Voliera Project – ESA contract 4000128511/19/NL/MP

VIDEO ODOMETRY WITH LIDAR AND EGNSS FOR ERTMS APPLICATIONS

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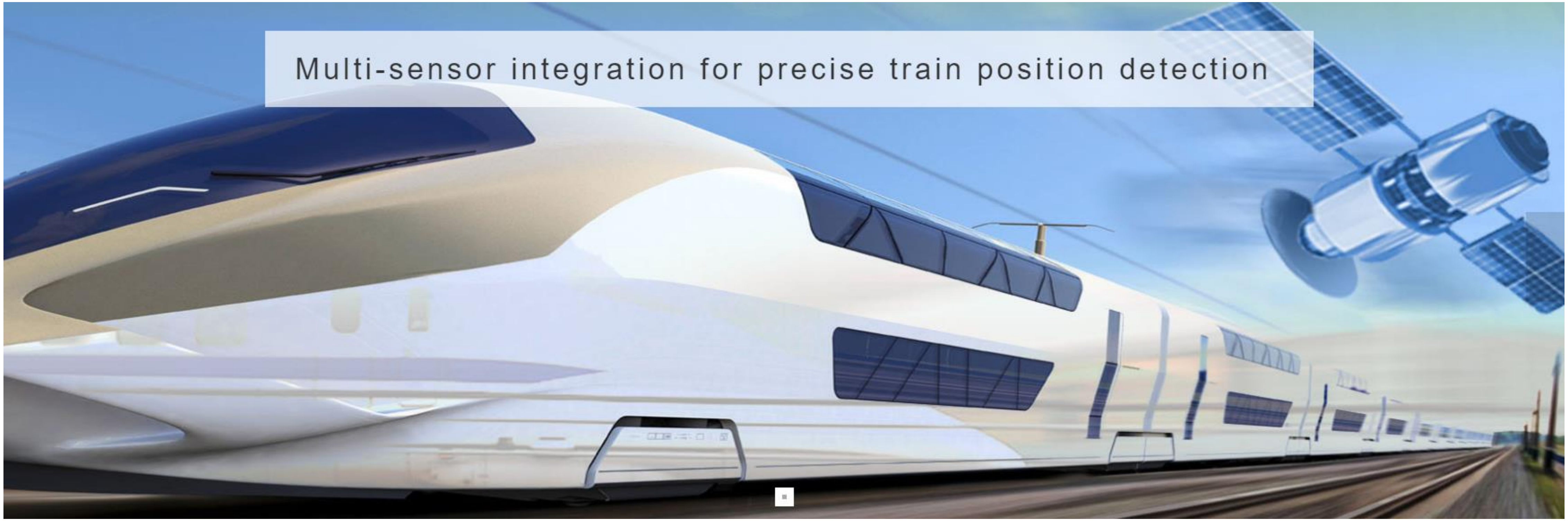
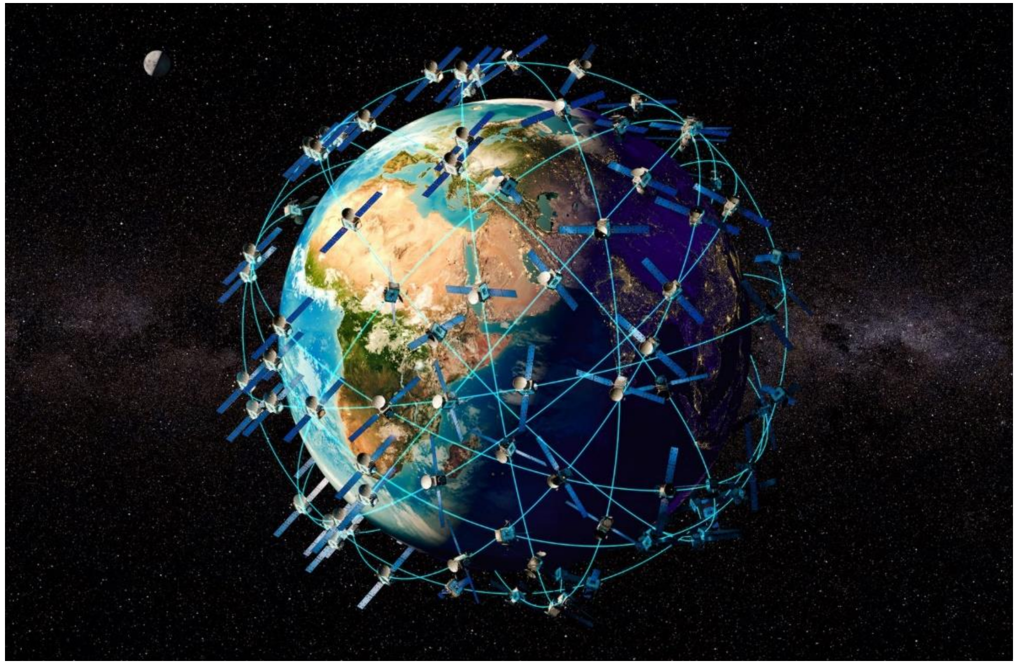
Introduction

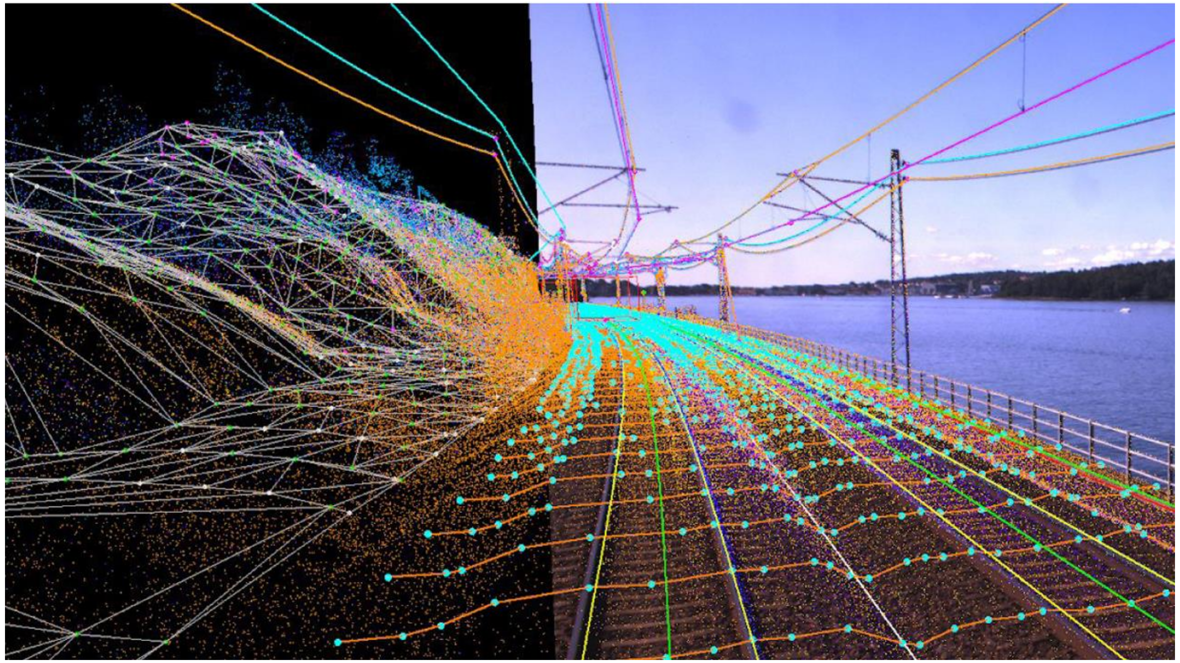
Video **O**dometry with **LI**DAR and **E**GNSS for **ER**TMS **A**pplications



Scope

VOLIERA project addresses the aim to develop an innovative train positioning system based on the fusion of measurement data coming from different sensors and technologies.





Consortium

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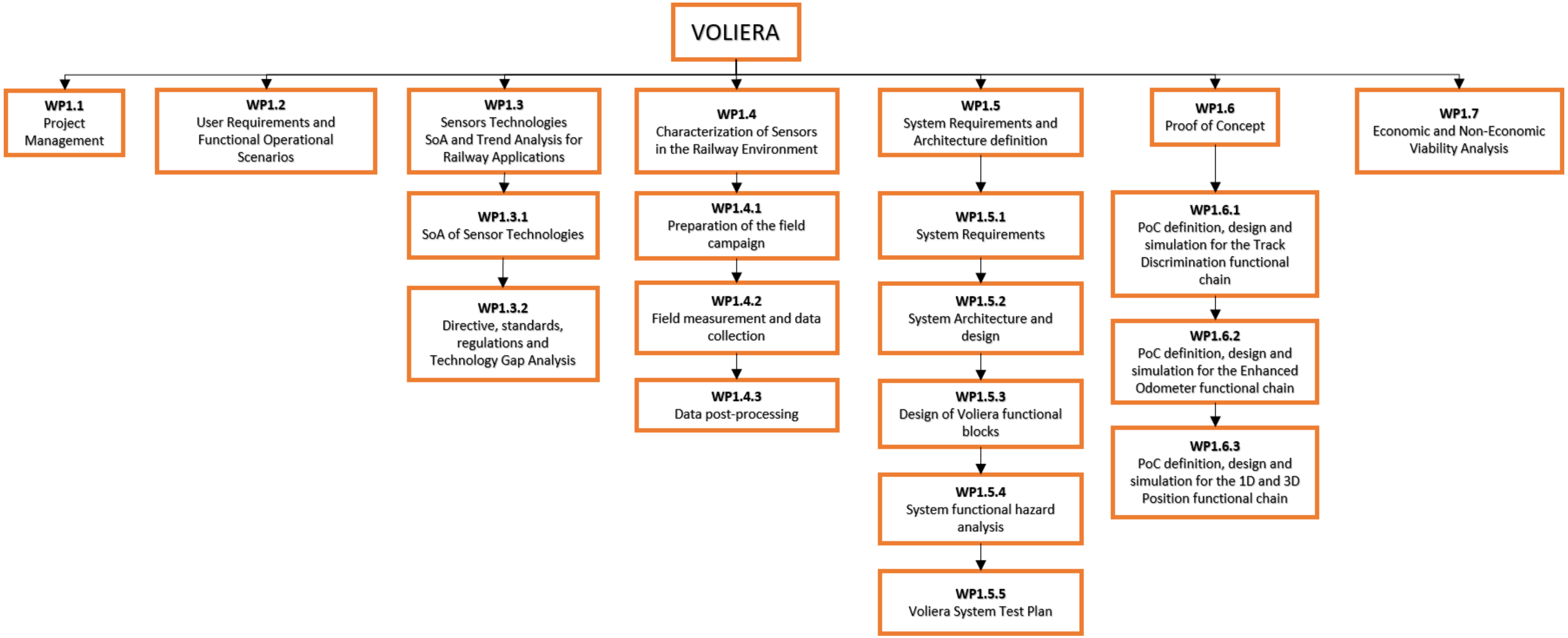
Work Breakdown Structure



Milestones

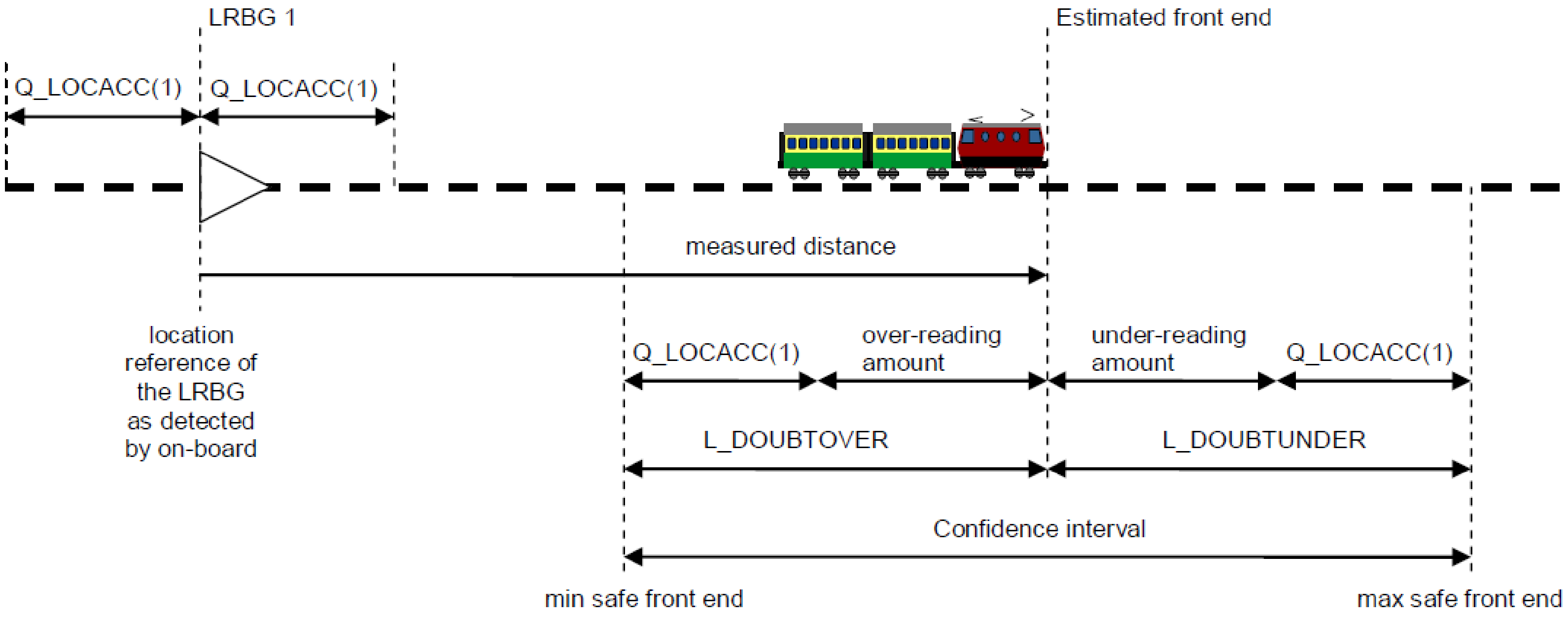
MILESTONE	OBJECTIVES
Baseline Design Review (BDR)	1. Voliera Concept, User Requirements and Functional Operational Scenarios. 2. Review of Directives, standards, regulations and technology gap analysis. 3. Review the SoA sensors technologies.
System Requirements Review (SRR)	Review the system requirements specifications.
Preliminary Design Review (PDR)	1. Review of functional architecture specification and confirmation of the feasibility and correctness of the architectural design. 2. Review of preliminary component design specifications.
Mid-Term Review – Critical Design Review (MTR – CDR)	1. Review of component design specifications and provide final assessment of design feasibility. 2. Confirm correctness of design and its readiness for starting the prototype development. 3. Review of component test specifications, integration test specification. 4. Review and agree on required acceptance test. 5. Review of Proof-of-Concept results.

Baseline Design Review (BDR)

MILESTONE	OBJECTIVES
Baseline Design Review (BDR)	1. Voliera Concept, User Requirements and Functional Operational Scenarios. 2. Review of Directives, standards, regulations and technology gap analysis. 3. Review the SoA sensors technologies.

Voliera Concept, User Requirements and Functional Operational Scenarios (1/4)

The on-board equipment continuously performs the speed and the distance monitoring based on the train front-end (rear-end) positions and the train speed.



ERTMS Train confidence interval and train front end position (Source Figure 13c in Ch. 3 Subset 026)

Voliera Concept, User Requirements and Functional Operational Scenarios (2/4)

(MAIN) USER REQUIREMENTS	
UREQ_00	VOLIERA shall provide train position information continuously to train consumers. Considering that this information should be supplied to on-board ATP system, the minimum frequency is 20 Hz.
UREQ_01	VOLIERA shall work under all rail operational conditions, such as: – Slip and slide; – From standstill until maximum speed.
UREQ_02	VOLIERA shall work under all rail environmental conditions, such as: – All weather conditions; – All type of loco environment; – All types of Rail infrastructure (e.g. tunnels, bridges, with or without catenary, concrete track, ballast track, etc.); – All types of physical environments such as station areas surrounded with high buildings, forests, etc.
UREQ_03	Upon start-up, VOLIERA shall reach full operational capability in minimal time (i.e. from 3 to maximum 5 minutes) with minimal human supervision.
UREQ_04	VOLIERA shall provide train position information with accuracy greater than the current ERTMS localisation subsystem (SUBSET 041).

