario, over-safe
  - « X-satellites-faulty » CI → realistic scenario without safety demonstration (to be made and not implemented)
  - « All Fault-Free » CI → optimistic scenario with safety deficiency

- Simulation of the double chain architecture to relax the challenging CI THR allocated to the single chain

Safety conclusions

- Output functions:
  - 1D Position and 1D speed shall be provided in SIL4. 1D acceleration and the track ID are also expected in SIL4 but needs to be confirmed.
  - No need of safety related to 3D data up to now

- In the context of the architecture developed in CLUG2, an EGNOS for Rail service (with a failure rate of 2.4E-6 per hour) is considered necessary to achieve the safety targets of the LOC-OB system

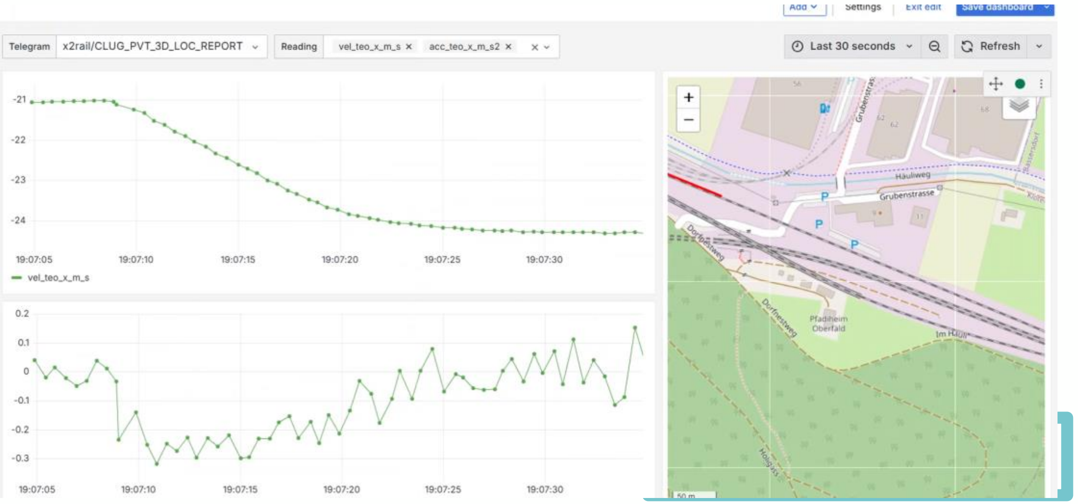
- The certifiability of Kalman Filter in SIL2 (dual chain) or SIL4 (single chain) shall be demonstrated in a future project

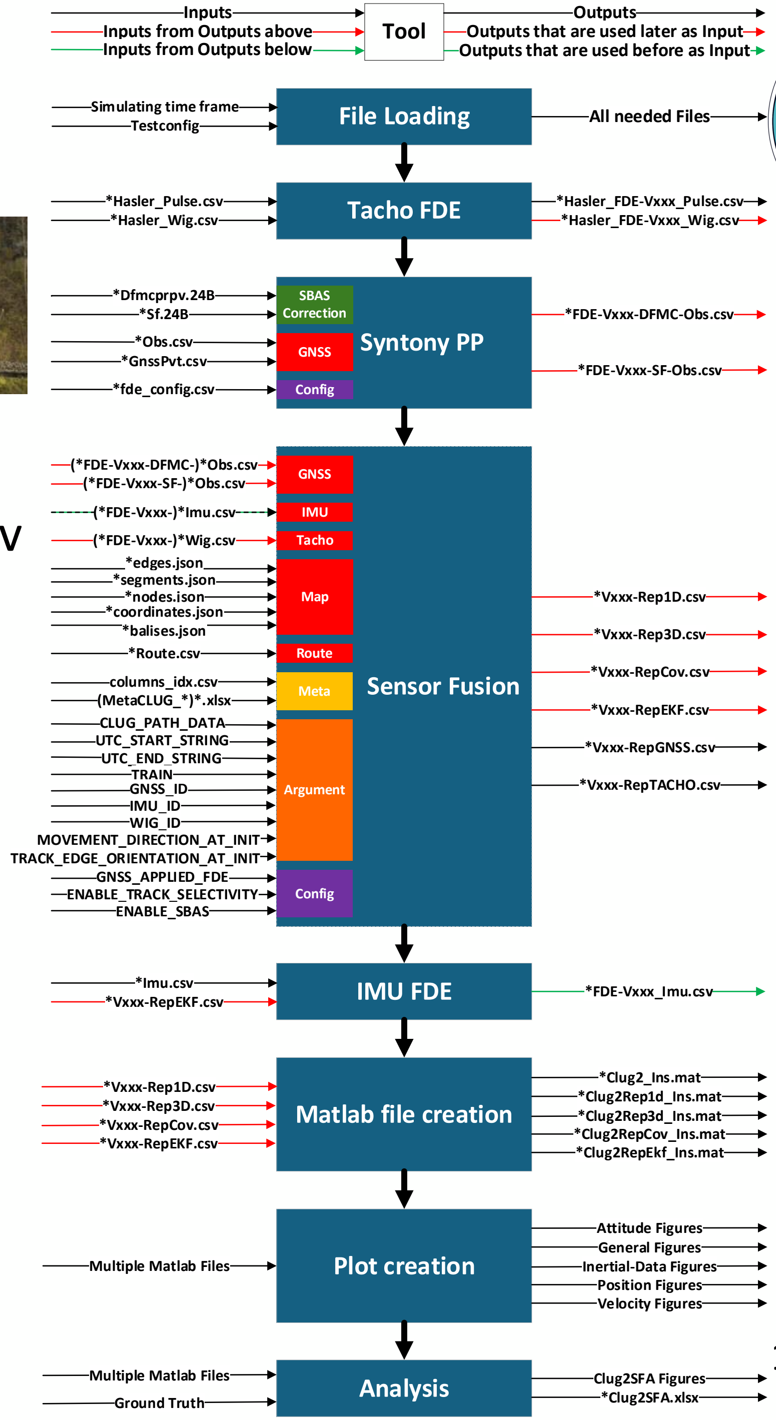
- To consolidate the safety approach, a full characterisation of the different FDE's will need to be performed to validate their expected failure rates

