Final Book

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TABLE OF CONTENTS

CHANGE RECORDS **2**
1 EXECUTIVE SUMMARY **8**
1.1 General 8
1.2 Project Setup 8
1.3 Project Boundaries 8
1.4 Main Results and Conclusions 8
1.5 Way Forward 9
2 INTRODUCTION **10**
2.1 Overview 10
2.2 Project Setup 10
2.3 Project Boundaries 10
2.4 Challenges 11
2.5 Project Assumptions 11
3 PROJECT EXECUTION **14**
3.1 WP2, Preparation of Campaign 14
3.1.1 Specification of the Measurement Information 14
3.1.2 Measurement Procedures 14
3.1.3 Identification of the Representative Railway Lines 14
3.1.3.1 Introduction 14
3.1.3.2 Czech Republic 15
3.1.3.3 Italy 15
3.1.3.4 Switzerland 16
3.2 WP3, Field Measurement, Data Collection 17
3.2.1 Procurement of Equipment 17
3.2.1.1 Introduction 17
3.2.1.2 Czech Republic / AZD 17
3.2.1.3 Italy / Ansaldo 18
3.2.1.4 Switzerland / Siemens 18
3.2.2 Design, Installation, commissioning and certification of Equipment 19
3.2.2.1 Czech Republic / AZD 19
3.2.2.2 Italy / Ansaldo 26
3.2.2.3 Switzerland / Siemens 27
3.2.3 Execution of Measurements 31
3.2.3.1 General 31
3.2.3.2 Czech Republic 31
3.2.3.3 Italy 32
3.2.3.4 Switzerland 35

3.3 WP4, Data Post-Processing 39
3.3.1 Pre-Processing of measured data 39
3.3.2 Analysis of pre-processed of data 39
3.3.3 Railway environment characterization 40
3.3.4 Manual Data Analysis using Siemens Ground Truth Visualisation 41
3.4 WP5, EGNOS Technology Feasibility Study 44
3.4.1 General 44
3.4.2 Analysis using the SPRING tool 45
3.4.3 Analysis using the Septentrio SBF Analyzer 48
3.5 WP6, Impact Analysis 50
4 PROJECT RESULTS 51
4.1 WP 2, Preparation of Campaign 51
4.2 WP3, Field Measurement, Data Collection 52
4.2.1 Czech Republic 52
4.2.2 Italy 53
4.2.3 Switzerland 54
4.3 WP 4, Data Post-Processing 55
4.3.1 Introduction 55
4.3.2 Data exchange, reference data set 55
4.3.3 Selection of methods and software tools for data analysis 58
4.3.4 Raw data processing 59
4.3.5 Data post-processing 60
4.3.6 Detection and Identification of the negative phenomena 60
4.3.7 Railway environment characterization 64
4.3.7.1 Clear sky view, on line and in station (ASTS, Sardinia test track) 66
4.3.7.2 Forest, normal and extreme case (AZD, South Bohemia test track) 68
4.3.7.3 Mountain scenario (Siemens, Switzerland) 70
4.3.7.4 Acceleration from the station scenario (Siemens, Switzerland) 71
4.4 WP 5, EGNOS Technology Feasibility Study 74
4.5 WP 6, Impact Analysis 77
5 CONCLUSIONS 82
5.1 WP 2, Preparation of Campaign 82
5.2 WP 3, Field Measurement, Data Collection 82
5.3 WP 4, Data Post-Processing 82
5.4 WP 5, EGNOS Technology Feasibility Study 84
5.5 WP 6, Impact Analysis 84
6 PROJECT SUMMARY 86
6.1 Lessons Learned 86

6.2 Limitation of Performance 86
6.3 MOPS for Railway Applications 87
6.4 Other Issues 89
6.5 Cost / Benefit Issues 89
6.6 Other Findings 90
6.7 Way Forward 90
7 REFERENCES 92

LIST OF ACRONYMS

3InSat	Train Integrated Safety Satellite System, an EU funded Research Project
ALS	Alstom Transportation
ASCII	American Standard Code for Information Interchange
APV	Analyzed parameter value
ASTS	Ansaldo Signalling and Telecommunication Systems
AŽD	Automatizace železniční doprav, Czech Signalling Supply Company
BCR	Benefit Cost Ratio
BT	Bombardier Transportation
CAF	Construcciones y Auxiliar de Ferrocarriles
CBA	Cost Benefit Analysis
CH1903+/LV95	Swiss National Grid Coordinate System
C/N	Carrier to Noise
CSV	Comma Separated Values
DOP	Dilution Of Precision
DMU	Diesel Multiple Unit
ECEF	Earth-Centred Earth-Fixed Coordinate System
EDAS	EGNOS Data Access Service
EGNOS	European Geostationary Navigation Overlay Service
EGNSS	European Global Navigation Satellite System
EMI	Electro Magnetic Interference
EMU	Electric Multiple Unit
ENPV	Economic - Net Present Value
ERR	Economic Rate of Return
ERSAT-EAV	ERtms on SATellite - Enabling Application & Validation, an H2020 funded Research Project
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System

ES	Evaluation Symptom
ESA	European Space Agency
EU	European Union
Galileo	European Global Positioning System
GBAS	Ground Based Augmentation System
GEO	Geo-Stationary Satellite
GDOP	Geometric Dilution Of Precision
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSA	European Global Navigation Satellite Systems Agency
GT	Ground Truth
HNSE	Horizontal Navigation System Error
HPL	Horizontal Protection Level
IM	Infrastructure Manager
IMU	Inertial Measurement Unit
I/Q	In-Phase-&-Quadrature
L1/L2/L3	ETCS Level 1/2/3
L1	GPS Primary Frequency Band, 1563 – 1587 MH7
L2	GPS Secondary Frequency Band, 1215 – 1239.6 MHz
L1/E1	Combined GPS L1 / Galileo E1 Band, 1559 – 1591 MHz
L5/E5a	Combined GPS L5 / Galileo E5a Band, 1164 – 1189 MHz
LHCP	Left Hand Circular Polarisation
LNA	Low Noise Amplifier
LOS	Line of Sight
MOPS	Minimum Operational Performance Standard
MPL	MultiPath Level
NGTC	Next Generation Train Control, an H2020 funded Research Project
NLOS	Non Line of Sight
NPV	Net Present Value
NSE	Navigation System Error
OBU	On-Board Unit
PPS	Pulse Per Second
PP-SDK	Post-Processing Software Development Kit, professional software development kit from Septentrio
PVT	Position Velocity Time
RADLBS	RadioLabs
RF	Radio Frequency

RFI	Rete Ferroviaria Italiana
RFID	Radio Frequency Identification
RHCP	Right Hand Circular Polarisation
RIL	RF Interference Level
RINEX	Receiver Independent Exchange Format
RPS	Record Playback. System
RTKLIB	Open Source Real Time Kinematic Software Library
RTCA	Radio Technical Commission for Avionics
RU	Railway Undertaking
SBAS	Space Based Augmentation System
SBB	Schweizerische Bundesbahnen (Swiss Federal Railways)
SBF	Septentrio Binary File
SC	Steering Committee
SIE	Siemens
SIL	Safety Integrity Level
SIS	Signal in Space
SPRING	Simulateur de Performances de Récepteurs Intégrant la Navigation par GNSS
SVF	Satellite Visibility Factor
SWIPOS	Swiss Positioning Service
TASF	Thales Alenia Space France
TEQC	Tool for pre-processing of GNSS data
THR	Tolerable Hazard Rate
TMT	Technical Management Team
TTS	Thales Transportation Systems
TUBS	Technische Universität Braunschweig
UBOC	Università Commerciale Bocconi Milano
UNIFE	Union des Industries Ferroviaires Européennes
UMTS	Universal Mobile Telecommunications System
UTC	Universal Time Coordinated
WGS84	World Geodetic System 1984
WP	Work Package
X2R	Research activity, which is part of Shift2Rail, a large-scale European rail research joint undertaking
ZCU	Západočeská univerzita, University of West Bohemia

1 EXECUTIVE SUMMARY

1.1 GENERAL

STARS is an EU funded research project, which is being managed by GSA, the European Global Navigation Satellite Systems Agency.

It has been set up to investigate the specific characteristics of the railway environment in regard to GNSS performance. This includes negative effects on accuracy, availability and safety by local environmental effects such as multi path signals (e.g. by reflections on buildings), signal attenuation (e.g. by leaves of trees), electromagnetic interference (e.g. by the train itself, or other sources) and reduced visibility of satellites (e.g. due to masking by buildings and mountains).

1.2 PROJECT SETUP

The project has been set up to perform the following main activities:

- Collect raw GNSS data, as well as data required to generate the true position of the train, which is being used as a reference against which GNSS performance is evaluated
- Analyse the collected data to identify
    - locations where GNSS performance is degraded, as well as
    - the root causes which degrade the performance
- Determine what contributions EGNOS can make for railway applications, respectively which changes in EGNOS would be required to increase the contributions of EGNOS
- Analyse the cost and benefits of using GNSS to reduce the need for Eurobalises in the track.

1.3 PROJECT BOUNDARIES

The investigations performed in the STARS project have concentrated on using GNSS in interoperable, safety critical railway applications, especially ETCS, and across the European railway network.

If GNSS is applied outside these boundaries then some results might change significantly, especially regarding the cost/benefit analysis.

1.4 MAIN RESULTS AND CONCLUSIONS

The main results and conclusions of the project can be found in the Project Summary in Chapter 7 of this document.