Voliera Concept, User Requirements and Functional Operational Scenarios (3/4)

Wake Up Scenario	
Zone Applicability	**Depot Zone, Station Zone**
Operations Description	1. VOLIERA is powered-on while the train is located in the Depot Zone; 2. VOLIERA provides operational data after a maximum initialization latency equal to 5 minutes.
Nominal Scenario	
Zone Applicability	**Depot Zone, En Route Zone, Station Zone**
Operations Description	1. After Wake Up, VOLIERA is operational and maintains nominal performance as long as the system is switched on. The nominal scenario comprises: - Tracks with no wayside localization systems (no balises); - Steep-sided tracks; - All weather conditions, day or night; - Train at stop for long durations; - Train speed up to 140 km/h.

Voliera Concept, User Requirements and Functional Operational Scenarios (4/4)

Low Adhesion Scenario	
Zone Applicability	**Depot Zone, En Route Zone, Station Zone**
Operations Description	1. VOLIERA is operational and the train is moving; 2. Slip and slide phaenomena occur due to poor wheel/rail adhesion (especially at low speed); 3. VOLIERA remains operational and maintains the same level of performance.
Tunnel Scenario	
Zone Applicability	**Depot Zone, En Route Zone, Station Zone**
Operations Description	1. VOLIERA is operational and the train is moving; 2. The train enters in a tunnel; 3. VOLIERA remains operational and maintains the same level of performance.
Multiple Tracks Scenario	
Zone Applicability	**Depot Zone, En Route Zone, Station Zone**
Operations Description	1. VOLIERA is operational and the train is moving on a railway line with multiple adjacent tracks; 2. VOLIERA properly discriminates the track on which the train is located.

Review of Directives, Standards and Regulations

Railway standards and regulation have been analysed to identify the most relevant ones to be taken into account in the context of VOLIERA project.

For sake of clarity, the standards have been grouped into the following categories:

- Standards related to electrical design, components and cabling;
- Standards related to mechanical design;
- Standards related to components installation;
- Standards linked to the usage of visual sensors (i.e. LIDAR)

Based on the standard analysis a non-intrusiveness analysis has been realized in order to have the authorization to use the Voliera System on a commercial train.

Review of SoA Sensors and Technologies (1/5)

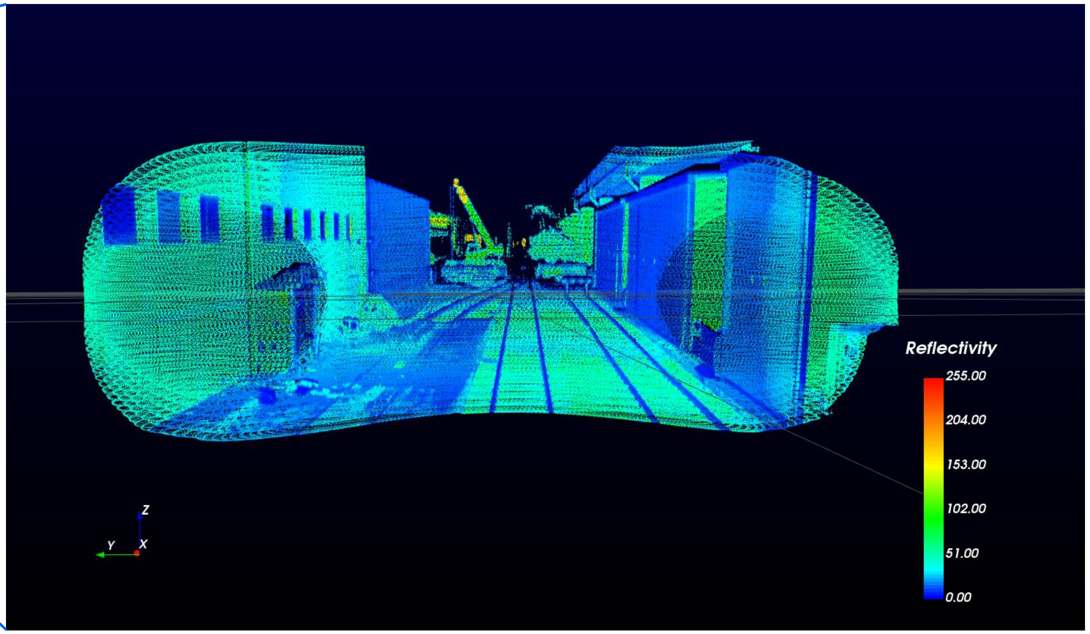
The review of SoA sensors and technologies has been carried out to identify the most suitable technologies to be part of VOLIERA on-board measurement subsystem.

The following sensors and technologies have been investigated:

- LIDAR (Laser Imaging Detection and Ranging);
- (Stereo) – CAMERA;
- ToF Camera
- IMU (Inertial Measurement Unit);
- GNSS (Global Navigation Satellite System).

Review of SoA Sensors and Technologies (2/5)

LIDAR – Laser Imaging Detection and Ranging



Railway Pointcloud Example

Output Information
Pointcloud (i.e. x,y,z coordinates and associated reflectivity of the surrounding environment)

Review of SoA Sensors and Technologies (3/5)

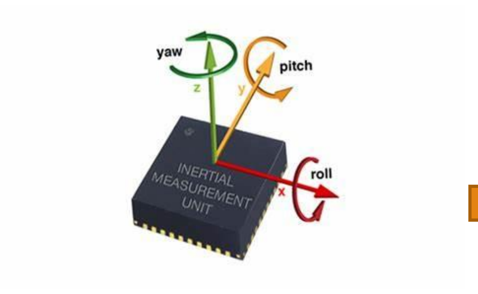
(Stereo) – CAMERA

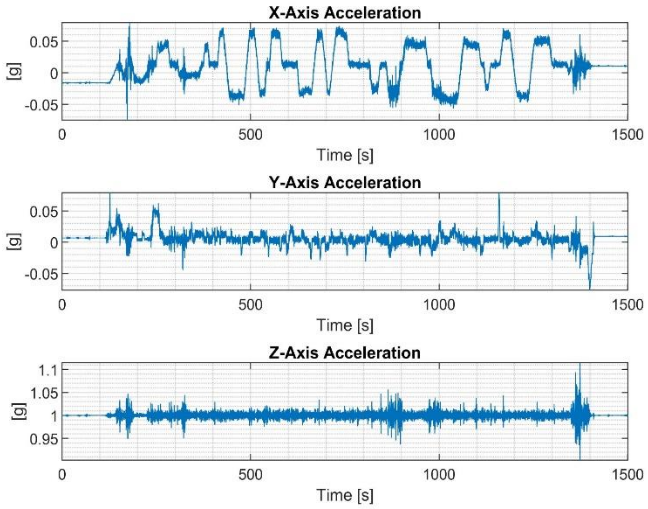
Railway RGB Image Example

Output Information
RGB and/or Intensity Image

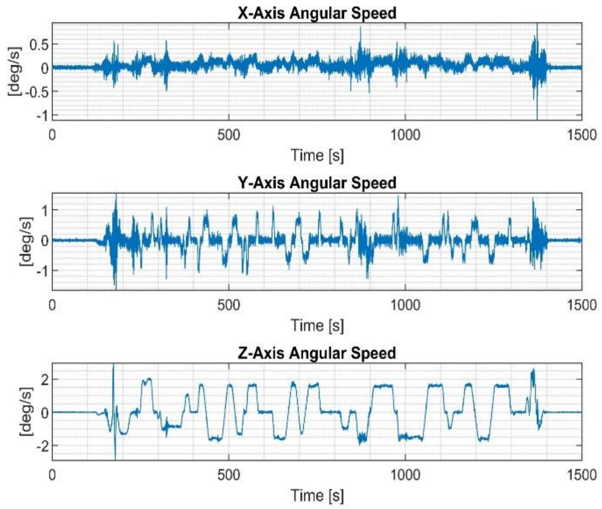
Review of SoA Sensors and Technologies (4/5)

IMU – Inertial Measurement Unit





Acceleration



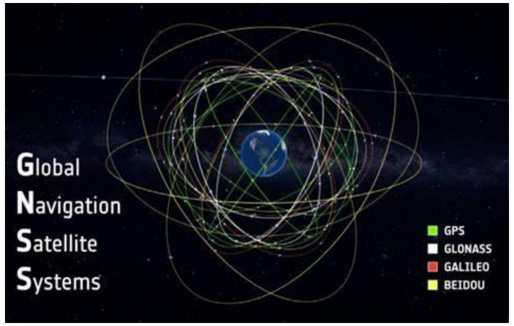
Angular Speed

Output Information

3-axis Acceleration and Angular Speed

Review of SoA Sensors and Technologies (5/5)