Performance analysis platform

- Data collection and preparation
  - Train preparation
  - Ground Truth definition and validation
  - ICD preparation and dataset format definition (CLUG 2.0 .csv files)
  - Postprocessing tool chain set-up

- Live demonstration of the Along-Track algorithm





Performance analysis results

- Single chain (GNSS) performance analysis conclusions based on real data postprocessing
  - The along-track position half-MCI requirement in "non-constrained" areas (60 m) is always achieved (fault free CI) in all trips (nominal and worst cases) and in all environment combinations.
  - The half-MCI requirement in "constrained" areas (10m) is achieved (fault free CI) in Open sky & suburban areas. Elsewhere balises could be used: every 500m for straight track, higher distance on curvy track
  - The « All satellites and speed sensor Faulty » restrictive assumption prevents to comply to the position MCI requirements
  - The along track-speed half-MCI requirement ([2 12]km/h) is achieved (fault free CI) in almost all trips; exceeding performances targets were observed in rare worst-case trips (GNSS-denied / tunnel and straight track) and can be solved by fine tunning the algorythmes.
  - Above results from real data postprocessing are consistent with the simulated performances (T4.11)

- Dual chain(GNSS//map matching) performance analysis conclusions based on simulation
  - Modelisation of the map matching chain may need to be consolidated in R2DATO.
  - Differences of CI amplitude between the two chains may penalise the SIL4 outputs of the combiner, because GNSS chain CI performance depends on local environment (clear sky to denied area) whereas shape map matching chain CI performance depends on track geometry (curved to straight)

Cost Benefit Analysis

- The CBA performed in CLUG 2.0 is oriented to the overall system costs and benefits but does not explicitly consider modularity.

- Considering 40k€ as a price assumption for the onboard unit, LOC-OB shows potential for profitability even for Eurobalise reduction ratios <50%, with a shift of cost from trackside to onboard

- Larger scale implementation yields overall better results

	Sub-comparison 1 (ETCS L2 fixed block)	Sub-comparison 2 (ETCS L2 MB hybrid)
REF scenario	ETCS L2 (without TIMS) with odometry	ETCS MB hybrid (with TIMS) with odometry
TARGET scenario	ETCS L2 (without TIMS) with LOC-OB	ETCS MB hybrid (with TIMS) with LOC-OB

Gap Analysis

- The gap analysis highlighted the level of maturity of LOC-OB specifications and the technology readiness, notably the remaining open points to be solved.

- The gaps between the current ETCS and the future ETCS compatible of LOC-OB have been analysed, concluding that introducing LOC-OB will have significant impact on TSI CCS

- Backward compatibility between trackside (balise layering) and onboards (train equipped with LOC-OB or not) will be an important factor in decision-making

Way forward

Future activities for LOC-OB development

- Solution development targeting TRL ramp-up to consolidate the safety and performance demonstrations
  - Development of the second chain (Shape map-matching) and the combiner to validate the performance
  - The FDE should be better characterized to consolidate the achievable safety level and associated CI
  - Compromise should be found in the integrity concept between safety and availability to optimize the performance
  - Refinement of the sensor models will increase performances without degrading safety
- Test of the LOC-OB with real DFMC data

Way forward in Europe's Rail

- CLUG 2.0 is one stone on the path to certification. Continuation of the activities lead to Europe's Rail:
  - CLUG 2.0 specifications have been pushed to FP2-R2DATO, in which specifications have been written at sector level and pushed to System Pillar for consolidation
  - CLUG 2.0 prototype pushed to FP2-R2DATO during which complementary developments and demonstrations are made (Shape map-matching, Combiner, "All-Faulty" CI consolidation)
  - CLUG 2.0 CBA pushed to SP-Train CS as input for the ASTP cost analysis realized at sector level
  - CLUG 2.0 Gap Analysis pushed as input to FP2-R2DATO WP22.5 in which the critical points will be analysed in more details at sector level

THANK YOU

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