They can however be summarised as follows:

- Thanks to the significant amount of data which has been collected on the three test sites and the subsequent, detailed data analysis, a characterisation of the railway environment in regard to the impact on GNSS performance has been achieved.
- From these results it can be concluded that GNSS has potential in safety critical applications in the railway environment.
- Significant work will however still have to be done to solve the identified issues resulting from a number of characteristics of the railway environment, which are significantly more challenging than e.g. those in the aviation environment.
- A MOPS similar to the one produced for aviation applications can not properly reflect the situation in the railway environment, as GNSS is not working continuously due to environmental effects but is subject to frequent interruptions or distortions.
- GNSS will likely have to be supplemented with additional sensors and/or map matching functions to achieve the required performance in all but the most open, GNSS friendly environments.

- These supplements will have to be standardised due to interoperability requirements, which require a predictable performance of each on-board system under defined conditions.
- EGNOS has also been thoroughly analysed, both regarding availability, if received from geostationary satellites, and possible contribution to increase performance, if available continuously.
- It can be concluded that EGNOS coverage is too limited on most railway lines if provided by geostationary satellites, an alternative solution to distribute EGNOS data to on-board units will therefore have to be defined and standardised, preferably using the ETCS radio.

Regarding cost – benefit analysis the summary is as follows:

- A model to analyse cost – benefit for individual applications has been developed.
- Once legal issues were solved, which would have resulted from sharing cost data between suppliers, analysis showed that a positive Benefit/Cost ratio can be achieved in local and regional lines. This however depends on a number of conditions, which are specific to different applications.
- The sensitivity analysis has shown that the share of Eurobalises, which can be eliminated by GNSS, and the cost of the additional on-board module are much more relevant than the cost of maintaining balises, meaning CAPEX dominate over OPEX.
- The results of the cost – benefit analysis will however need to be refined, as a number of cost items will need to be included once the use of additional sensors and/or map matching functions has been defined. Work on these issues is currently being done under the Shift2Rail programme.
- Also, the scenarios for local, regional and main lines will need to be refined, in order to better represent practical applications of ETCS on the Trans European Network, where an open access to all railway lines is crucial.
- Finally, a solution will have to be found to balance costs and benefits between participants, as the benefits of using GNSS lie mostly trackside, whereas most of the cost is generated on-board.

1.5 Way Forward

Based on the results from the STARS project a number of recommendations have been produced for technical areas, which should be investigated further in future projects. They can be found in chapter 7.7.

Some of the identified topics are being addressed in Shift^{2}Rail, such as the investigation on which additional sensors, or functions will have to be developed and standardised to support GNSS in the railway environment.

Several additional topics will however have to be investigated in the frame of not yet defined, future research project, such as:

- The development of new, standardised PVT and PL algorithms, which can better cope with the environment, but still provide high performance.
- The development of cost effective on-board functions for the detection and mitigation of environmental influences, in order to decide where the GNSS positions cannot be trusted.
- The development of a standardised solution to provide EGNOS data to on-board units.

2 INTRODUCTION

This document contains an overall description of the STARS project, from the initial definition through execution to results and conclusions. It forms a final report, which was not originally planned to be a deliverable. The project team however considered it appropriate to produce such a report, as many aspects of the project would otherwise not have been documented anywhere.

2.1 OVERVIEW

STARS is an EU funded research project, which is being managed by GSA, the European Global Navigation Satellite Systems Agency.

It has been set up to investigate the specific characteristics of the railway environment in regard to GNSS performance. This includes negative effects on accuracy, availability and safety by local environmental effects such as multi path signals (e.g. by reflections on buildings), signal attenuation (e.g. by leaves of trees), electromagnetic interference (e.g. by the train itself, or other sources) and reduced visibility of satellites (e.g. due to masking by buildings and mountains).

It has always been expected that the occurrence of such local phenomena is more frequent and their magnitude significantly stronger in the railway environment, compared to other safety critical applications of GNSS such as in aviation or at sea, but this has never been thoroughly investigated and documented.

2.2 PROJECT SETUP

The project has been set up as a sequence of tasks which depend on each other:

- Definition of the measurements campaign
- Procurement, installation, commissioning and certification of equipment on test trains
- Execution of measurements, including generation of ground truth data
- Analysis of measured raw data in regard to environmental impacts
- Analysis of contribution of EGNOS
- Identification of EGNSS target performances to meet railway requirements and definition of a reference architecture to integrate EGNSS into ETCS
- Assessment of EGNOS performances in the railway environment in regard to accuracy, integrity and availability and evaluation of different error budget models to handle local effects
- Preliminary definition of EGNOS Services for application in ETCS

Parallel to these activities a cost/benefit analysis has been performed.

2.3 PROJECT BOUNDARIES

The investigation performed in the STARS project on using GNSS in railway applications is based on the following assumptions:

- The focus is on safety critical applications in signalling.
- GNSS is used as “stand alone” application, combining GNSS with other sensors is out of the scope of the STARS project.
- Galileo and GPS augmented by EGNOS have been considered, local augmentation systems have not been considered due to the geographical extent of the railway network, and the resulting cost.
- The so called virtual balise concept has been used where a functional system architecture was required, such as in the cost-benefit analysis.
- The project targets interoperable applications (identical and predictable minimum performance of on-board systems from different suppliers), especially in ERTMS/ETCS.

- The European Railway Network is assumed as service area, which defines the environment to be investigated.

If GNSS is applied outside these boundaries then some results might change significantly, especially in regard to the cost/benefit analysis.

2.4 Challenges

The project has been defined from the start with a very tight schedule, even though there were several tasks and dependencies between tasks identified already when the project was defined which were considered difficult to achieve. A number of these points led to delays, which required an extension of the duration of the project. They included delays in the procurement of equipment, in getting on-board installation approvals and in getting the equipment installed and commissioned.

2.5 Project Assumptions

A number of questions arose during the execution of the project, for which assumptions had to be made. They are listed in the following table, including consequences which result from them:

Title	Description of Assumption	Consequences
ETCS Level	The study analyses GNSS based train positioning on the basis of ETCS Level 2/3.	ETCS Level 2 is assumed to be a prerequisite and is therefore not included in the cost/benefit analysis. **Note:** Proprietary applications are not analysed, they might however be pursued by suppliers for applications where open access and interoperability are not required.
Method of integrating GNSS into ETCS	The way how GNSS is integrated (architecture) has a significant impact on many issues, such as how much GNSS contributes to the ETCS functionality, requirements from ETCS towards GNSS, impact of GNSS availability issues etc.	It was agreed that the virtual balise concept shall be used as a starting point.
Open access	Open access to lines relying on GNSS will only be possible for vehicles equipped with the necessary GNSS positioning system.	Lines relying on GNSS will have to specify the necessary equipment as access criteria, similar to Euroloop or radio infill. Rolling stock used on those lines will therefore have to be equipped accordingly. Backwards compatibility of non-equipped rolling stock is not ensured.
Interoperability	Interoperability between on-board equipment of different suppliers will have to be ensured	The performance of a virtual balise reader will have to be specified, and proven through testing
Engineering Rules	Engineering rules will have to be observed to define locations of virtual balises, as only a minimum, specified performance of interoperable equipment can be assumed.	The engineering rules will have to specify environmental conditions, which must be ensured where a virtual balise is placed
Architecture	GNSS will be integrated into ETCS via the so called virtual balise concept, which requires a virtual balise reader generating virtual balises as the train passes their location	Requires an onboard database which contains as a minimum the long/lat position of all virtual balises, as well as their telegram content. Note that the database can be pre-stored or loaded as needed during train operation.
On-board database	An onboard database which contains as a minimum the long/lat position of all virtual balises, as well as their telegram content	Such a database will have to be provided by the infrastructure manager of a line, be kept up to date at any time and transmitted to the trains by standardised means
Usage of EGNOS	Due to the poor EGNOS reception recorded even on rural lines in flat country, a transmission of EGNOS data via radio has been assumed.	A rail specific EGNOS service will be required to provide EGNOS data to each single train over a protected interface, preferably the ETCS radio.

Table 1: List of Assumptions

Note: Changes to these assumptions might be made over the future course of developing a GNSS based train positioning system. Such changes can have an impact on the results described in this document.

3 PROJECT EXECUTION

The following sections describe the actual execution of the work packages. It is intended as an overview and summary of how the work has, and also contains information not included in the respective deliverables, such as issues which have been encountered and had to be solved.

Note that the actual results are summarised in section 5 and the conclusions in section 6.

3.1 WP2, PREPARATION OF CAMPAIGN

3.1.1 Specification of the Measurement Information

The objective of this activity consisted in the identification of the information to be measured and recorded in the measurement campaign, with the aim to produce a measurement specification. The activity started by reviewing a measurement specification delivered by the ERSAT-EAV project, to which contributions have been collected, and discussed based on a clear methodology of identifying the sources of error (inside and outside human decision making) and then concluding with the required measurements to be performed taking into account the peculiarities of the GNSS technology.

The corresponding deliverable has been prepared specifying a detailed list of measurements to be performed with related unit, resolution, and measurement rate. This initial step has been performed without specifying specific equipment to be used.

3.1.2 Measurement Procedures

The minimum common set of equipment was identified, specified and purchased to record the measurements required in previous task, after performing a thorough investigation of the offered functionalities and the possibilities of different equipment to satisfy the afore-mentioned measurement specifications. Equipment providers and distributors have been contacted to reach a decision on which equipment to purchase.