GNSS – Global Navigation Satellite System

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I    2 C5A L5A                                              SYS / # / OBS TYPES
```

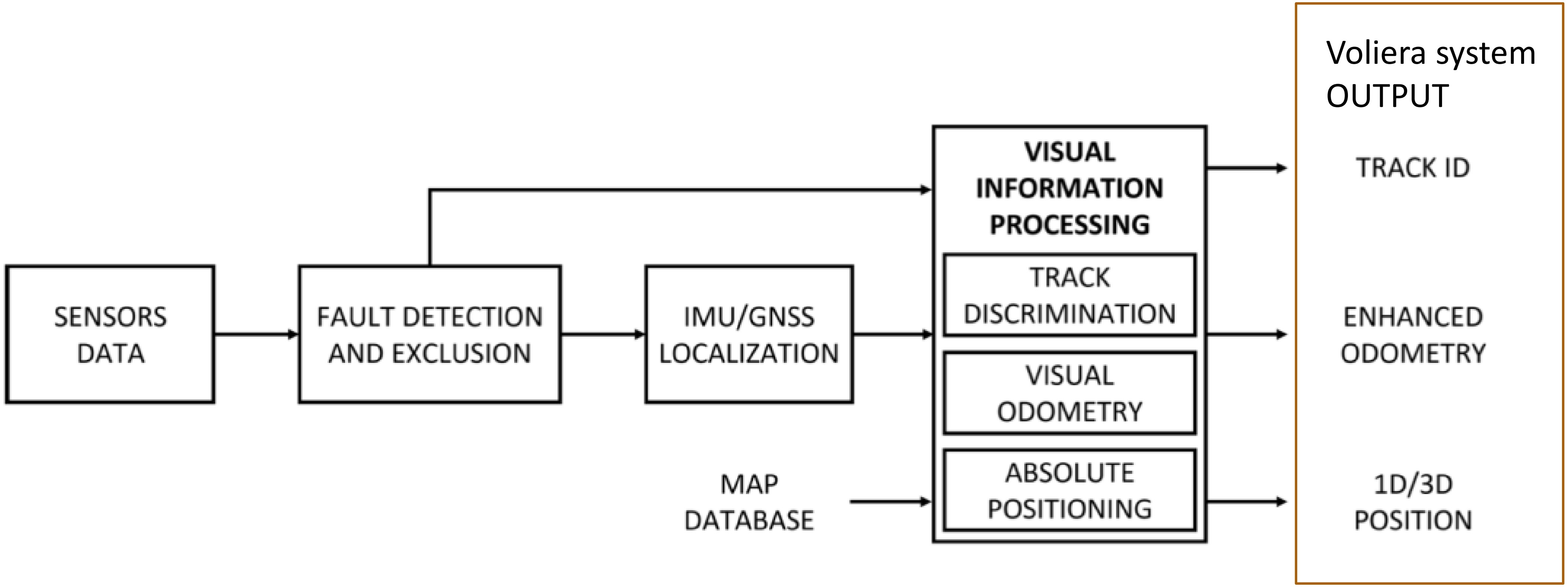
RINEX 3.04 Example File

Output Information
PVT and GNSS Observables

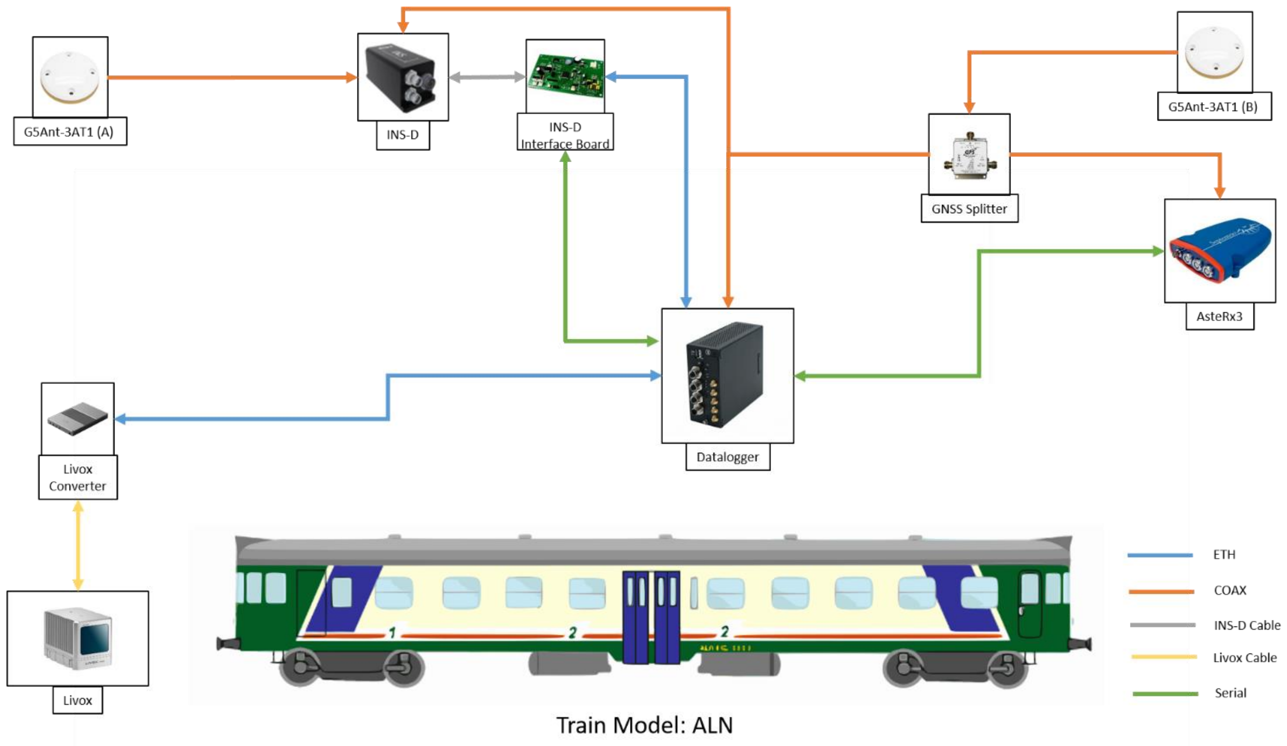
System Requirements Review

MILESTONE	OBJECTIVES
System Requirements Review (SRR)	Review the system requirements specifications.

Functional Architecture



Physical Architecture



Technology	Sensor
IMU	Inertial Labs INS-D
GNSS	Septentrio AsteRx3
LIDAR	Livox Horizon
Datalogger	Eurotech BoltGATE 20-31

Preliminary Design Review (PDR)

MILESTONE	OBJECTIVES
Preliminary Design Review (PDR)	1. Review of functional architecture specification and confirmation of the feasibility and correctness of the architectural design. 2. Review of preliminary component design specifications.

Testing Strategy

The strategy adopted to verify VOLIERA system has foreseen the execution of several test.
For sake of clarity, these test can be grouped into three main categories:

- **Sensors Verification Test [VER-SEN]**
  These tests have the aim to verify that each sensor part of the VOLIERA system is properly working after finalizing the installation activities;
- **System Verification Test [VER-SYS]**
  These tests have the aim to verify that the overall VOLIERA system (Sensors + DataLogger) is properly working after finalizing the installation activities;
- **Data Collection Test [DCT]**
  These tests have the aim to acquire the measurement data coming from VOLIERA system while the test train is running along the test railway lines.

Field Test Campaign

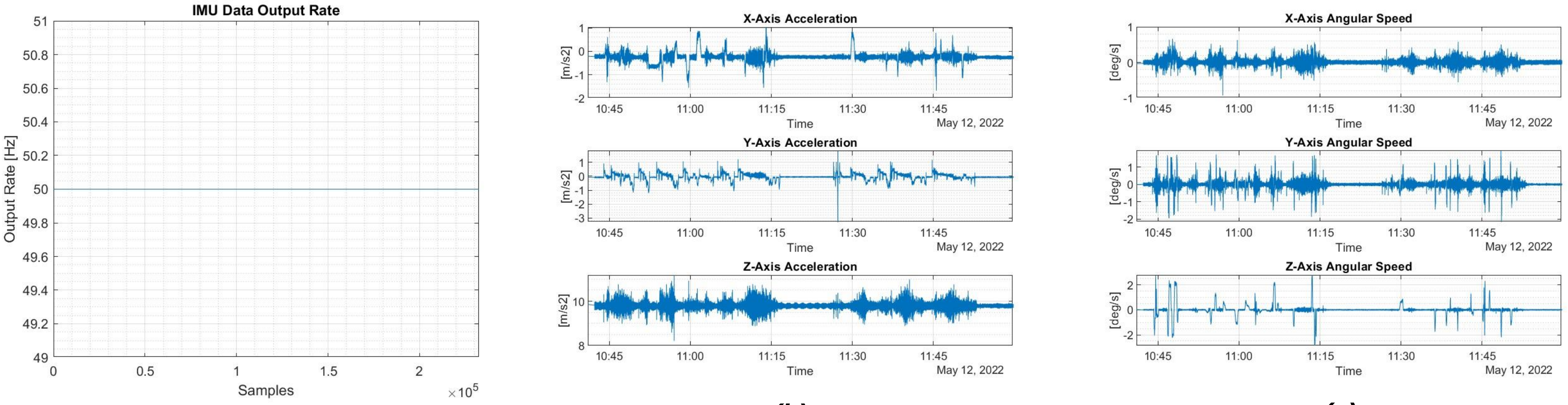
Trenitalia commercial train (ID ALN668-3136) has been equipped with VOLIERA on-board measurement subsystem. The following table outlines the field test campaign:

TEST DATE	RAILWAY LINE ID	START STATION	END STATION	TEST RUN LENGTH [km]	TEST RUN SIZE [GB]
220512	CAG-IGL	Cagliari	Iglesias	53,9	21,5
220513	CAG-CAR	Cagliari	Carbonia	67,2	26,3
220513	IGL-CAG	Iglesias	Cagliari	53,9	4,51
220513	IGL-VIL	Iglesias	Villamassargia	9,1	5,08
220513	VIL-IGL	Villamassargia	Iglesias	9,1	6,07
220527	CAG-ORI	Cagliari	Oristano	93	28,1
220527	CAG-SAG	Cagliari	San Gavino	49,6	19,2
220530	SAG-CAG	San Gavino	Cagliari	49,6	4,13
220601	CAG-IGL	Cagliari	Iglesias	53,9	25,7
220601	IGL-VIL	Iglesias	Villamassargia	9,1	1,22
220601	VIL-IGL	Villamassargia	Iglesias	9,1	4,15

On Field Measurement Data Analysis (1/4)

Inertial Measurement Unit