The measurement procedures have been specified in detail after thorough discussions of different possible methodologies and taking into account technical implementations due to specific conditions on the different measurement sites. Measurement acquisition, data format, techniques for the synchronization of measurement data and for the assessment of GNSS position errors with respect to a position reference have also been discussed.

Measurement procedures related to the minimum common set of equipment for GNSS performance assessment, procedures related to EGNOS data collection, procedures related to individual line equipment for Ground Truth assessment, and procedures related to test line specific data have been defined, namely test vehicle/track identification, test environment conditions, weather conditions, geo-referencing conditions, GNSS and European augmentation service performance forecast for campaign scheduling.

3.1.3 Identification of the Representative Railway Lines

3.1.3.1 INTRODUCTION

The original scope of the project was to perform measurements on three different sites, managed by Ansaldo in Italy, AZD in the Czech Republic and Siemens in Germany. The selection of the countries was made on the basis of discussions with infrastructure managers and train operators in the respective countries prior to the start of the project, where they indicated they would support the project.

This selection was also reflected in the project budget, where the cost was included for the three sites within the budgets planned for the three companies.

For a number of reasons, the measurement campaign managed by Siemens has been shifted to Switzerland, the reasons being described in the respective section below.

3.1.3.2 CZECH REPUBLIC

Introduction

Line selection in the Czech Republic was done with the aim to perform measurements in one of the target environments of GNSS based train positioning, which is rural, secondary lines.

Selection of Railway Line

The selected line in South Bohemia is around 60 km long and quite representative of is rural, secondary lines. It runs through rural terrain with open areas, forests and some hills, but no significant built up areas beyond typical countryside villages. Contributing factor for the selection of the line was that the track axis of the line was recently surveyed with very high accuracy.

Selection of Test Vehicle

The diesel multiple unit class 814 “Regionova” was selected as it operates back and forth over the above-mentioned line once or twice per a day. Also, the driving trailer car of this unit provided enough space for the installation of the measurement equipment, for antennas on the roof and for sensors on the axles and under the car for generating odometry and reading tags for position referencing.

As mentioned in the introduction, good support from Czech Railways was also an argument, as they indicated interested in research activities in the field of the satellite localization on railway when the STARS project was initially set up.

3.1.3.3 ITALY

Introduction

The lines to be managed by Ansaldo in Italy were planned to be in the Pontremolese and Sardinia area to build on interesting results achieved by past projects, such as 3InSat and ERSAT-EAV. These projects already investigated the suitability of EGNSS (including EGNOS and Galileo early services) for fail-safe train positioning in ETCS/ERTMS, and particularly in regional lines scenarios, which have been targeted as application of providing safe train localization based on satellite technologies.

Selection of Railway Line

In Italy, two lines were selected with different characteristics such as environmental conditions and vehicle types. The Pontremolese line of around 120 km long presents challenging conditions in terms of obscuration (terrain, bridges and tunnels…) and is electrified. Contrary to that the Sardinia line of around 50 km long mostly presents open sky conditions in a typical rural environment, with only some low height industrial facilities and few bridges and overhead passes. It is also operated by Diesel engine powered vehicles. Also, the track axis and relevant objects on both lines were surveyed with very high accuracy in the frame of previous projects.

Selection of Test Vehicle

The test vehicles were selected in Italy in accordance with the motivations put forth previously in the “Introduction” for the selection of the test sites. In particular, a diesel powered, and an electric powered vehicle were used for measurements on the lines in Sardinia and Pontremolese respectively. These vehicles have been used in previous, GNSS related projects, where it was already demonstrated that they are suitable for the installation of antennas, temporary equipment for measurements, as well as for Eurobalise reading and odometry measurements.

Both vehicles operate in regular, commercial service, travelling back and forth several times during the day over the respective lines.

3.1.3.4 SWITZERLAND

Introduction

The site to be managed by Siemens was initially planned to be located in Germany. For that reason, related cost and manpower for the installation of the equipment and the execution of the measurements had been budgeted for Siemens Germany. A number of reasons led however to the selection of Switzerland for the measurements:

- Measurements in Germany would likely have been in an environment similar to the one in the Czech Republic, where else the environment in Switzerland differs significantly from the sites in the Czech Republic and in Italy, covering rural, mountainous and urban area. This significantly expanded the environments, in which measurements could be performed.
- No trackside infrastructure exists in Germany, which could have been used as absolute reference points to generate the Ground Truth. This would have required installation of e.g. RF ID tags, as used in the Czech Republic. In Switzerland however, the entire standard gauge rail network has recently been converted to ETCS Level 1, providing Eurobalises to be used as absolute position references everywhere.
- In Germany it would likely have been necessary to survey the precise track position of the line to be used, where else very precise track data is available from Swiss Federal Railway for the entire network, creating the opportunity to perform measurements not only on a dedicated test line, but anywhere on the network.
- Trains in Germany and Switzerland are typically part of a fleet which is being used on multiple lines, rotating between lines. While this provided the opportunity to perform measurements in many different environments in Switzerland due to the availability of Eurobalises and track data for the entire network, it would have limited the number of possible measurements in Germany as only a single line would have been equipped with RF ID tags.

Another coincidence also supported the decision to perform the STARS measurements in Switzerland, instead of Germany. A company internal project required an on-board test installation in Switzerland, with very similar requirements in regard to the required on-board equipment. Only small extensions were required to make that installation also suitable for performing STARS measurements. This generated significant synergies:

- By combining the two installations only one installation had to be produced, produced, installed and certified, resulting in significant savings.
- Measurements for both projects could be done in parallel, whether on-board the train or by remote access. This generated significant cost savings as well.
- A number of data post-processing tools developed for the Swiss project could be used by the STARS project, especially to produce the Ground Truth.

Due to the relocation of the test site to Switzerland, the difficulty of separating cost for the installation and certification between the two projects and the special situation in regard to H2020 financing of Swiss participants, the cost of the on-board installation has not been charged to the STARS project. The only exception is the special equipment explicitly and solely used for the STARS project. This explains the underspending of Siemens for this position.

Selection of Railway Line

Due to the above described situation no specific railway line had to be selected. Instead, measurements were performed wherever the selected train operated.

Selection of Test Vehicle

A Domino train was selected for the test installation. Domino trains are used in Switzerland for local and regional services. A total of 128 Domino trains were originally produced under the designation NPZ (Neuer Pendelzug) between 1984 and 1996. They have been refurbished and significantly upgraded between 2008 and 2013, when they were renamed as Domino. They consist of a power car (RBDe 560), a varying number of between one and three coaches and a control cab car.

The Domino train was selected for two main reasons. First of all it is equipped with ETCS, which was a precondition as the ETCS on-board system is used to provide balise and tacho information to the measurement equipment, which were required for generating ground truth data. Then the Domino power cars still contains a baggage compartment, which is not used operationally anymore. This provided sufficient space for the installation of the combined equipment. Installing the equipment in the baggage compartment also allowed performing attended measurements during normal train operation without interfering with or disturbing the driver or passengers. Then there were a number of other reasons, which made the Domino a good measurement platform:

- Domino EMU's are used in both local and regional services, resulting in different speed profiles.
- The selected type is part of a larger fleet, which rotate between different sites for maintenance reasons, resulting in operation over different lines.
- The use of the train for the already mentioned, company internal project required dedicated test trips. This permitted STARS measurements also under unusual scenarios, such as at low speed over extended distances.
- The measurement equipment could be installed at the same time as the ETCS Level 2 equipment, which minimised the installation cost and required no additional standstill time.
- The antenna could be installed on top of the power car, which generates electromagnetic interferences similar to a locomotive, providing a more challenging environment for GNSS.

3.2 WP3, Field Measurement, Data Collection

3.2.1 Procurement of Equipment

3.2.1.1 Introduction

The procurement of the equipment as defined in WP2 has proven to be a critical issue in the project for a number of reasons:

- Suppliers were not able to deliver equipment in the times indicated during the selection process.
- For antennas the required certificates required by national rules could not be provided, which required selecting alternative products.

3.2.1.2 Czech Republic / AZD

The AZD measurement system had to be completely built from scratch, all the components of the system had to been purchased new. Procuring all the components took significant time, as many of the components are quite special parts, which are usually not on stock at suppliers. It also took significant time to integrate all components and to test and install the system.

Some of the special components had to be procured directly from the manufacturer. One of them was the GNSS antenna Antonics OmPlecs-TOP 200 AMR 1500 B L1/I2 with an external LNA. It is designed and approved for the use in railway applications and it has been agreed as the common GNSS antenna by the companies responsible for the three measurement campaigns. Delivery of the antenna took more than 2 months, as the supplier waited for other customers orders to achieve the minimum quantity to start antenna production. Another such component was the military GNSS antenna G8Ant-52A4SC1-RL suitable for reflected GNSS signal reception due to its capability to receive signal in both RHCP and LHCP polarizations. The purpose of purchasing the antenna had to be explained and justified and an End User Statement provided to the manufacturer before the start of custom production. Also taking into account the company's management approval process for purchasing equipment the procurement of the antenna took nearly 6 months.

Expensive components like the Moxa industrial computer, RPS Spirent and Aaronia spectrum analyser required careful and time-consuming specification of hardware and software options before ordering. Significant time was spent to obtain approval for these unplanned investments, as only a small percentage of the purchase price was covered by the STARS project.

Selection and procurement of the RFID system used for absolute position references in the odometry system took also some time, since the system has never been used before in such a railway application in the Czech Republic or elsewhere. Different RFID readers, transponders and antennas had to be tested in a short time to achieve sufficient performance of the RFID system for the intended purpose.

Finally, procurement of various cables approved for the railway vehicle installation (Ethernet, CAN, power supply, etc.) also took some time, since only small quantity (several tenth of meters at maximum) were required.

Although the delivery time of some components took several months, the start of the measurement was delayed mainly for another reason as described below in Chapter 4.3.2.1.

3.2.1.3 Italy / Ansaldo

The procurement process of most of the equipment went smoothly, although one GNSS antenna supplier delivered the product many months after the promised date, which made it impossible to meet the project deadlines and therefore the Antonics antenna which was planned to be one of the common equipment on all three sites was not installed on the vehicles running on the sites in Italy.

3.2.1.4 Switzerland / Siemens

The procurement of most of the STARS related equipment went smoothly, the only exception being the wide band GNSS antenna required to perform measurements in all GNSS bands, as well as to perform spectrum analysis.

Swiss Federal Railway requires that all antennas mounted on any type of rolling stock are certified to withstand contact with a dropped catenary, which in the Swiss case carries 15 kV, 16.7 Hz AC, in order to avoid stray voltages entering the vehicle which could harm persons or damage equipment. Most GNSS antennas currently in use, which are certified to withstand such voltages, are supporting the L1 band only, meaning they are not suitable. They are typically used in simple, not safety critical applications such as diagnostics, passenger information etc., for which a receiver using GPS L1 only is sufficient.

A quick investigation of the certification process revealed that certifying an antenna specifically for the STARS project was out of question, as the time required, and the resulting cost would have been prohibitive. In addition, there was also a risk that any non-certified antenna would not pass the test, possibly requiring a complex and time-consuming redesign.

Other projects avoided that problem by designing an isolated, autonomous measurement system installed in a container on the roof of a vehicle, so that any contact with the catenary would be shortened to the vehicle body, with no cabling of any form protruding into the vehicle. This was however not feasible due to the required setup of the test installation, with interfaces to other sensors and the train's power supply.

A market research showed that there is currently only one suitable multi-band antenna available on the market, which is the Antonics OmPlecs-TOP 200 AMR 1500 B L1/I2.

While the actual antenna was delivered within four weeks of ordering, the corresponding LNA (low noise amplifier) was only delivered more than two months after the antenna. Due to this, integration testing and subsequently the start of the measurements was delayed by approximately three months.

3.2.2 Design, Installation, commissioning and certification of Equipment

3.2.2.1 Czech Republic / AZD

As described in Chapter 4.3.1.2 the measurement system had to be completely designed and built from scratch. In addition, some special components that conform to requirements of railway standards but are not approved for railway applications have been designed for use in the system. Apart from that a new odometry system also had to be installed. The both new systems were installed on the selected type of railway vehicle for the first time. These facts caused a significant delay in the start of both the system installation and, as a consequence of this, the measurement.

A lot of time has been spent for negotiations with the railway operator (the owner of the vehicle) on the system design, individual components and the design of the installation. Different documents, such as compliance agreements, measurement protocols, parameter specifications (and its translations in terms of the railway standards) of individual components, static review of the console for components of the odometry system etc. had to be delivered, especially for all components which were not generally approved for the use on railway vehicles. Only once all of these components had been installed the documentation for the installation and installation agreement could be completed.

The approval process of the Railway Authority also required more time than usual due to the assessment of the components not approved for installation on railway vehicles, as well as the unique design of the installation of both systems on the selected vehicle.

Although the start of the measurements was significantly delayed (the system could only be put in operation at the end of July 2017), a large amount of data was acquired in only a few months due to daily operation of the vehicle and the design of the measurement system which permitted unattended execution of measurements. In addition, the installation of the components not approved for railway vehicles, such as the panoramic camera or the dual polarization antenna, enabled to use new efficient methods in the railway environment characterization.

Trackside

An RFID system was selected to generate absolute position references. More than 200 hundred RFID tags were installed on the line, and their position surveyed. Some of tags were also installed in the proximity of switches in stations to distinguish between parallel tracks.

The following figure shows an example of the documentation prepared for installation and surveying of RFID tags in Čííčenice railway station.

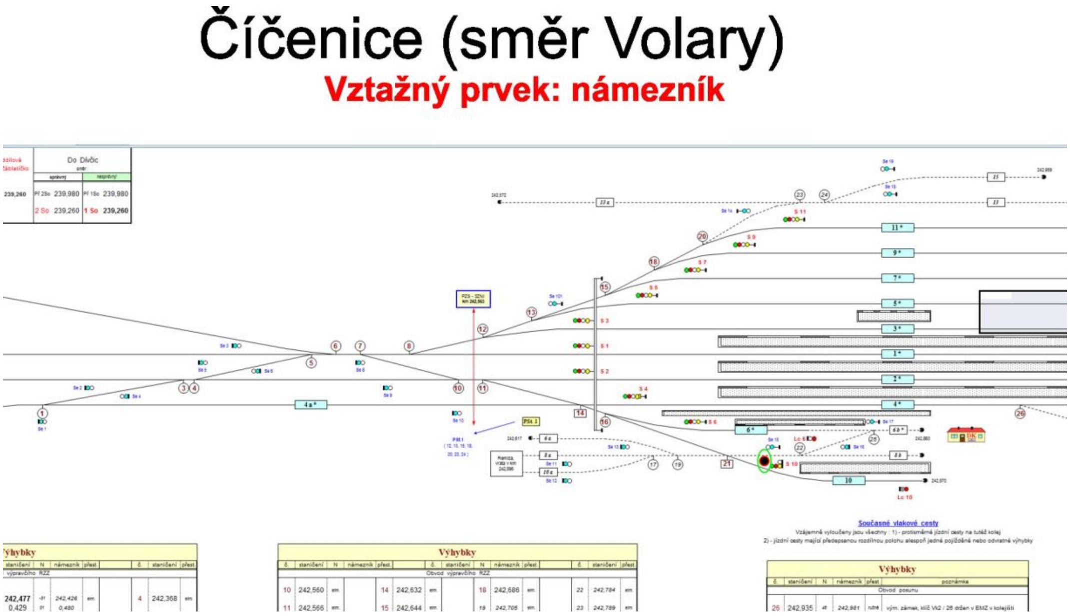


Figure 1: Track layout of Číčenice station

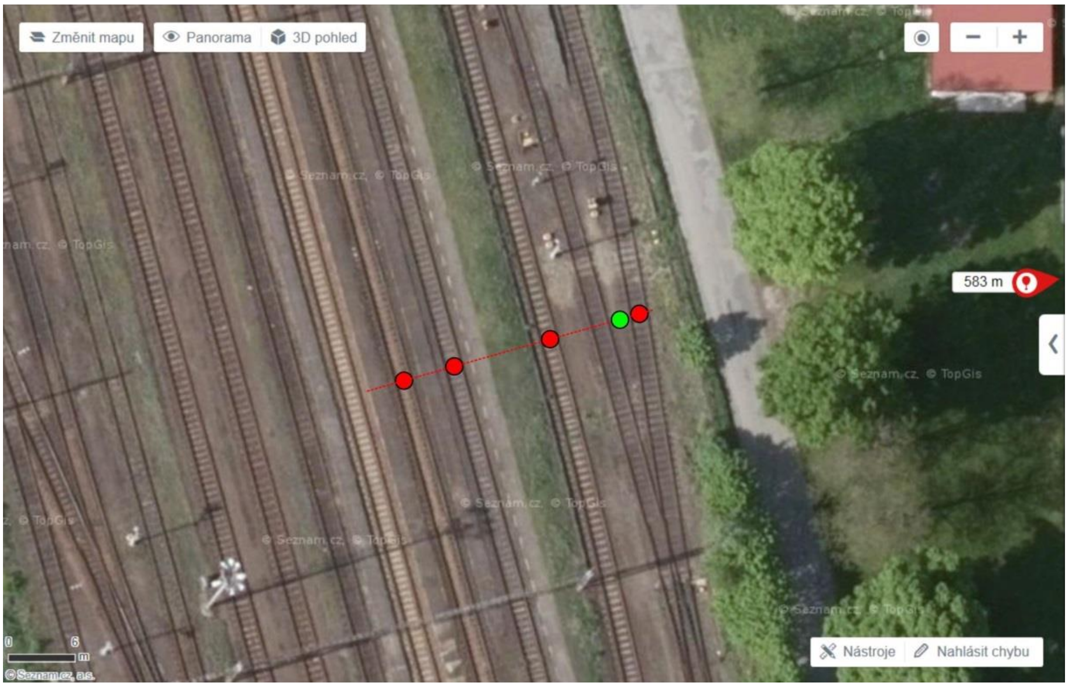


Figure 2: Placement of RF ID tags to distinguish tracks

Figure 3: Sample of RF ID tag to distinguish tracks

For the purpose of odometry error reset, the tags were fixed to sleepers in a distance of typically 500 m, occasionally a bit closer or farther apart (+/- 100m) in locations where impaired sky visibility conditions existed. The figure below shows some examples of the installed tags.