For each test, it has been verified that the IMU data provided by the INS-D are compliant to the set configuration, both in terms of output rate (50 Hz) and output dataset.



(a) (b) (c)

CAG-IGL IMU Data Analysis Example: (a) IMU Data Output Rate, (b) Acceleration Data and (c) Angular Speed Data

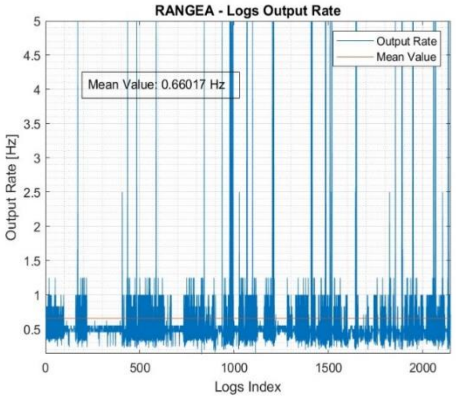
On Field Measurement Data Analysis (2/4)

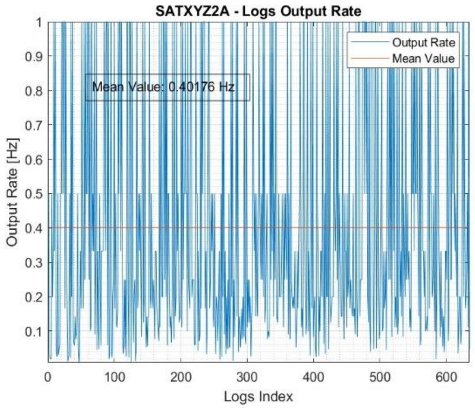
Raw GNSS

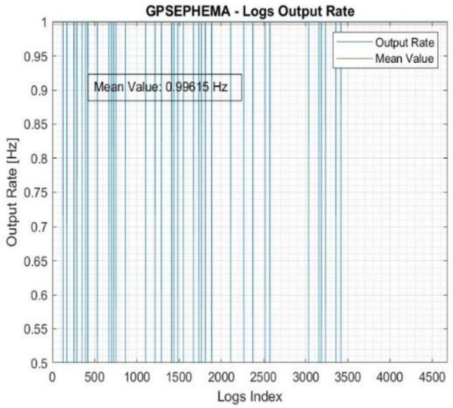
The GNSS Raw Data verification process has been carried out by analyzing, for each run, the following information:

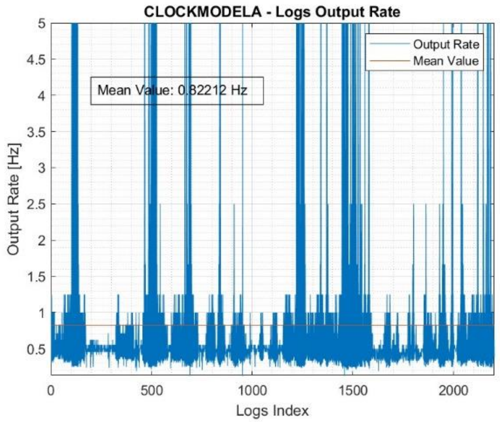
- Presence of the GNSS logs expected to be provided as input of the task 1D/3D Positioning. The logs needed are RANGE, SATXYZ, GPSEPHEMA and CLOCKMODEL;

- Consistency of the synchronous logs output rate with respect to the configuration.









On Field Measurement Data Analysis (3/4)

Pointcloud

The PointCloud Data verification process has been carried out by analyzing, for each run, the Status Code associated to every 3D Point of the PointCloud. The Status Code directly reports information about the Livox Horizon status. The Status Code Legend is reported in the next table:

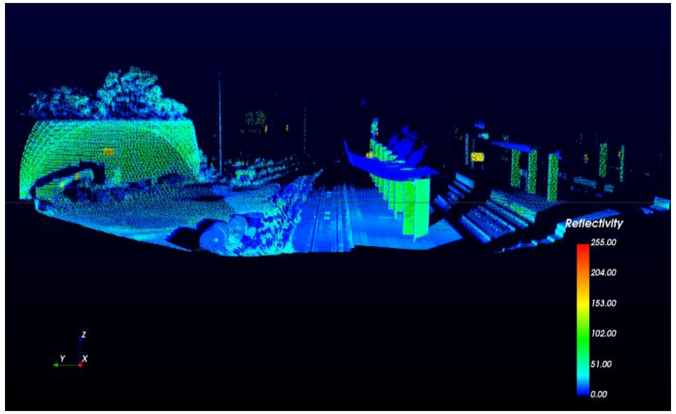
STATUS CODE EXTENDED ID	STATUS CODE COMPRESSED ID	STATUS CODE INFORMATION
0x0000C200	0xC200	PPS Synchronization
0x00010000	0x10000	Using PTP 1588 Synchronization
0x00010040	0x10040	Dirty or Blocked + Using PTP 1588 Synchronization
0x00010200	0x10200	PPS signal is OK + Using PTP 1588 Synchronization
0x0000C000	0xC000	Using PPS synchronization
0x0000C240	0xC240	Dirty or Blocked + PPS signal is OK + Using PPS synchronization
0x00010240	0x10240	Dirty or Blocked + PPS signal is OK + System Time synchronization is abnormal
0x0000C040	0xC040	Dirty or Blocked + Using PPS synchronization

For each test run, a table summary of the Status Code values will be reported into a dedicated section. The Status Codes associated to faulty conditions are:

1. 0x10040;
2. 0xC240;
3. 0x10240;
4. 0xC040.

On Field Measurement Data Analysis (4/4)

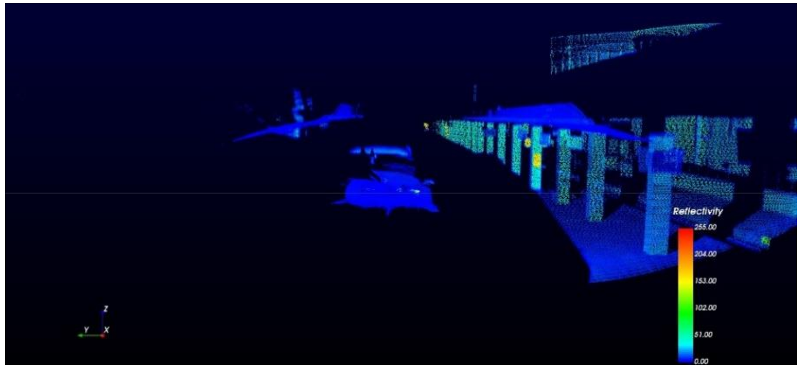
Pointcloud



NUMBER OF POINTS = 30835138

STATUS CODE	COUNTER	PERCENTAGE (%)
0xc200	16291347	52.83
0x10200	90214	0.29
0x10000	14367437	46.59
0xc000	86140	0.28

Healthy Dataset



NUMBER OF POINTS = 28477248

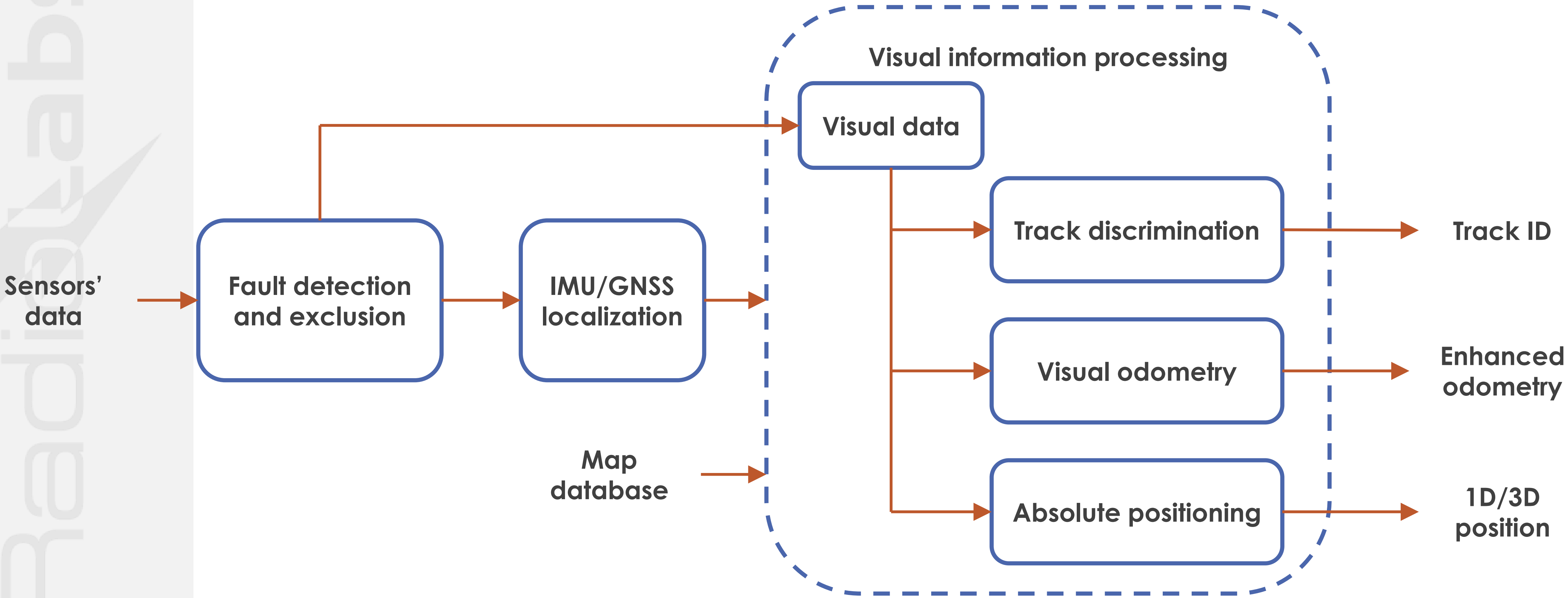
STATUS CODE	COUNTER	PERCENTAGE (%)
0xc200	9693	0.03
0x10000	6493742	22.8
0x10040	18683295	65.61
0xc240	3279598	11.52
0x10240	5811	0.02
0xc040	5109	0.02

Faulty Dataset (Dirty Lens)

Mid-Term Review – Critical Design Review (MTR – CDR)