Figure 4: RF ID tags as installed in the track

On-board installation

A diesel multiple unit class 814 “Regionova”, owned and operated by Czech Railways, was selected for the measurement campaign in the Czech Republic. This unit consists of class 814 driving motor car and class 914 driving trailer car. It can also be formed into a 3-car unit (class 814 driving motor + class 014 trailer + class 814 driving motor). These units are extensively rebuilt and modernized older units (class 810 driving motor and class 010 driving trailer) and are operated on regional or local services on not electrified lines.

Once the approval from the Railway Authority was obtained, the system could be installed on-board the selected DMU, a final revision carried out by the authorized body and the system put into operation. Necessary corrections or modification of system components (e.g. replacement of a defective camera or the replacement of the RFID antenna with a model with a higher gain, etc.) was taken in the terminal station or depot.

Figure 5: Diesel multiple unit class 814 “Regionova”

The measurement system was installed in a class 914 driving trailer. The following activities had to be performed to successfully install the equipment and obtain an approval from the Czech Railway Authority to operate it in commercial services. This required a significant effort, and led tom some delays in starting the measurements:

- inspection of the DMU
- design of the installation of the measurement system
- negations with the owner of the DMU and the Czech Railway Authority on the design of the installation, and on the components used
- design and manufacturing of all required supporting parts, such as fixtures
- assessment of the design of the console under the vehicle carrying the tag antenna and radars by an accredited reviewer
- procurement of all system components and the necessary accessories required for the installation
- negotiation with the operator on system installation (DMU availability, standstill time, location

etc.)
- the actual installation of the system
- testing and approval of the installation by an authorized body
- assessment by the Railway Authority, which then issued an approval to operate.

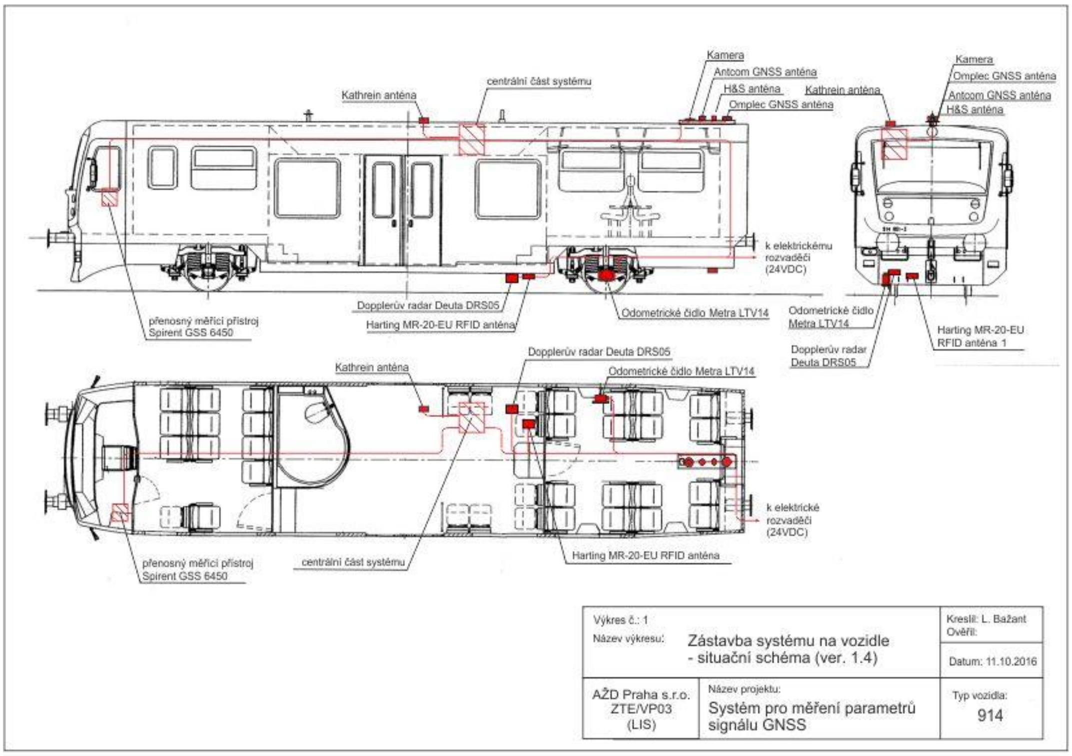


Figure 6: Class 814 on-board installation

At the beginning of the project it was intended to possibly carry out measurements on two different lines, using two different types of vehicles (the second vehicle proposed was a class 362 AC/DC electric locomotive). For this purpose, some parts of the measurement system were designed to be portable. This included the three 19” sub-racks (the core of the system) and the roof console (see figure below), carrying all the necessary antennas and the panoramic camera.

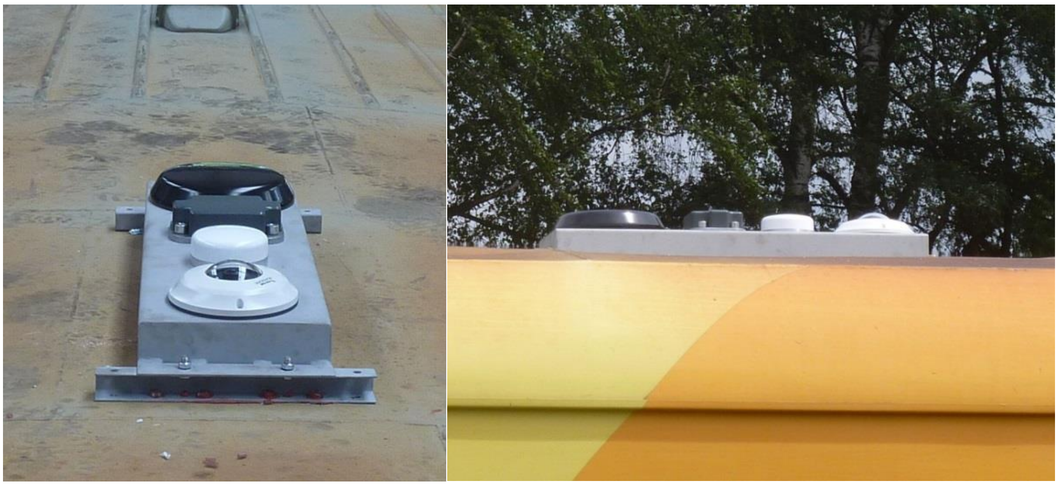


Figure 7: Class 814 antenna and roof camera installation

The RPS Spirent also belonged to the portable parts of the system. It was temporarily installed in the vehicle cab as depicted on the following figure, for the train runs which were attended by AZD personnel.

Figure 8: Class 814 temporary installation of RPS Spirent

The parts of the system required to generate ground truth were different for both vehicles, and therefore permanently installed in each vehicle. An odometry system had to be specially developed for the DMU, as this vehicle was not equipped with any system providing information on the travelled distance.

The selected track was not equipped with any type of markers or balises usable as absolute position reference required to regularly correct the odometer error. An RFID system was therefore selected as a cost-effective solution for this purpose. Because the system was employed for the first time in an application under a railway vehicle its performance had to be verified in regard to achievable accuracy and reliability under different conditions, such as speed, orientation and distance between RFID tag and RFID reader antenna. The following figure shows the test arrangement used in the laboratory, with a conveyor belt onto which the tag was installed and by which it could be run underneath the reader antenna at different speeds.

Figure 9: RF ID tag test installation in laboratory

The figure below shows the some of the sensors used for the odometry system (microwave Doppler radar on the left and RFID antenna on the right), as installed under the floor of the DMU.

Figure 10: Class 814 RF ID antenna and radar installation

The actual measurement system consisted of three 19” sub-racks. The first one contained various subsystems, such as the GNSS receivers, interface cards and data storage for the odometry system, RF splitters and DC blocks, power supplies etc. The second sub-rack was the Aaronia spectrum analyser. The last one included a Moxa industrial computer used for recording and storing data from the GNSS receivers and the camera, a PoE injector to power the camera, the RFID reader and a short-time power backup (a pair of supercapacitors). The sub-racks were installed in a rack located under the roof of the DMU, which is shown in the following below.

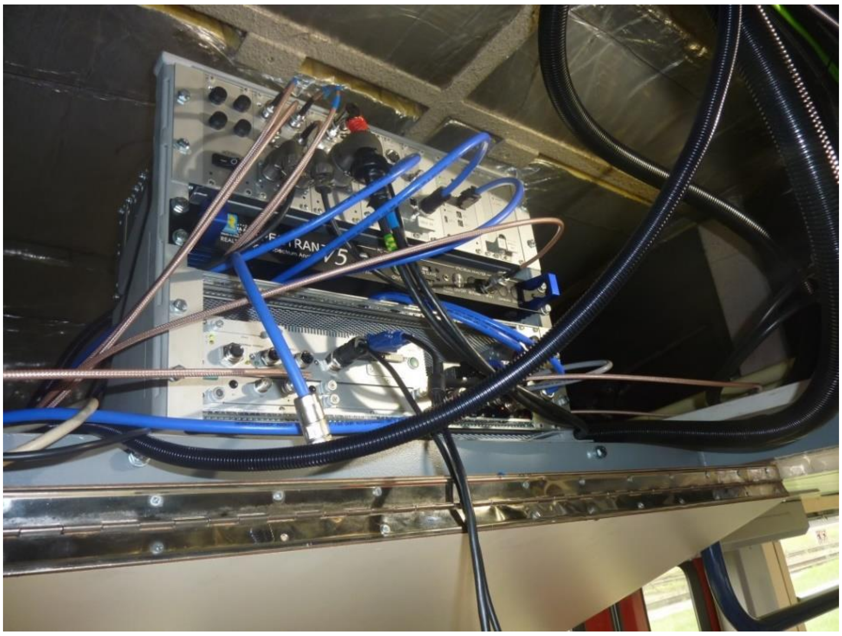


Figure 11: Class 814 On-board measurement equipment installation

3.2.2.2 ITALY / ANSALDO

Trackside

No installation of trackside equipment was required, as the balises used as position references for producing ground truth data were already installed; some activities have however been performed for keeping GT balises operative after some tracks replacement by RFI, which required the reinstallation and validation of a number of balises.

On-Board

On the Cagliari – San Gavino test site an ALn668 diesel powered train has been used for measurements. The same train was used in previous, GNSS related project and operated in regular, commercial service. The installation therefore consisted of upgrading the already installed equipment inside the train after asking authorization from Trenitalia to substitute the GNSS antennas, and to make additional changes for the temporary installation of equipment. In fact, additional RF components (Spirent RF recorder, Tektronix and Aaronia Spectrum analysers), a video camera and corresponding RF and USB cables were needed for the temporary installation of the portable equipment, as well as the installation of data acquisition PCs with high capacity disk due to the distributed architecture of the measurement system.

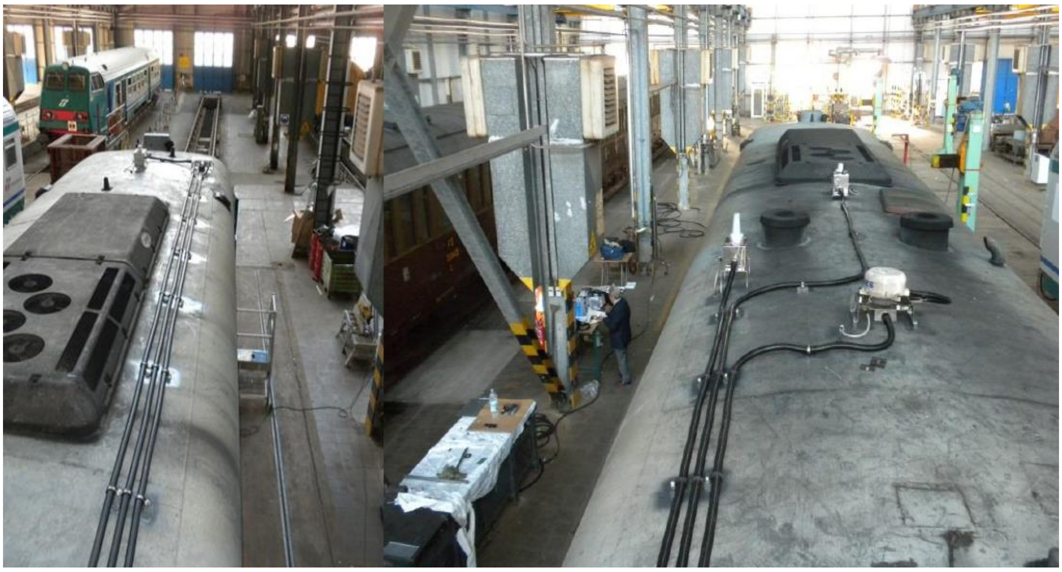


Figure 12: GNSS antenna and cables installed on Cagliari-San Gavino train (ALn668)

On the Parma-La Spezia (Pontremolese) test site two ALe642 electric railcars have been equipped for the measurements. The same trains were also already used in previous, GNSS related projects. The installation consisted again of upgrading the already installed equipment inside the train after asking authorization from Trenitalia to substitute the GNSS antennas, and to make additional changes for the temporary installation of equipment. In fact, additional RF components (Spirent RF recorder, Tektronix and Aaronia Spectrum analysers), a video camera and corresponding RF and USB cables were needed for the temporary installation of the portable equipment, as well as the installation of data acquisition PCs with high capacity disk due to the distributed architecture of the measurement system.

Figure 13: GNSS antenna and cables installed on Pontremolese train (ALe642)

3.2.2.3 SWITZERLAND / SIEMENS

Trackside

Due to the above described condition it was not necessary to install specific elements, such as RF-ID tags, on the track to support the generation of ground truth data. Swiss Federal Railway (SBB) had just finalised replacing two legacy train control systems with ETCS Level 1 across their network, which included the placement of around 50'000 Eurobalises on the 3'000 km of lines. As ETCS Level 1 requires accurate track geometry data, these balises were included with their precise location in the already available track database of SBB, which includes surveyor quality track geometry data referenced to the Swiss National Grid. This data, together with the balise locations could then be converted to WGS84 format, creating the required database against which GNSS data could be evaluated.

On-Board

The measurement system was installed in the baggage compartment, which provided sufficient space to install a full 19" cabinet.

SBB required a number of issues to be clarified and demonstrated in a safety case before the installation, as the train operates in commercial service. This included the following points:

- All equipment installed had to be marked as being part of a test installation, this had to be documented in the papers of the train and the train had to be marked accordingly on the outside.
- The equipment had to be installed in an enclosed cabinet, as the drivers and other staff regularly enter the baggage compartment.
- It had to be ensured that any of the installed equipment would not interfere with the operation of the train, and the escape route out of the cab had to remain clear.
- The cabinet has to withstand a 5 g impact without damage.
- The interface to the power supply of the train, as well as to any input signals from the train had to be designed in a way which prevented any interference with the safe operation of the train.
- It had to be ensured that the equipment can be isolated by the drivers, and that it disconnects automatically in case the supply voltage of the battery falls below a minimum voltage.
- A GPS antenna had to be used which is certified to withstand contact with the catenary, carrying 15 kV, 16.7 Hz AC

- The installation of the equipment had to be done in a way that it would not interfere with operation of the train, and specifically not obstruct the emergency exit from the cab
- It had to be demonstrated that the power drawn from the train's battery could not deplete the battery when the train is parked with the pantograph lowered.
- It had to be demonstrated that any interfacing to sensors used by the active train control system, such as tachos and balise reader data could not cause safety risks or disturb operation.

The following picture shows the test train, with the baggage compartment located behind the driver's cab. The large door of the compartment can be seen just behind the driver's side window.

Figure 14: Domino EMU

The actual design of the on-board equipment resulted from what has been agreed as reference equipment in WP2 of the project, as well as the requirements on sensors to produce Ground Truth data. The following figure shows a block diagram of the final installation (STARS Project parts only):

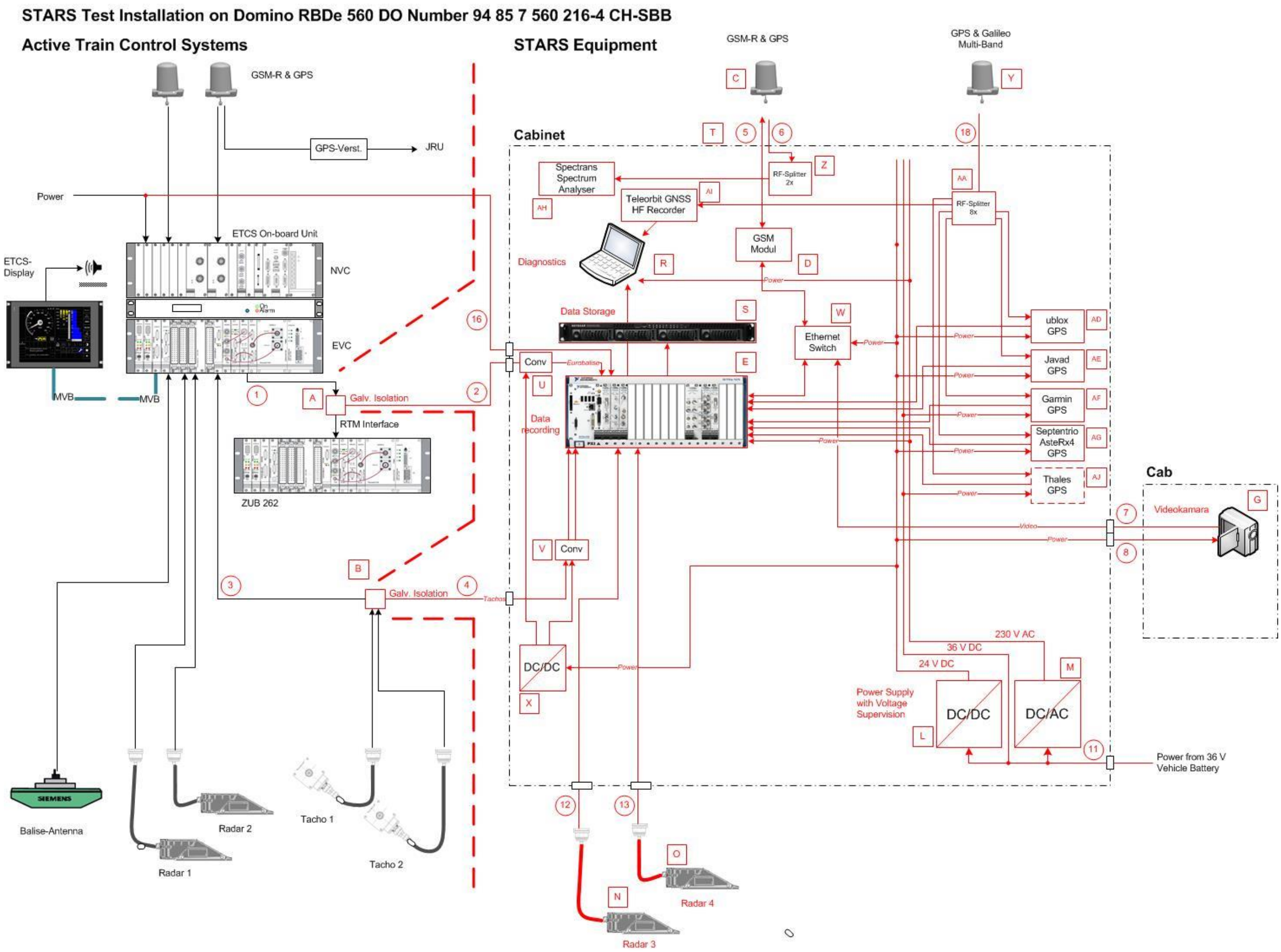


Figure 15: Block Diagram of STARS Equipment

On the left side the existing, active train control systems ETCS and ZUB 262 (national Class B system) are shown, from which balise and tacho data is extracted. This is done by two galvanic isolated interfaces, for which a safety case hat to be written to demonstrate that the STARS equipment cannot have any safety critical impact on these systems.