MILESTONE	OBJECTIVES
Mid-Term Review – Critical Design Review (MTR – CDR)	1. Review of component design specifications and provide final assessment of design feasibility. 2. Confirm correctness of design and its readiness for starting the prototype development. 3. Review of component test specifications, integration test specification. 4. Review and agree on required acceptance test. 5. Review of Proof-of-Concept results.

Voliera – architecture



Voliera – Functions

Three macro functional chains have been identified:

- **Track Discrimination** – Responsible for discriminating the Track where the train equipped with the Voliera Prototype is located
- **Enhanced Odometer** – Providing odometer information based on Subset 041 ISSUE 3.2.0
- **1D and 3D Position** – Responsible for providing 1D and 3D position
  - 1D position information is the estimated relative position of the train on the track
  - 3D position information is the absolute position information when the track has not been discriminated yet or the localization is totally unknown (e.g. start-up).

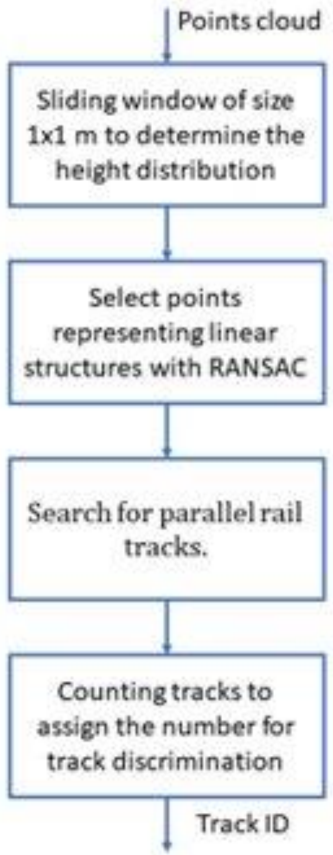
Rail Track Discrimination

The considered method for rail tracks discrimination is based on the exploitation of pointclouds of the observed scene.

The method detects and selects measured points on a railway track.

The detection algorithm is based on specific properties of the objects contained in the railway environment.

The track discrimination method can be described by means of the *block scheme* given in the figure.



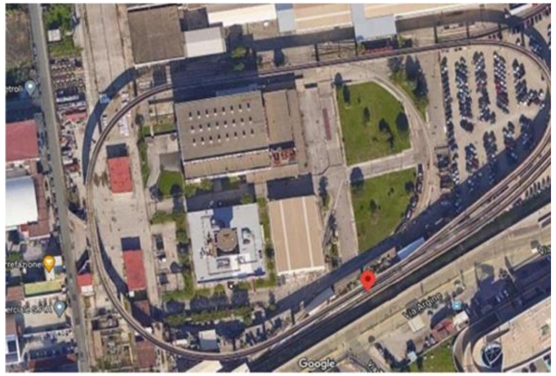
Testbed

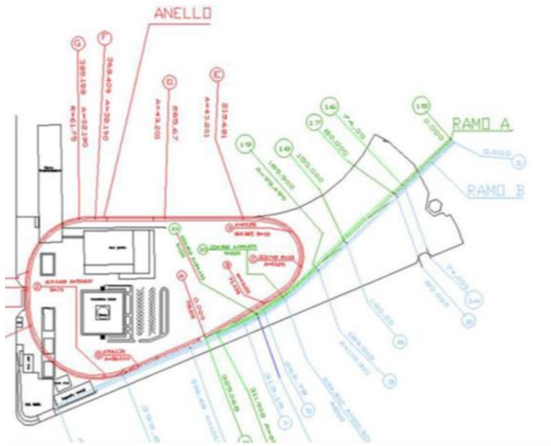
Test Track (TT) located in the Hitachi premises in Naples.

The TT is composed by three parts:

- Branch A of length 325,07 m
- Branch B of length 494,24 m
- Ring of length 731 m.

It includes three switches, one railway traffic light and four track-side railway signals.



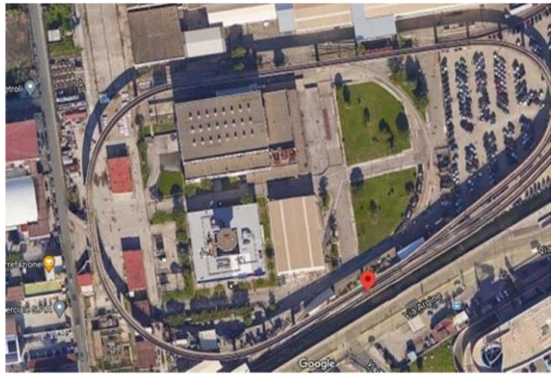


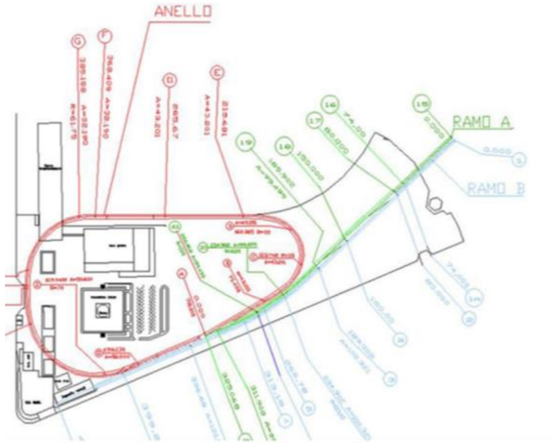
Testbed

The TT is characterized by:

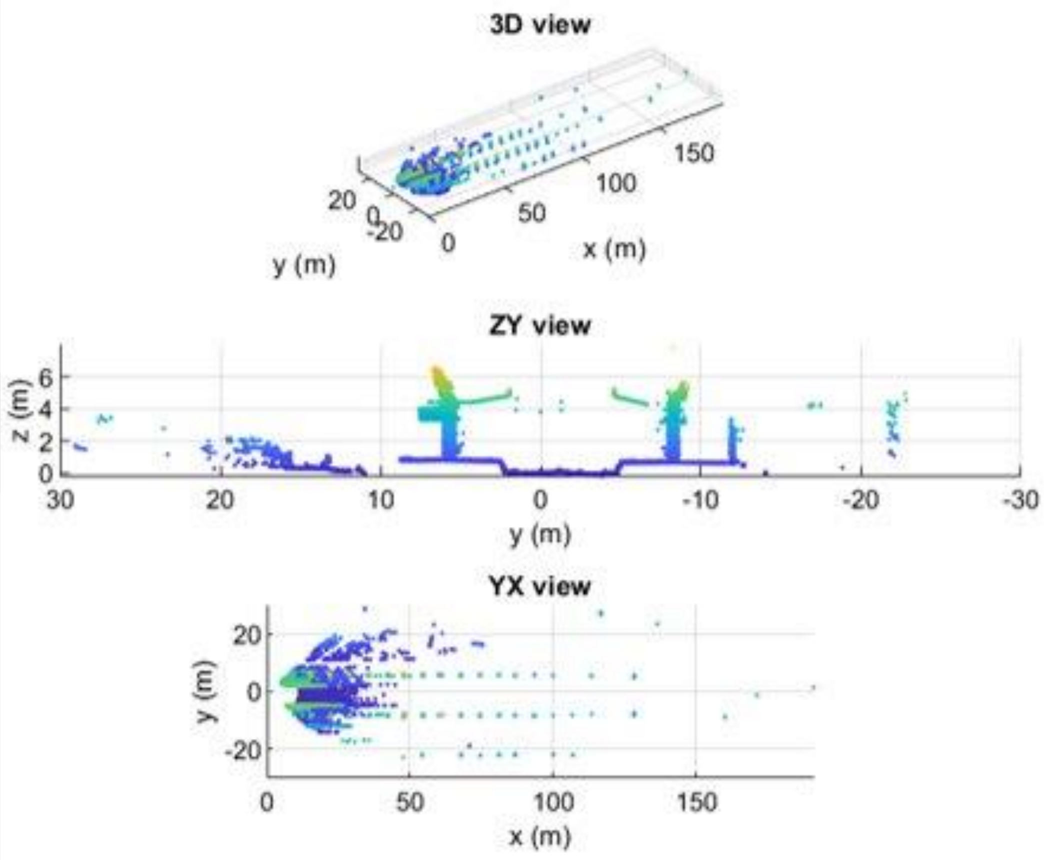
- a minimum curve radius of 35 m
- a maximum slope with respect to the access ramp of 40%
- a minimum vertical curve radius of 400 m
- a track gauge of 1435 mm
- a maximum allowed speed of 50 km/h.

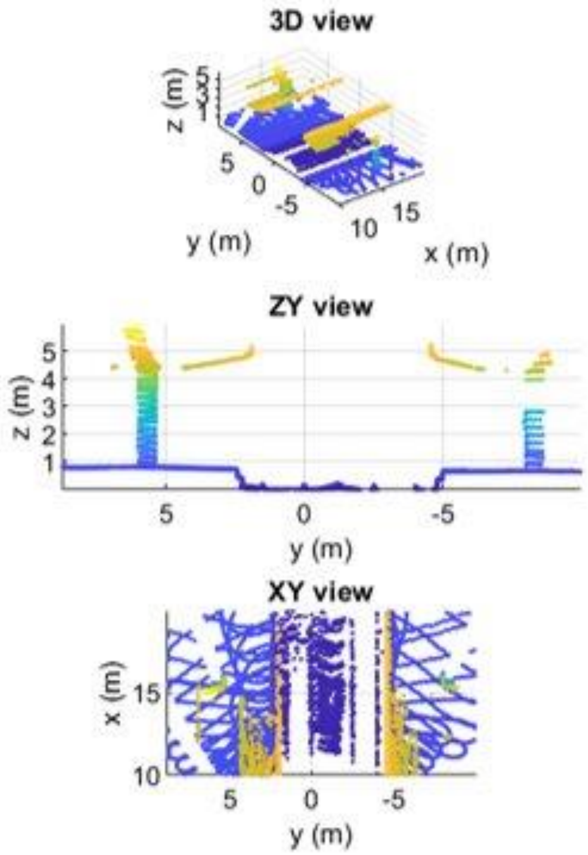
Data were recorded by using a rail cart equipped with two GNSS antennas, one INS-D from Inertial Labs and one LiDAR Livox Horizon.





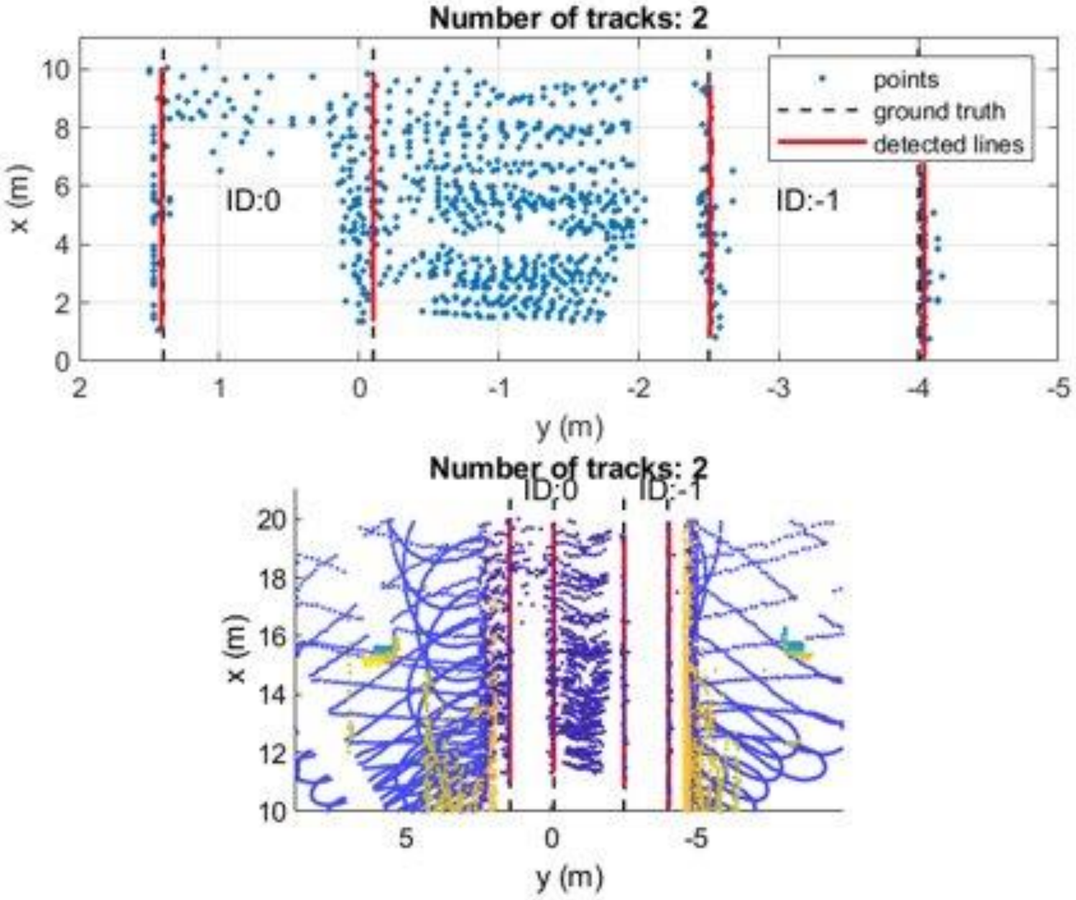
Rail Track Discrimination: Results