Note: Due to some technical constrains resulting from using the live ETCS system to read balises, measurements could only be performed in the forward direction.

On the right side the actual STARS equipment is shown, with the National Instruments Data Recorder in the centre and the various reference receivers on the right side.

The following figure shows the design of the cabinet, which was installed in the baggage compartment. The design of the mounting of the cabinet had to be proven in a safety case to withstand a longitudinal acceleration of 5 g.

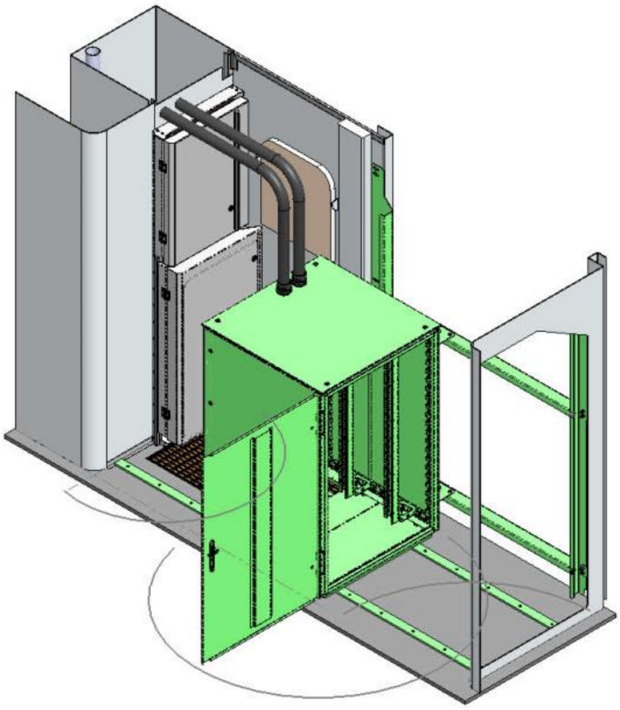


Figure 16: Design of Cabinet to install Equipment

Below the cabinet is shown, note the explanations of its purpose in three languages on the side, which also contains instructions who to contact in case of questions. This is another requirement from SBB on test installations, whose presence might raise questions from staff.

Figure 17: Cabinet as installed, with doors closed

Below the cabinet can be seen with the doors removed, with the equipment shown on the left side, and the power supply and isolating interfaces on the right side.

Figure 18: Cabinet as installed, with doors removed

3.2.3 Execution of Measurements

3.2.3.1 GENERAL

Below the execution of measurements is described for the three test sites, including data post processing and generation of Ground Truth. This description is done separately for each site, as significant differences exist due to local conditions.

3.2.3.2 CZECH REPUBLIC

Execution of Measurements

With the exception of the Spirent recorder, the entire system was designed to operate unattended.

The RPS Spirent was installed temporary, only for selected train runs, due to huge volume of data obtained in each train run. Two GNSS antennas1 installed on-board were alternately connected to the receivers, the time interval between changing these antennas was different from one day to several weeks, depending on visiting the system by AZD staff.

The GNSS dual polarization antenna Antcom provided C/N0 measurements in both polarizations, the second antenna Antonics was a compulsory part of the minimum common set of the measurement system and provided comparable measurements in all three campaigns.

The system started every time power was available, and automatically started recording. The operating status of the system could also be verified and controlled through a GSM connection. In the beginning it was foreseen to also download the data via GSM, but the instability of the GMS connection in the rural area, as well as the size of the data led to a solution using hard disks, which were exchanged at regular intervals.

Measurements with the Spirent recorder required attendance by AZD staff on the train.

Figure 19: Location of Measurements in the Czech Republic

Generation of Ground Truth

The Ground truth was calculated from recorded data of the onboard sensors such as odometer, accelerometer and microwave Doppler radar, from the time markers and RFID tag numbers obtained from RFID reader and from the track axis map. Some internal checks were implemented in the algorithm for ground truth calculation to mitigate unexpected travelled distance errors originated by different causes e.g. delayed reading of RFID tag due to possible buffering.

Note that unusual errors may still be present in the generated ground truth data, caused mostly by processing (splitting and merging) of data files due to e.g. their very large size, exclusion of the recorded data during train stop etc.

3.2.3.3 ITALY

Introduction

It has not been possible on both the Cagliari – San Gavino and the Pontremolese line to carry out measurements remotely due to safety issues related to the train battery. Therefore, ASTS personnel had to plan specific trips to the sites and be present on-board the train for data collection and measurement storage, in agreement with the railway and train operators.

Execution of Measurements

To carry out the measurements to collect the data listed in the data inventory, a specific procedure has been implemented and used in all measurement campaigns. In particular, the first step was to plan a trip to the test site with the set of portable equipment. The setup of the portable equipment and their manual configuration had to be realized each time by ASTS personnel, following the schematic of cable connections and well-defined procedures regarding the connection, configuration, and recording of measurements as defined in the project. Additionally, live technical supervision on the status of the measurements was going on during the entire trip to make sure that measurements were being recorded correctly.

The task related to the execution of measurements to collect the data listed in the data inventory was not so simple, due to coping with (a) unpredictable constraints associated with the unavailability of the test train (e.g. need to repeat field tests, plan additional travels), (b) the complexity in defining and setting up the Ground Truth and building the setup procedures to obtain the Ground Truth for each Train Run, and (c) tuning the procedure for collecting field data.

Planning of the measurement equipment usage, and the overall data estimation size resulted in acquiring many storage disks. Measurements performed have been extensively reported and documented in data inventories shared by partners to indicate those measurements (a) recorded and available, (b) unavailable data, (c) ground truth not produced which could be done, or/and which will not be done, (d) uploaded on the cloud, (e) planned to be uploaded on the cloud, (f) planned to be uploaded on the cloud but with low priority, (g) not planned to be uploaded on the cloud, (h) Data available but affected from wheel diameter misalignment and naming convention misalignment, (i) Data available but naming convention misalignment.

Preliminary test runs have been performed in April, May, June 2017 (57 train runs) in order to refine the acquisition procedures, to check the consistency among measurements and to receive preliminary feedbacks form STARS partners working on WP4 data elaboration. All these data have been uploaded on the cloud. The minimum number of hours available on the cloud corresponding to a complete set of measurements (Septentrio, Spectrans, GT, PVT, Spirent, Camera) without any wheel diameter misalignment and adhering perfectly to the defined naming convention is of the order of 18 hours with a relative data size of 3 TByte and have been carried out during two days in October and four days in November 2017.

Figure 20: Location of Measurements in Sardinia

It has initially been planned to also perform measurements on an electric powered vehicle running on the Pontremolese line between Parma and La Spezia. Although the activity of on-board equipment setup has been performed and some data collection took place in May 2017 on this line, it was not possible to proceed with further measurement campaign for issues related to ground truth. Some EGNOS related data has however been provided from that line to the project.

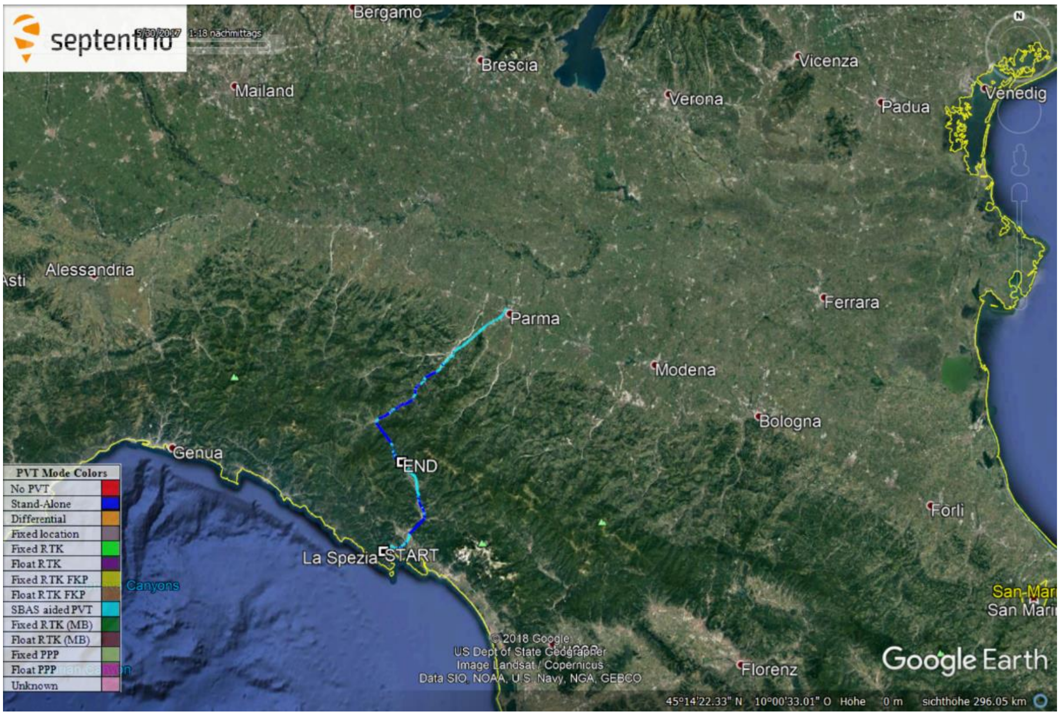


Figure 21: Location of Measurements in Italy

Generation of Ground Truth

In order to ensure a reliable "true" reference for the comparing operation with the PVT results, ASTS developed a methodology in STARS project for the generation of Ground Truth based on its own odometry system and a proprietary real-time acquiring system located on train board.