The effectiveness is demonstrated by means of tests performed on real-recorded data acquired on the test-track in **Sardegna (Italy).**

Rail Track Discrimination: Results



Train positioning based on landmark

Depending on the number of landmarks, a different processing workflow is automatically selected:

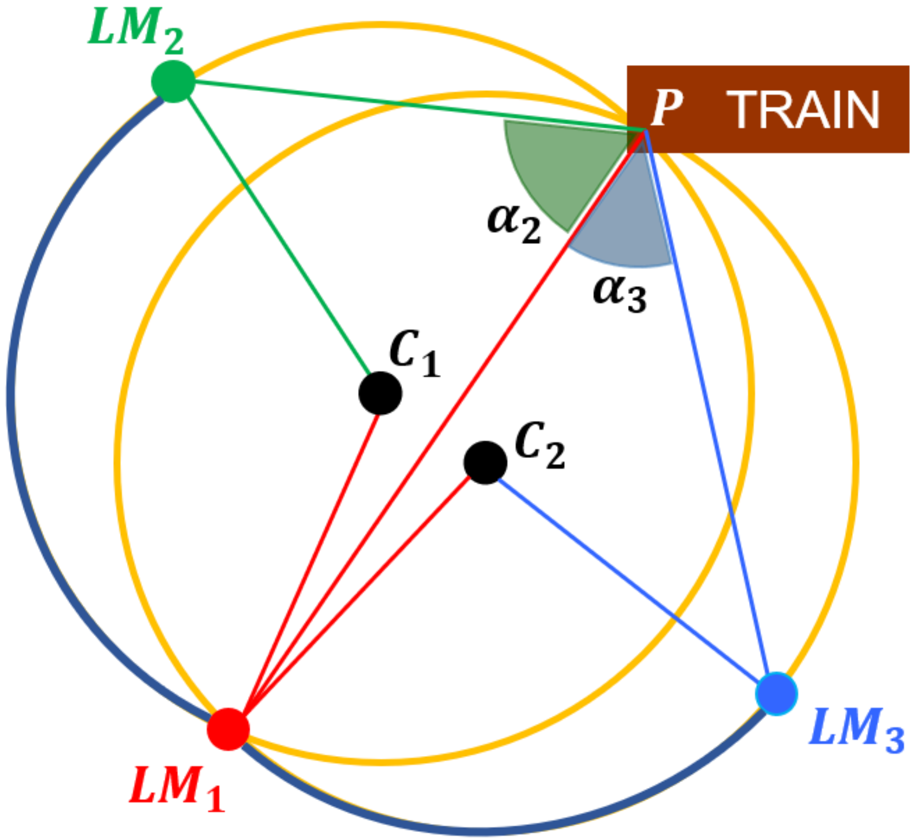
- Workflow #1 - Three landmarks in visibility
- Workflow #2 - Two landmarks in visibility
- Workflow #3 - One landmark in visibility

Workflow #1

Given N_{LM} landmarks, $\{LM_1, LM_2, \ldots, LM_{N_{LM}}\}$, we use LM_1 as pivot to compute the difference of LoS directions α_i.

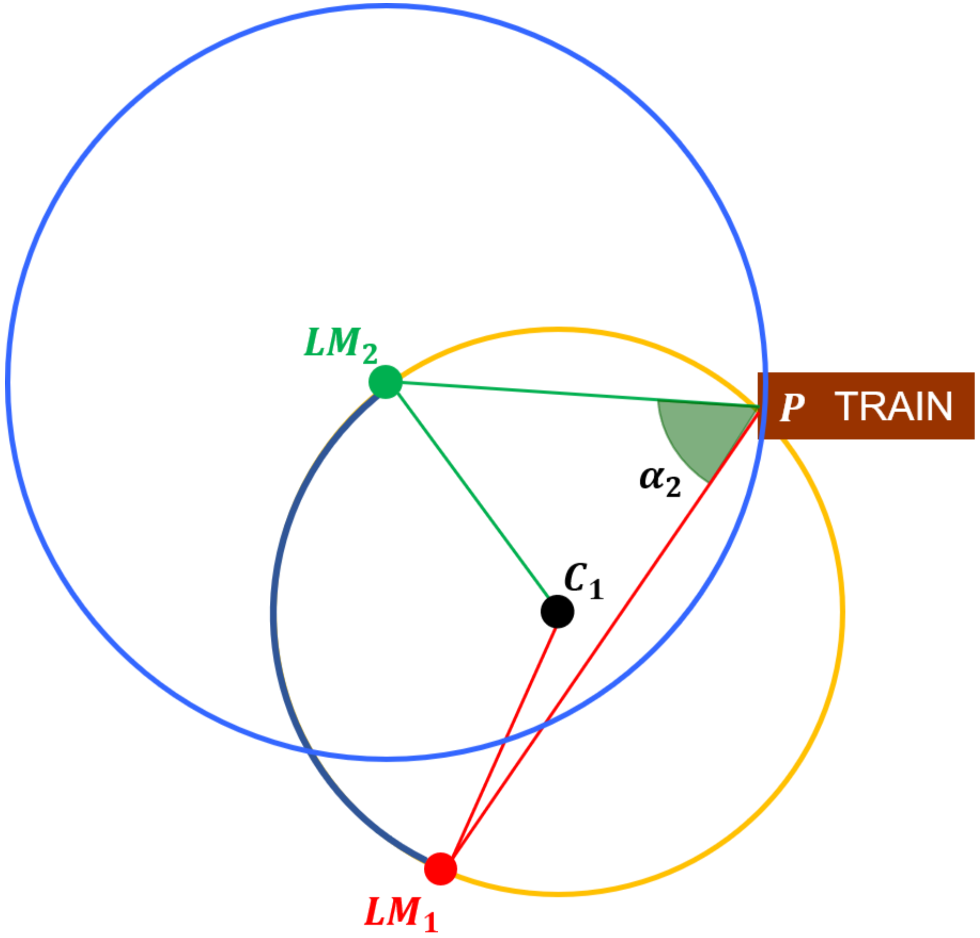
Then, given LM_i, the locus of points for which the viewing angle α_i remains constant is given by a portion of the circle passing through the points $\{LM_1, LM_i\}$ and the train location $P = [x_T, y_T]$. This circle can be split in two portions, one smaller and one larger than the semi-circle.

The two portions are specular with respect to the chord passing through the landmarks. If the angle α_i is smaller than $\pi/2$, the train lies on the larger circular arc and vice-versa.



Workflow #2

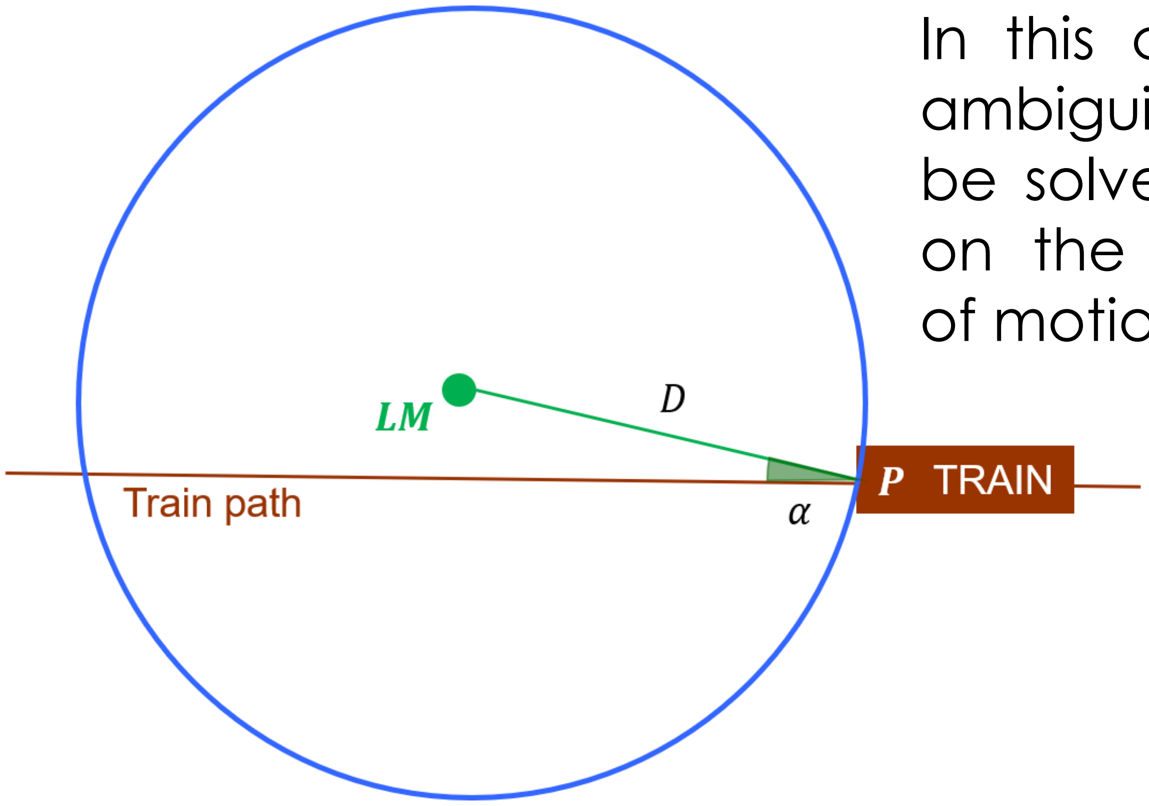
In this case the ambiguity is solved the two candidate train positions can be substituted in the distance equation corresponding to the second landmark.



Workflow #3

When only a landmark is present, a circle of radius D can be obtained by measuring the distance between the train and a landmark.

Given a train path, it is possible to compute the intersection between the aforementioned circle and the train path. The train will be located at this intersection.



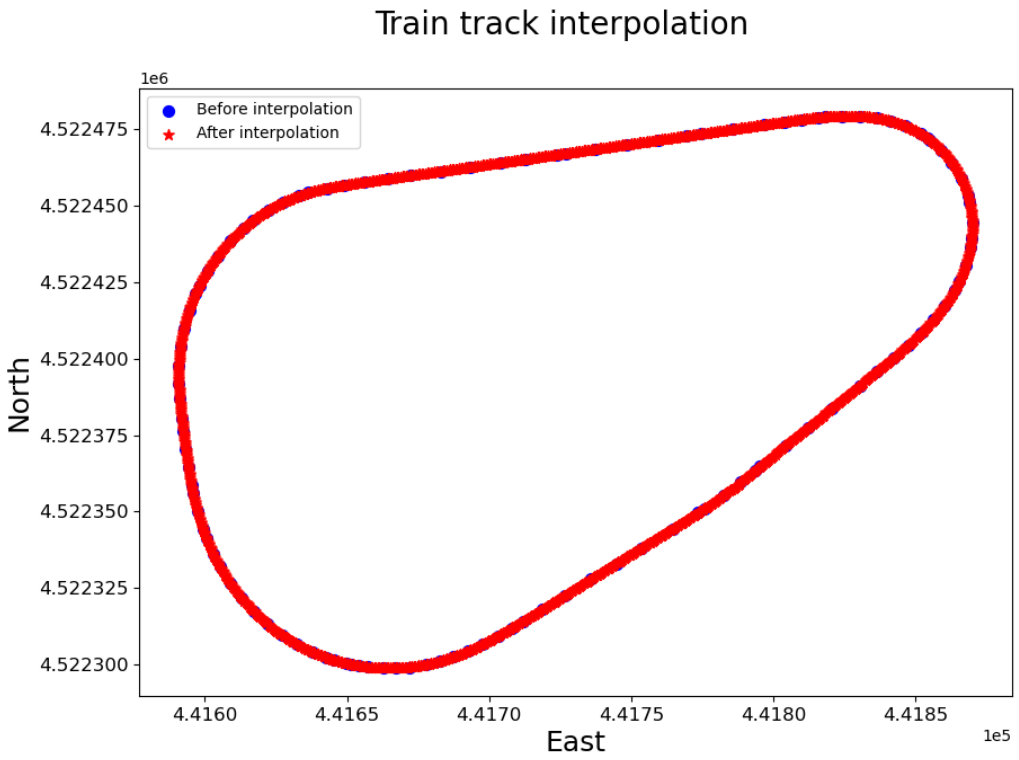
In this case, the ambiguity can be solved based on the direction of motion.

Results – 1 landmark

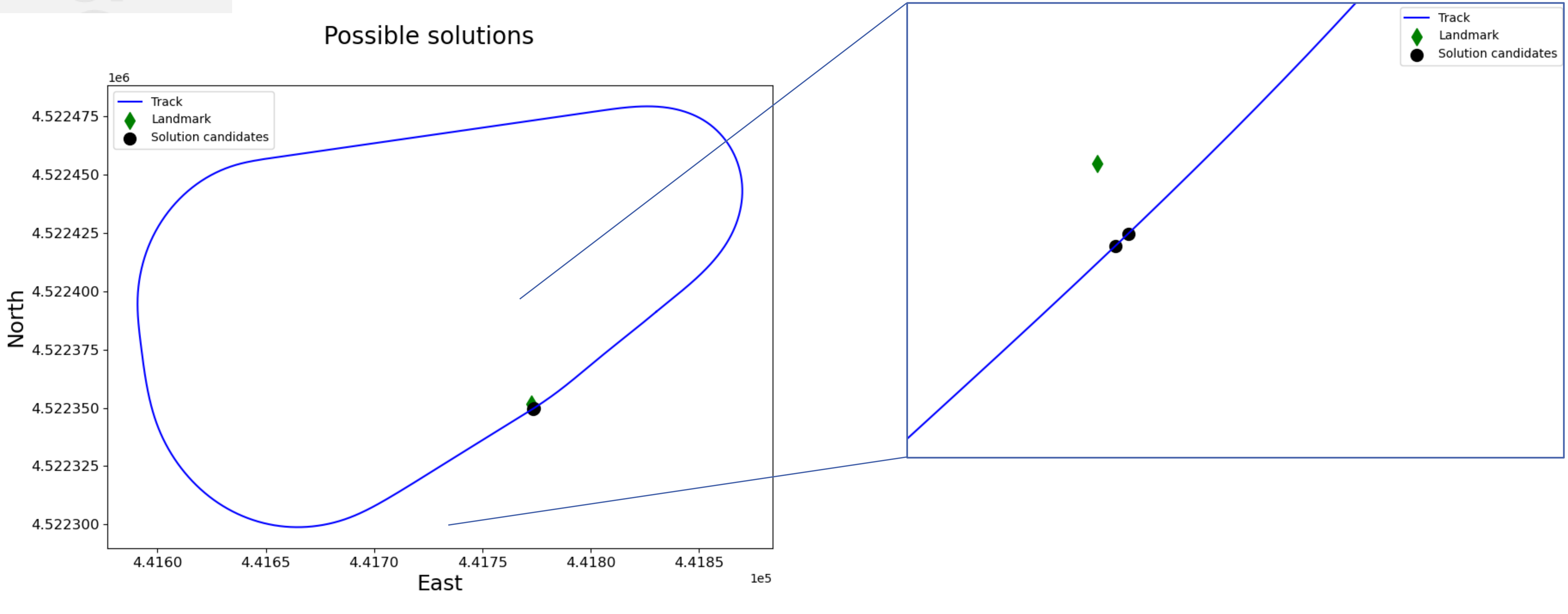
The algorithm has been tested both on real and simulated data.

REAL

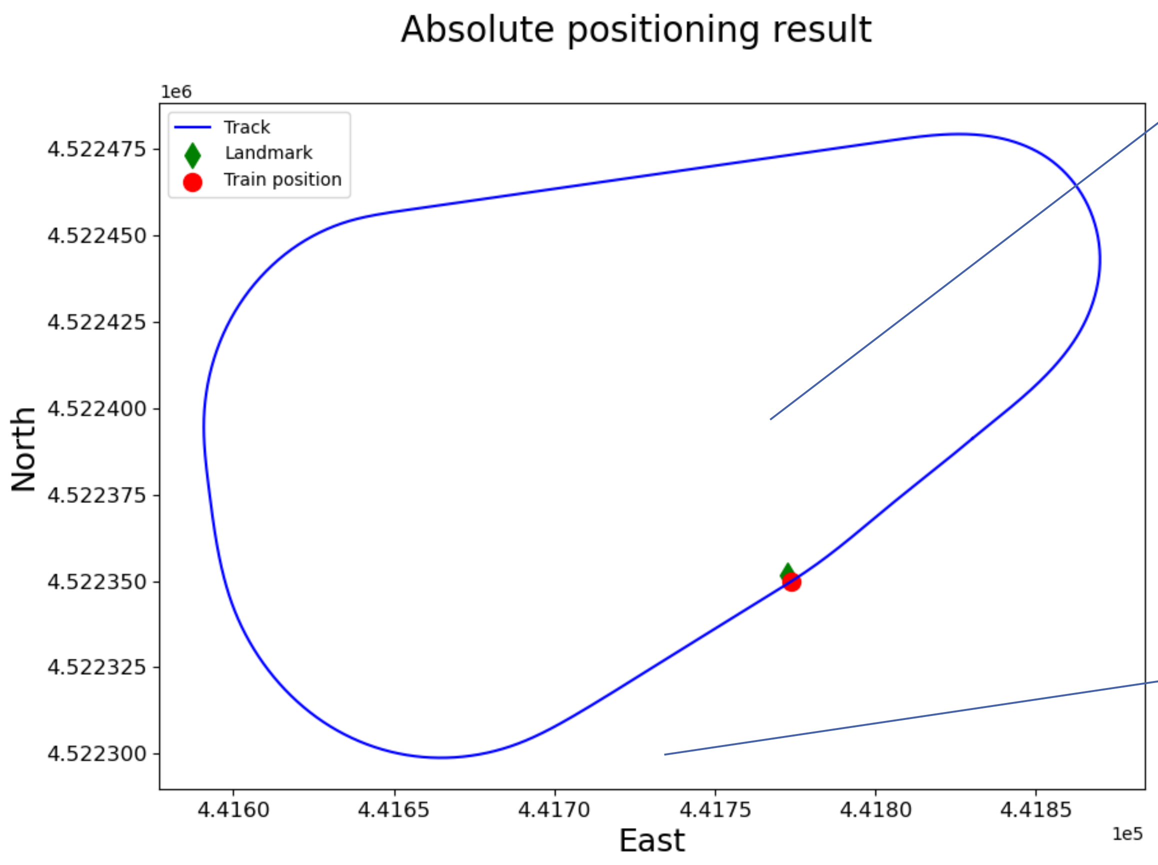
- Naples testbed
- Only one landmark in the LIDAR field of view
- Hand-crafted bounding boxes

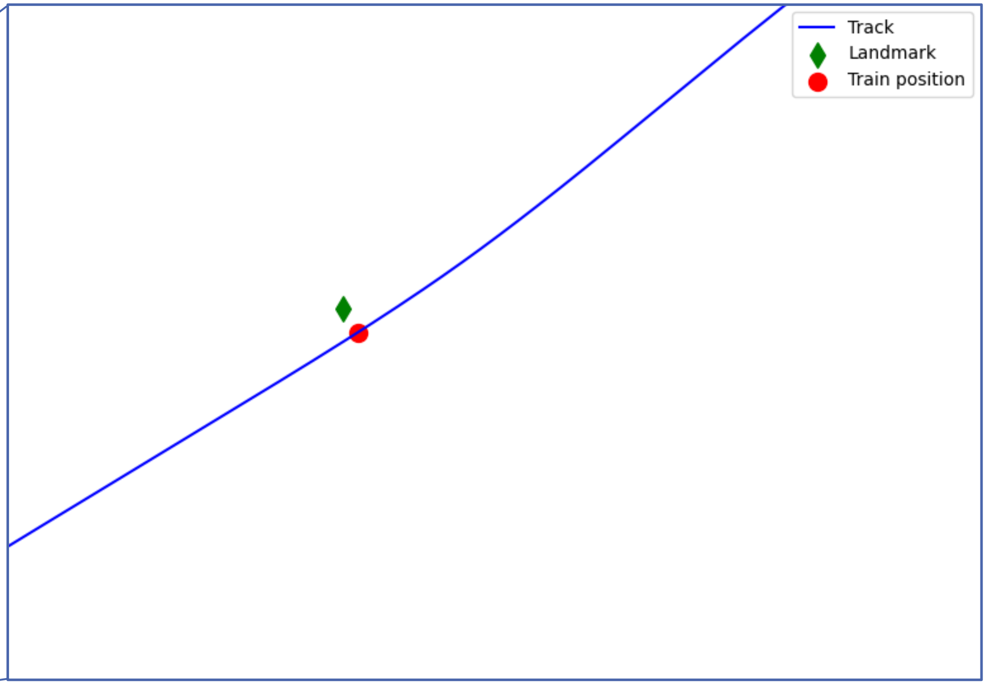


Results – 1 landmark



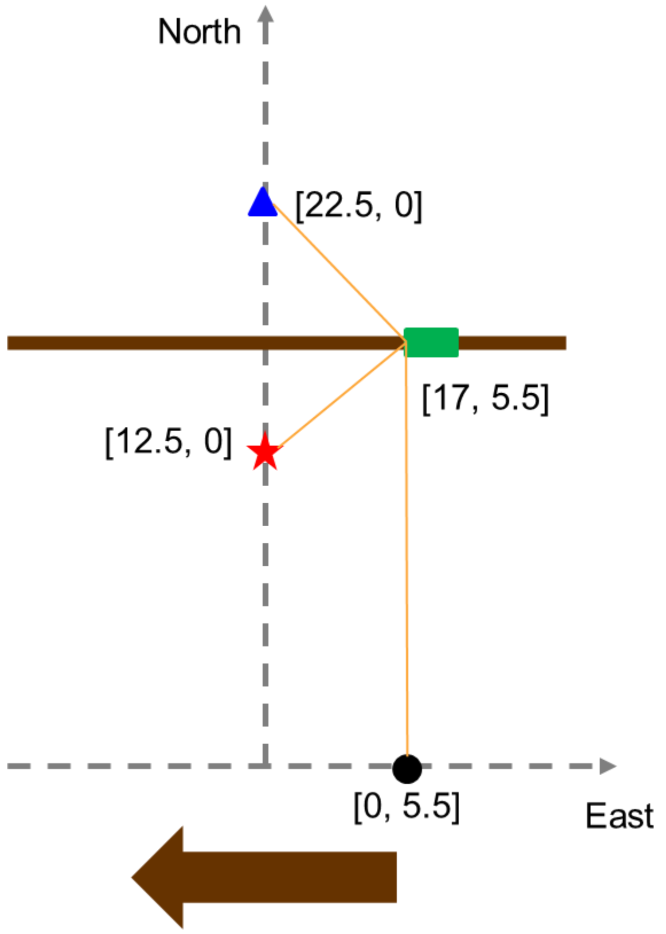
Results – 1 landmark

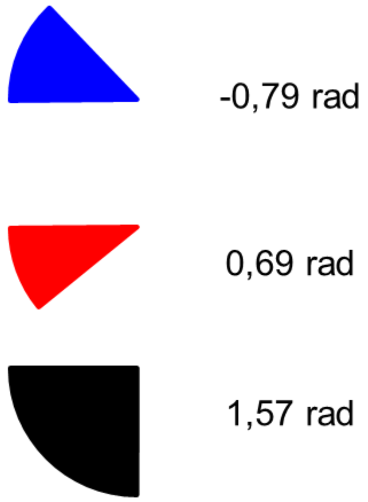




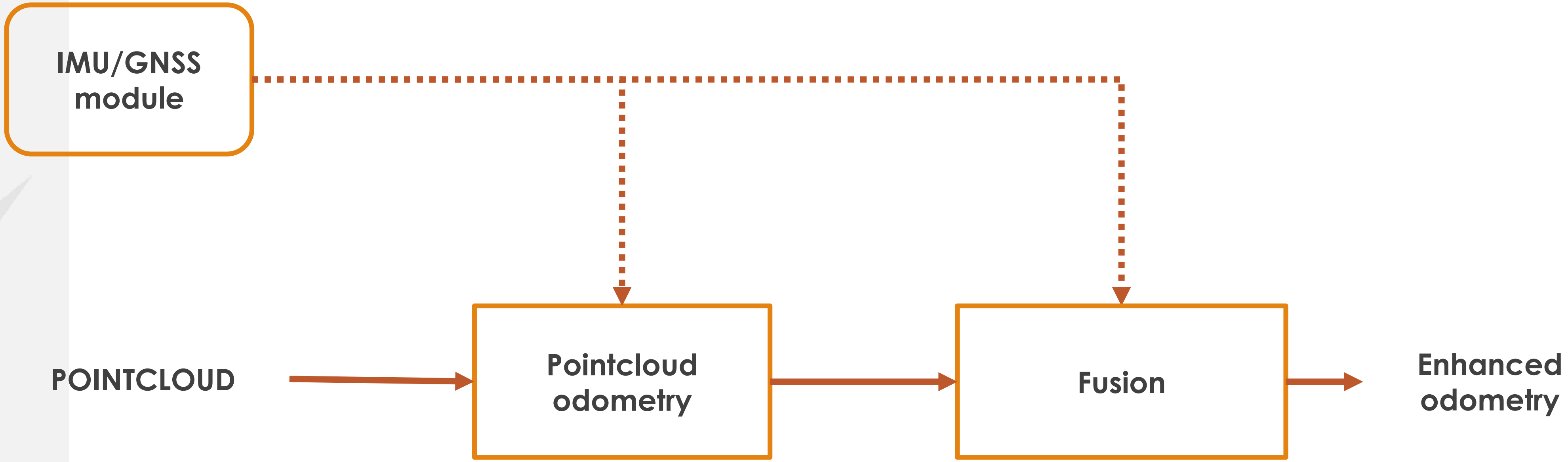
Results – Simulated scenario

Track along East
Forward run





Pointcloud odometry

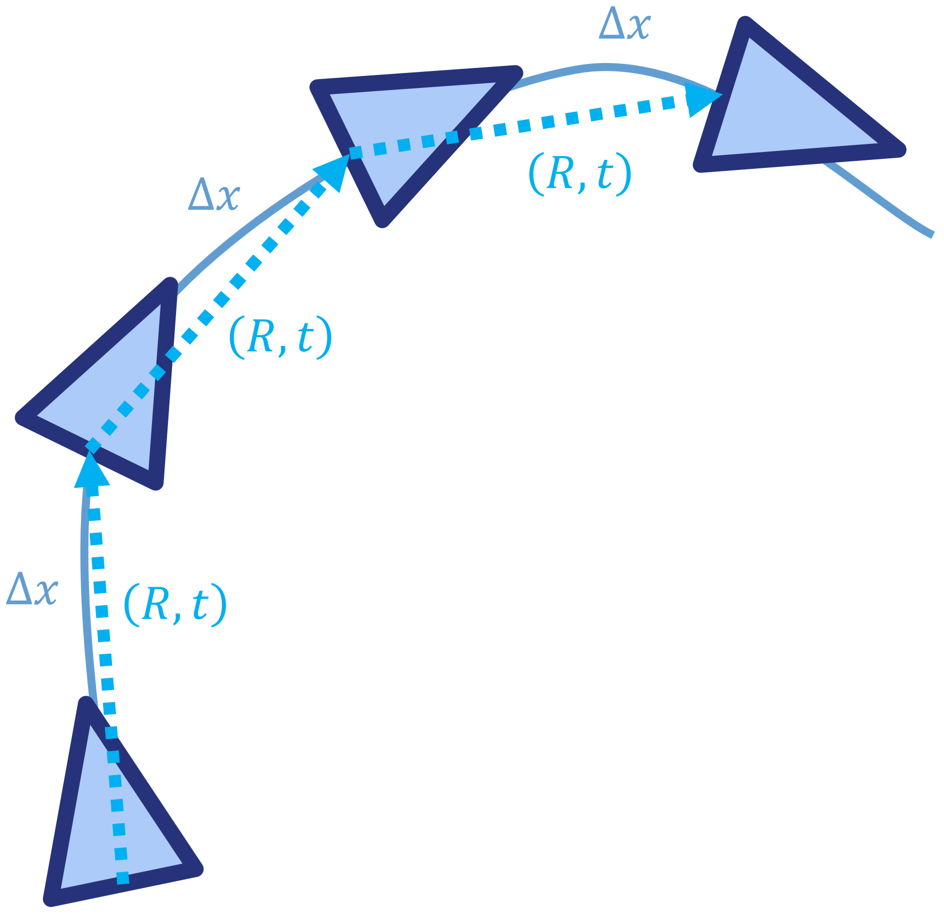


Position from the IMU/GNSS module can be used to initialize the pointcloud odometry registration algorithm.

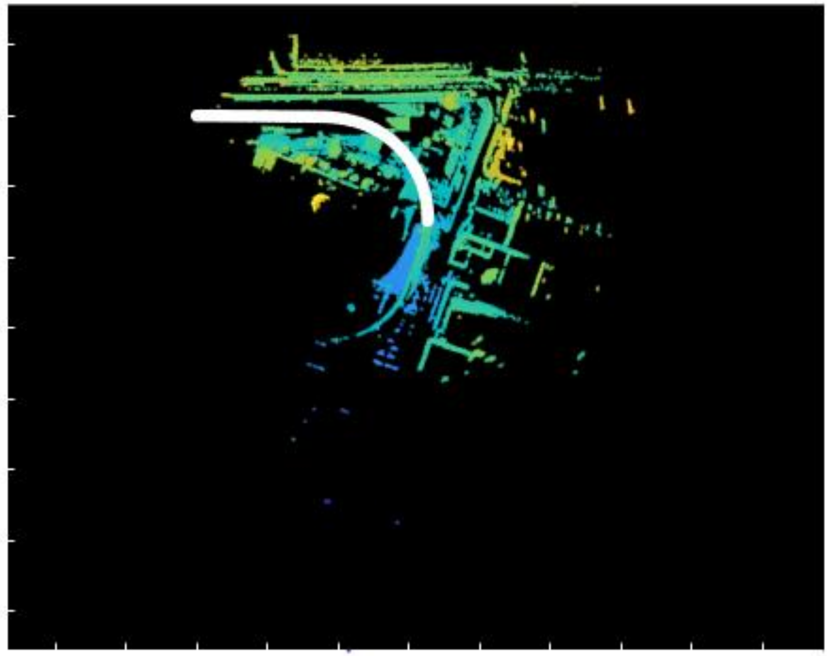
Pointcloud odometry

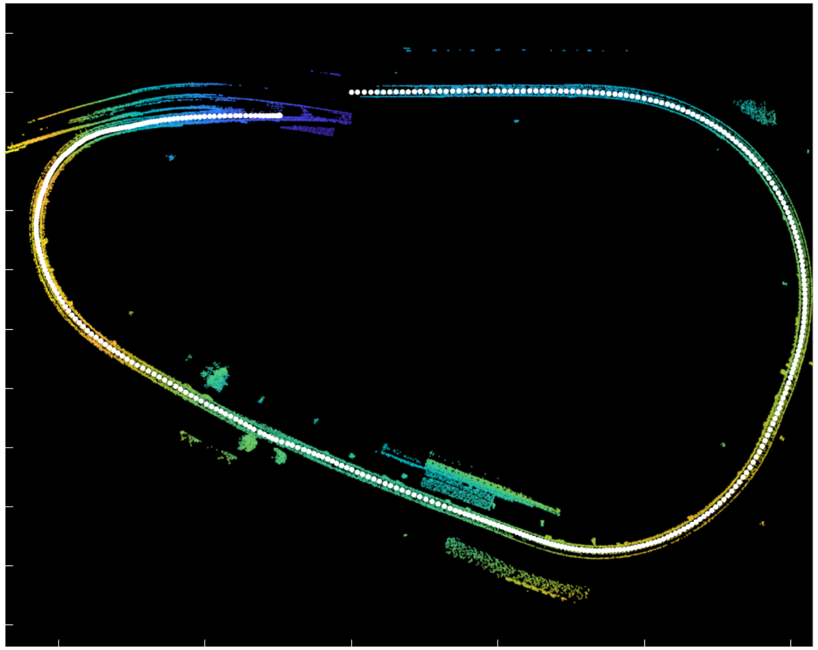
Pose graph optimization to compute a trajectory from relative pose measurements (from ICP) and movements (from the IMU/GNSS module)

Levenberg-Marquardt optimization to find the most-likely configuration of pose correction.



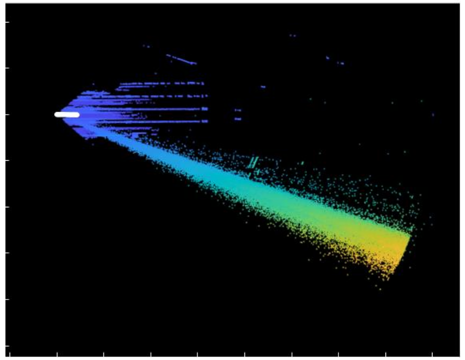
Pointcloud odometry: results

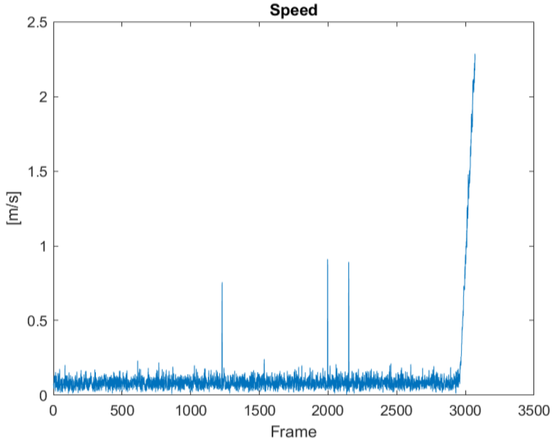


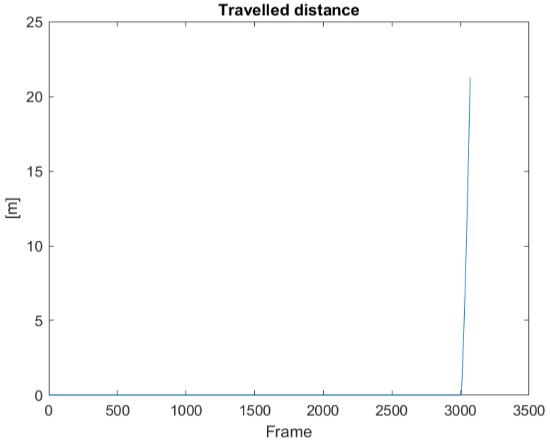


Pointcloud odometry: results

Test #001







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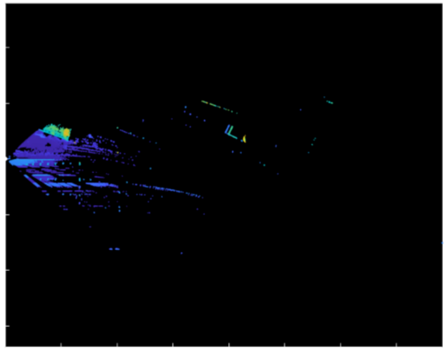
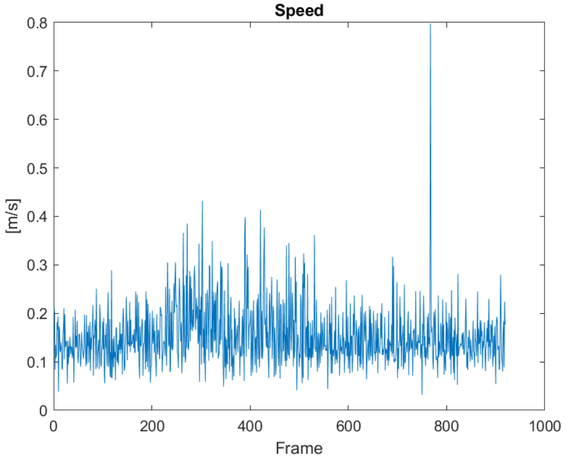
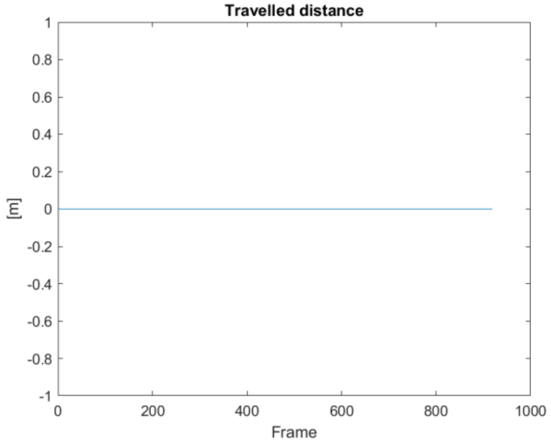
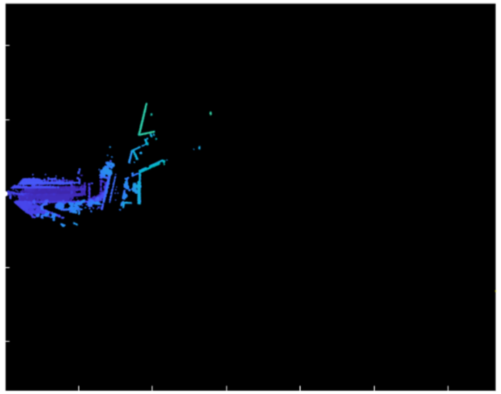


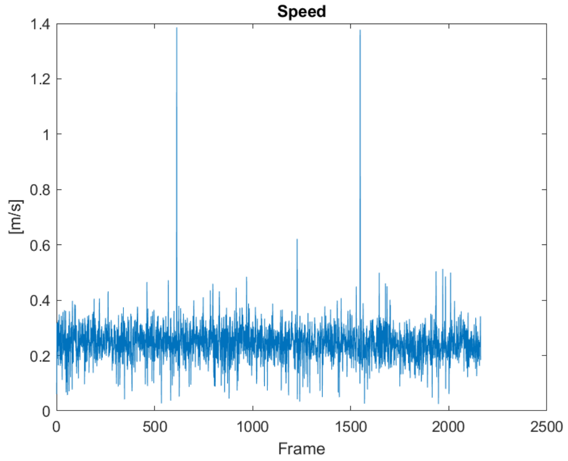


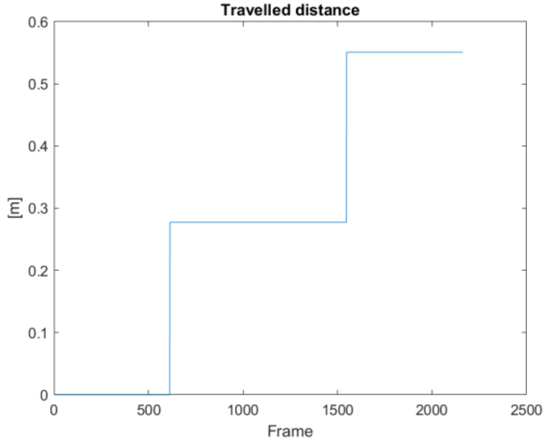


Pointcloud odometry: results

Test #003







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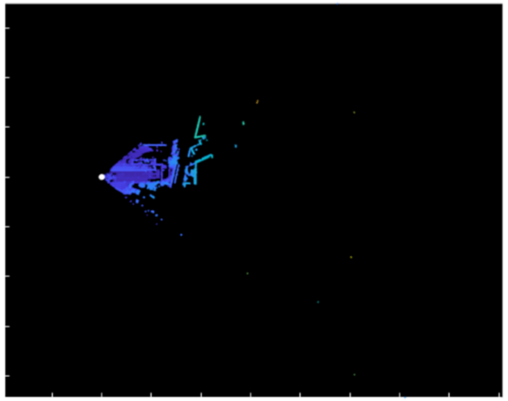
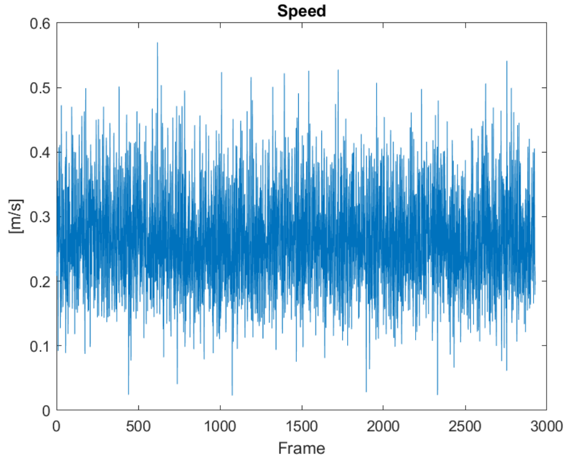
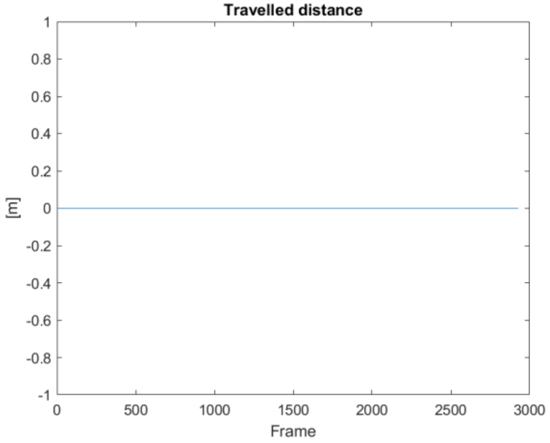
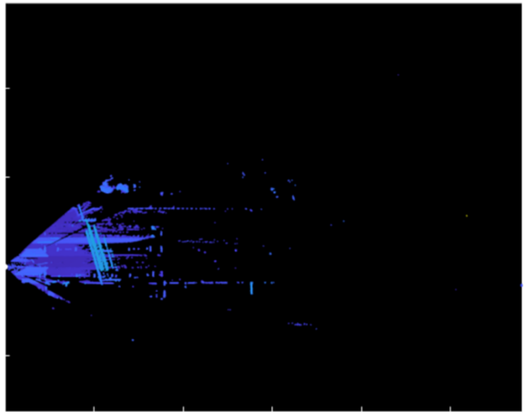


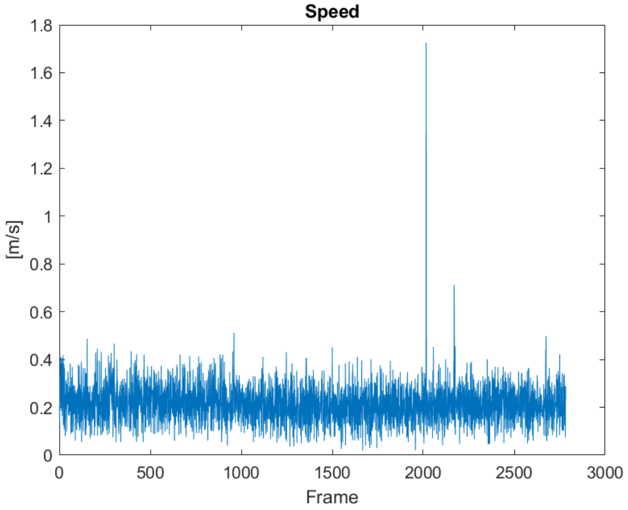


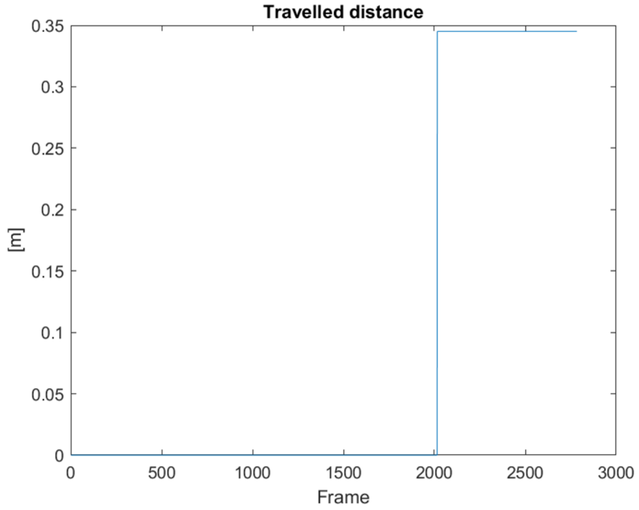


Pointcloud odometry: results

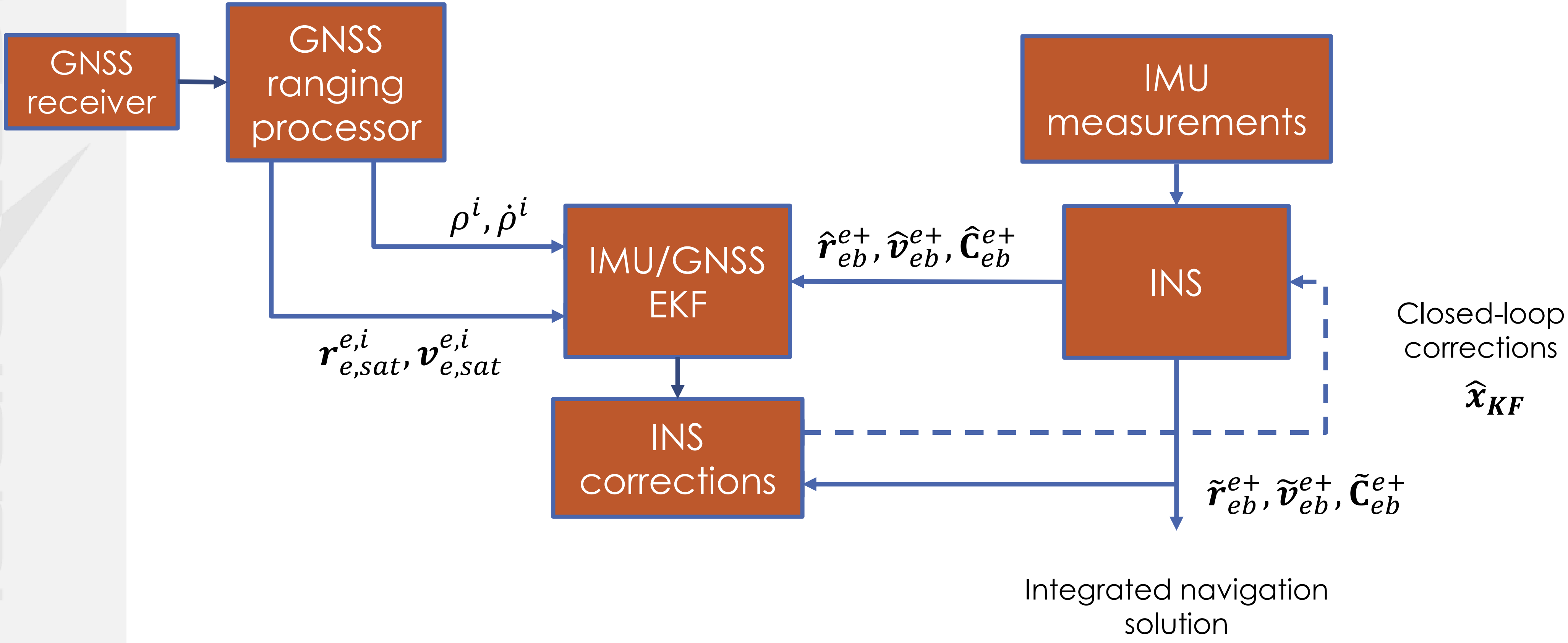
Test #005



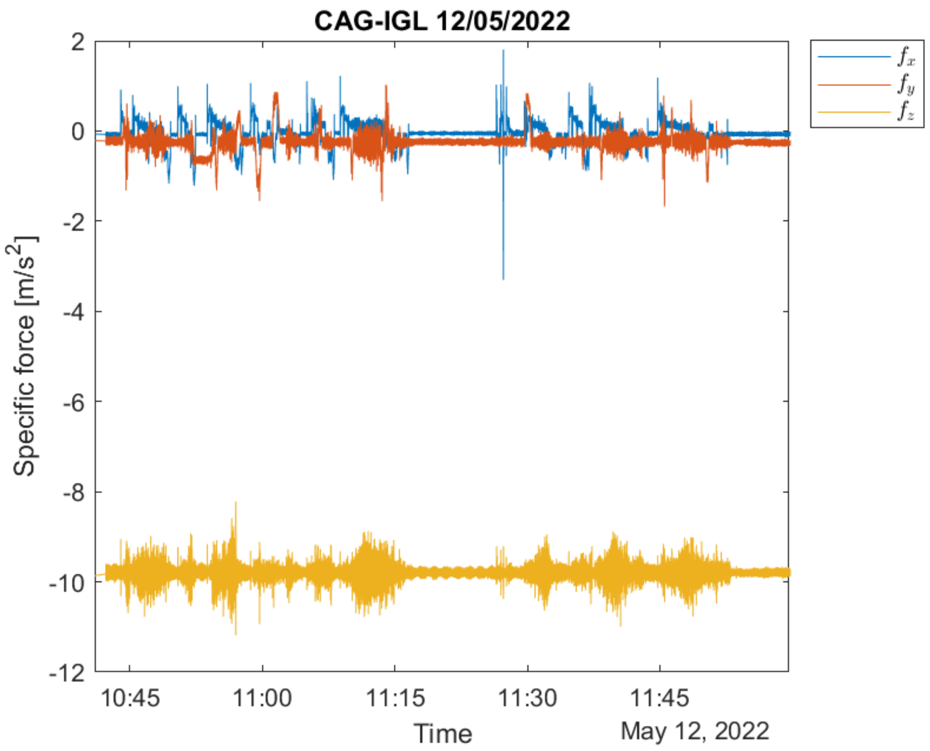


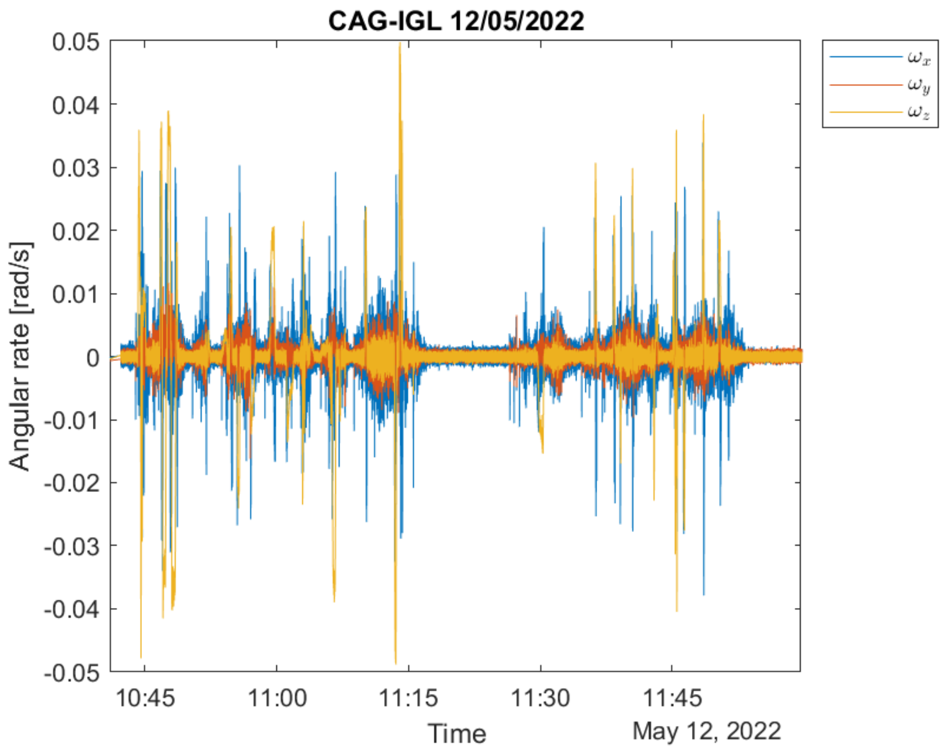


IMU/GNSS module

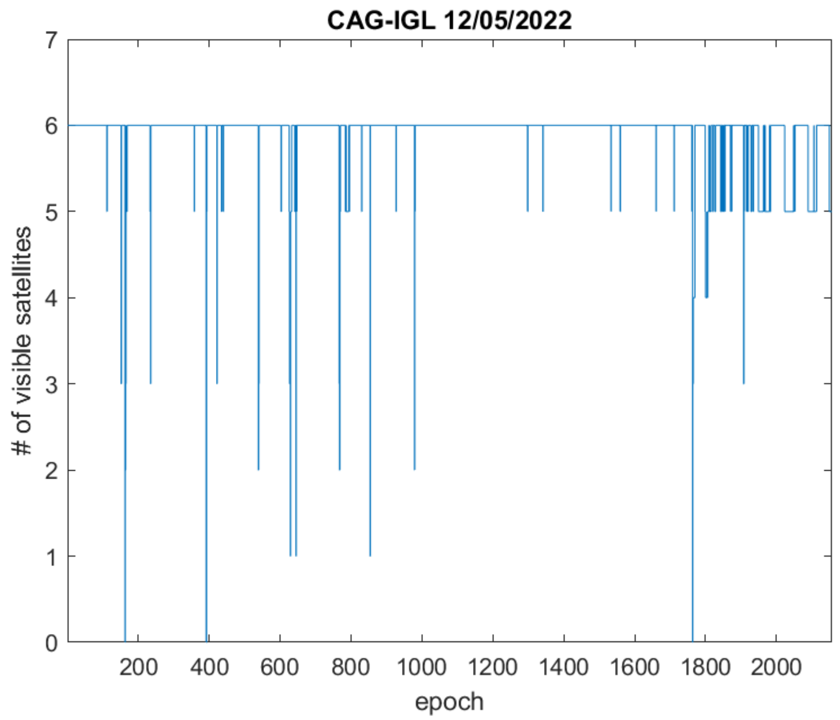


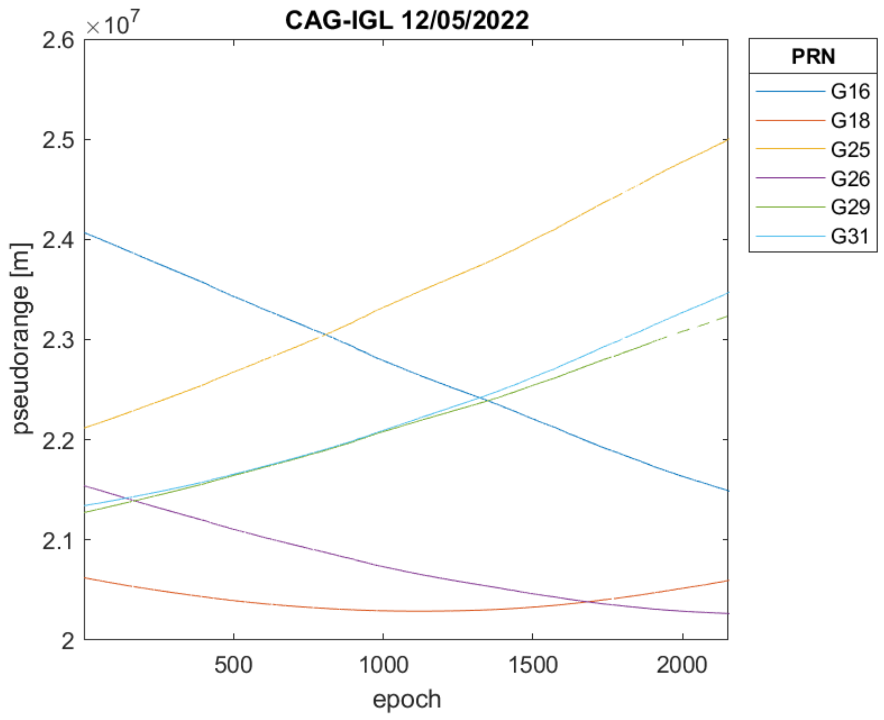
IMU characterization



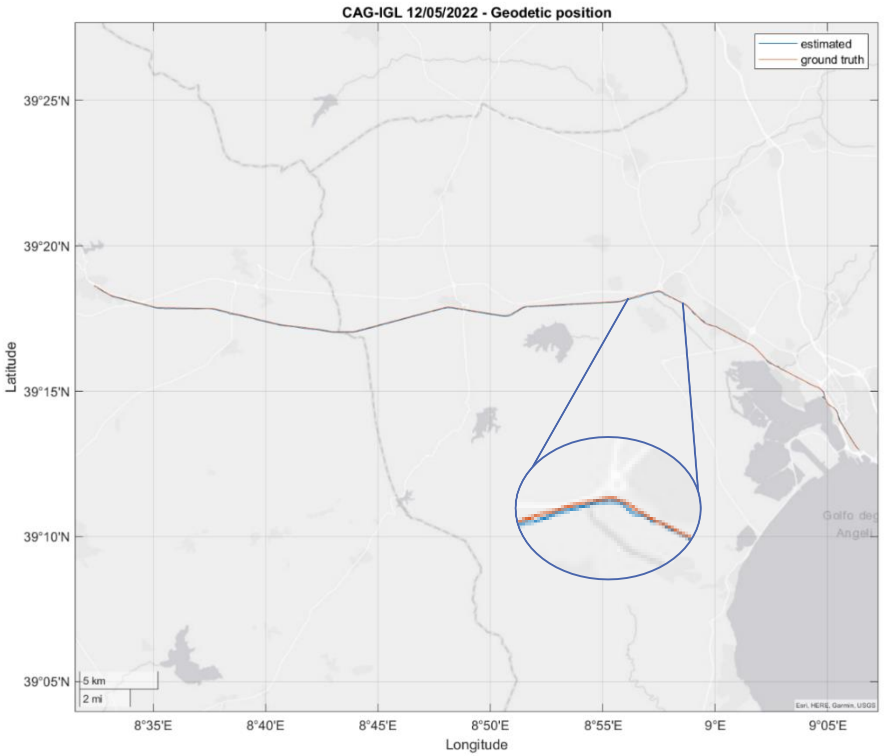


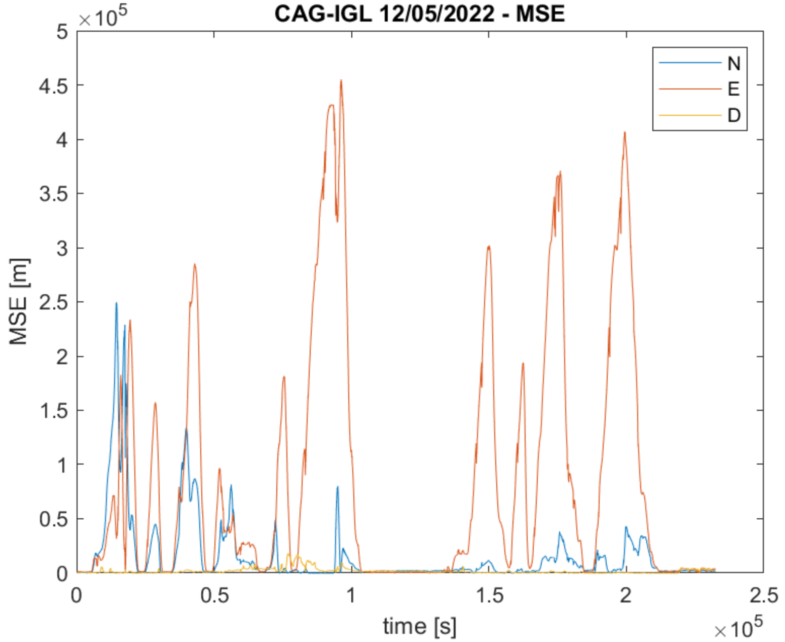
GNSS Visible satellites



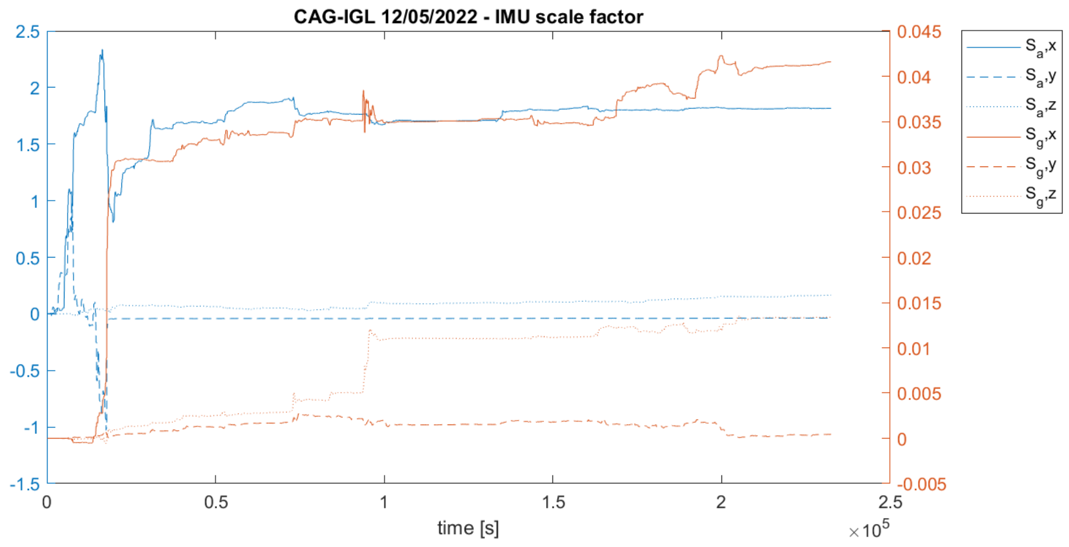


Results


CAG-IGL 12/05/2022 - Geodetic position
estimated
ground truth
39°25'N
39°20'N
39°15'N
39°10'N
39°05'N
Latitude
8°35'E
8°40'E
8°45'E
8°50'E
8°55'E
9°E
9°05'E
Longitude
5 km
2 mi


CAG-IGL 12/05/2022 - MSE
×10^5
N
E
D
MSE [m]
time [s]
×10^5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

Results - IMU errors



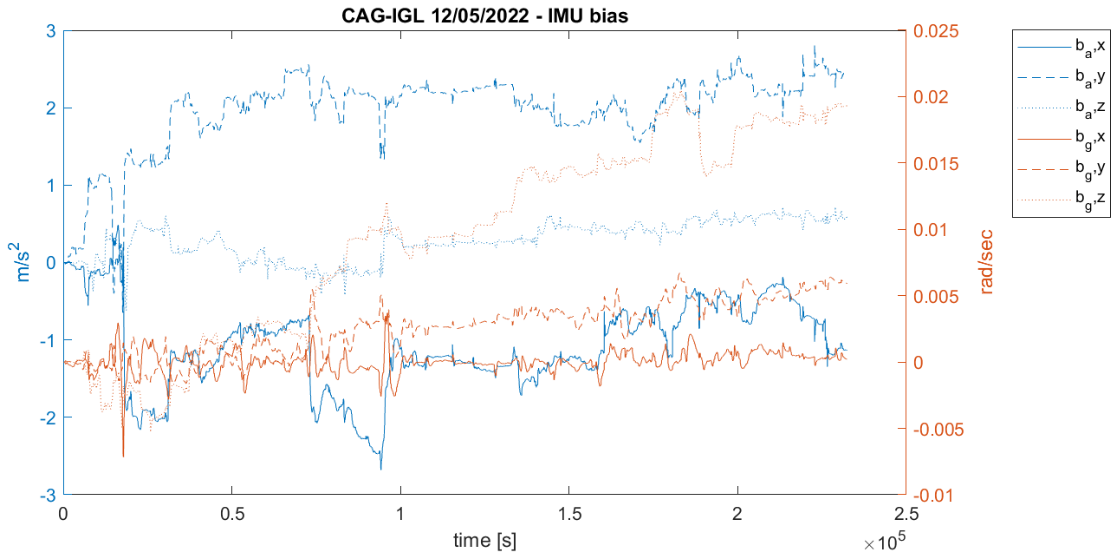


Table of Contents

Conclusion & Next Steps

VOLIERA PoCs have been verified with real railway data allowing to obtain very promising results.
To enhance VOLIERA PoCs robustness, the following three key aspects have to be properly taken into account:

- **GT Identification**, to ensure the quantitative assessment of each developed PoC;

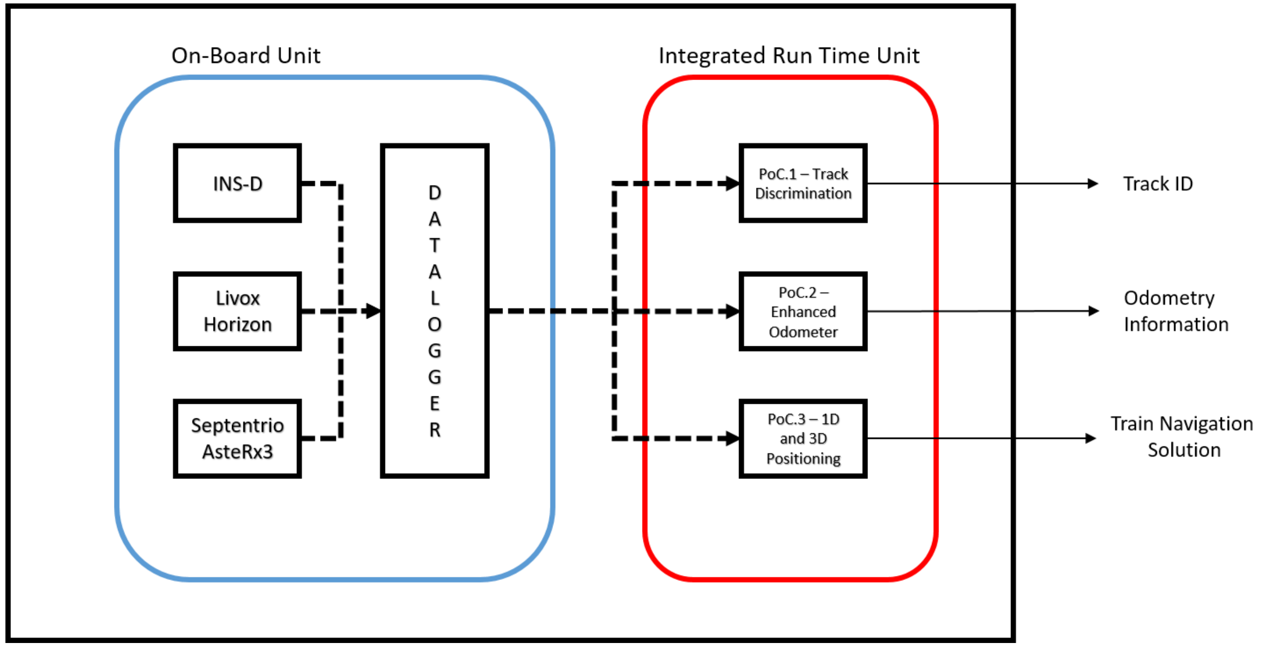
- **Time Synchronization**, to ensure time-correlation of measurement data coming from the different sensors part of the VOLIERA on-board measurement subsystem;

- **Extensive Field Test Campaign**, to collect a large amount of measurement data in order to verify and validate VOLIERA PoCs.

Development Plan

The Integrated Run Time Unit aims combining the developed PoCs in order to let the VOLIERA system providing at run time the expected output.

VOLIERA System



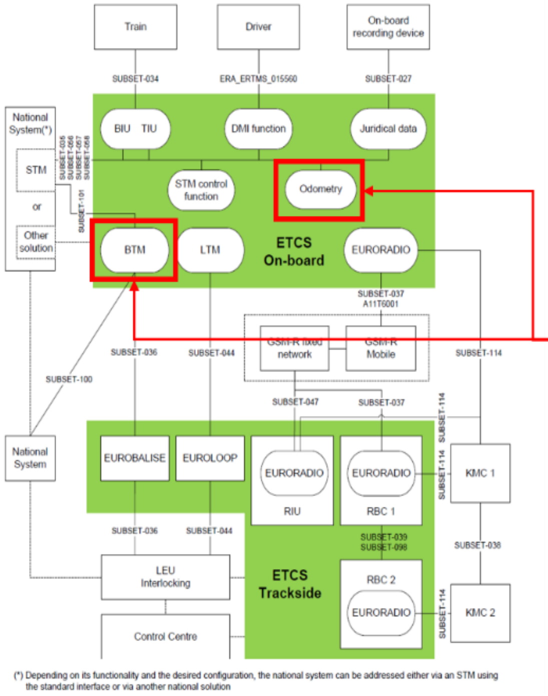
To this end, the following aspects have to be taken into account:

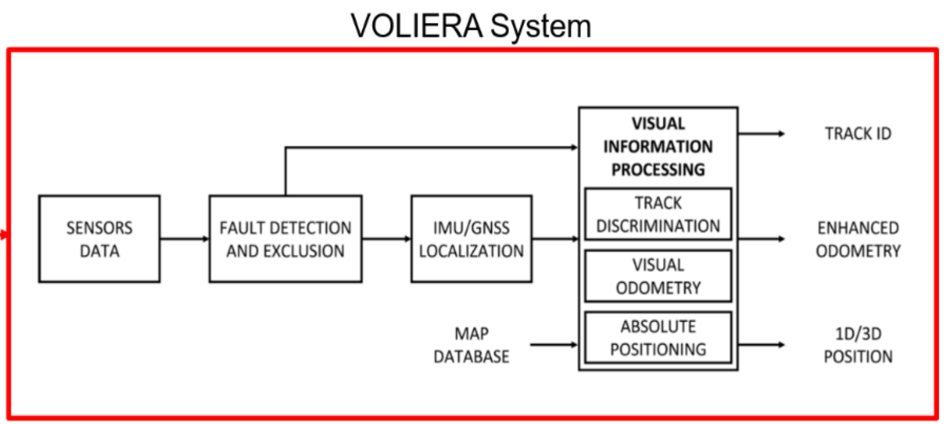
- HW identification;
- SW identification;
- Processing timing;
- Integrated system performance assessment.

Business Plan

To provide the Cost-Benefit Analysis a reference baseline solution is needed.

This reference solution is assumed to be the ERTMS L2 architecture, whose BTM and Odometry components functionalities could be replaced by the ones provided by VOLIERA system





Comparative Analysis (1/2)

Baseline: ERTMS L2 - railway line whose length is equal to 1 km

VOLIERA	
On Board Components	2 GNSS Antennas
	1 GNSS Receiver
	1 IMU
	1 LIDAR
	1 Sensor Fusion Unit
Wayside Components	Track Database

Baseline	
On Board Components	2 Wheel Sensors
	2 Monoaxial Accelerometers
	2 BTM antennas + 2 BTM readers
Wayside Components	4 Balises/km
	Track Database

Comparative Analysis (2/2)

		VOLIERA Solution	Baseline Solution
Design & Build Costs	**Wayside Equipment**	Availability of a Track Database	Availability of a Track Database 4 Balises/km
		TOT 0%	**TOT 31%**
	On-Board Equipment	Supply and installation of on-boards equipment, cabling and other mechanical hardware	Supply and installation of on-boards antenna, speed sensors, BTM, cabling and other boxes
		TOT 75%	**TOT 63%**
	Other Services	System Tuning and Functional Testing	Odometry characterization, tag layout and support design, installation technical specifications
		TOT 15%	**TOT 6%**
	TOT FIX COST	**90%**	**100%**

VOLIERA System Other Applications

Possible additional consumers based on HITACHI customers interview, have been identified:

- Fleet Management System, i.e. systems that can associate the 3D train position provided by VOLIERA system to the simultaneous information related to the train components health status;
- Asset Maintenance System, i.e. systems that can associate the 3D train position provided by VOLIERA system to possible fault conditions which affect the railway assets (es. catenary poles, tracks geometry, etc) determined during the train running.

It is already established to properly define the requirements according to customer indications in order to provide a quantitative CBA associated to the usage of VOLIERA system with respect to the previously mentioned use cases.

END of Presentation