Taking into account the starting point of the train, odometry estimates the travelled space meant as an offset from the starting point. Meanwhile, odometry system also measures the elapsed time (meant as a progressive monotonic time counter, usually with a high frequency, from the power-on of the train) and the speed (the first order derivative estimation of travelled space within the time interval). Because of the relationship between travelled space and movement of the wheels on the rail, phenomenon such as wheels slipping, or sliding could mislead the space estimation (and the related speed), so proprietary algorithms allow the detection and correction (or anyway the reduction) of misleading information.

With the odometry system as reference, GPS-based positioning provides homogeneous quantities that we could compare each other.

To properly managing the two homogeneous datasets, the estimation methodology foresees several elaboration steps. The first one is the timescales alignment which is required because GPS system and odometry system use two different and independent timescales to measure the elapsed time. The common time scale is the tick counter of the proprietary real-time acquiring system located on board, that collects both the interrupt coming from GPS receiver (that sends with a frequency of 1 Hz the PPS - Pulse Per Seconds - signal) and the interrupt coming from the Odometry system (that sends its time pulse at its working rate). In particular for the Ground Truth estimation, the methodology leverages on the PPS signal which allows to “taking a snapshot” of the system status and its input data, such as odometry time and GPS time with an accuracy of less than two milliseconds.

By leveraging on the timestamp alignment process, also the balises detection events are listed, aligned and ordered by time. Once prepared all needed datasets and, by knowing the exact position of balises through the line survey campaign, the next step foresees the elaboration of the ground truth.

The Ground truth generation is ensured by an automatic procedure that foresees a mapping between GPS time and the following estimates:

- Mileage meant as the travelled space (namely the offset expressed in centimetres) from the starting point of railroad;
- Speed of train;
- ECEF X,Y,Z are the Cartesian coordinates of a point of the track which refer to the mileage value

By leveraging on the mapping between time and space in the time of detection of balises, the elaborative process for the *Mileage* is focused to linearly interpolate the space between two real balises for each GPS Time, which spatially collocate every odometry sample in a well-defined position on the Track database.

Meaningfully (also by considering the preparation steps described above), the generic i^{th} sample of GPS time has an interpolated odometry value that is inside the time/space interval between two balises detection events.

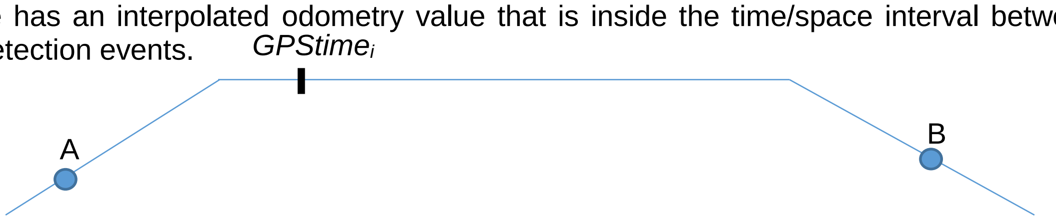


Figure 22: Insight on a given odometry value (@$GPStime_i$) between two balises (*A* and *B*)

By considering the above-mentioned assumption (which is also highlighted in the previous picture), the relative position of the generic i^{th} sample is computed twice. The first time as offset from the Balise A and the second time as offset from the Balise B. The aim of this double estimation is to reduce as much as possible the loss of accuracy of the odometry system, which is at most 5% of the measured, by averaging the estimations (weighted-average depending on the Balise distance).

Last elaborative step is the ECEF extrapolation: assuming that the track database can be considered as a set of adjacent segments spatially ordered, where each segment is a couple of Cartesian coordinates in the ECEF reference frame (hereafter *Nodes*), the cumulative geometric distance of each *Node* represents formally the *Mileage* value of each *Node.* For each *segment* it is possible to identify the gradient, that is the unitary vector that represent the direction of the track in the space in a given point.

To convert a generic *Mileage value* in ECEF coordinates, it needs of identify the segment which nodes include the given *Mileage* value. Once identified the segment, ECEF result in a geometric application of the proper offset to the track gradient.

Finally, for each ECEF coordinate related to the track, the elaborative process foresees the shift of the 3D point from the point of the track to the GNSS antenna position on the roof.

The resultant Ground Truth file is a CSV file with the above-mentioned fields (namely GPS time, Mileage Speed of train, ECEF coordinates of a point constrained to the track which refer to the mileage value).

3.2.3.4 SWITZERLAND

Introduction

The measurement campaign in Switzerland differed from the two others in one major aspect. Rather than performing measurements on a limited number of specified test tracks, tests were performed on many different lines. The reason for this is that the train, on which the test equipment has been installed, is part of a larger fleet which operates on most lines in the country. Individual vehicles of this fleet are assigned to different depots as needed, which made it impossible to restrict the train's operation to a specific line or area.

This limitation made it significantly more complex to perform measurements and to produce ground truth data, but on the other hand made it possible to collect data on many different lines, representing different environments.

The following map show the lines, on which measurements have been performed in Switzerland during the STARS measurements campaign.

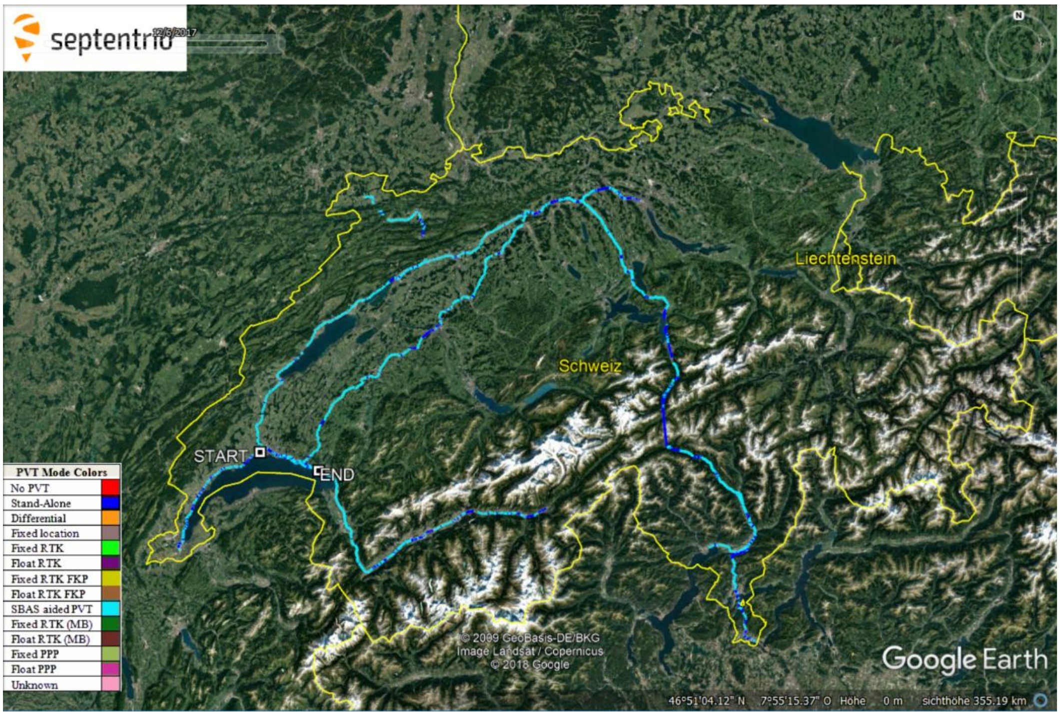


Figure 23: Location of Measurements in Switzerland

Execution of Measurements

The test installation on-board the train was designed in a way that all the essential equipment could be operated through remote access via an UMTS connection. Thanks to this, most measurements could be done from the Siemens office, without requiring physical presence of personnel on the train. The only exceptions were measurements with the TeleOrbit HF recorder, as well as the Spectrans Spectrum Analyser, with whom measurements could only be performed manually on-board the train.

Thanks to the installation of the test system in the baggage compartment attended measurements was however also possible, even during commercial operation of the train, without interfering with neither the driver, nor with the passengers. Thanks to access to the vehicle scheduling system of SBB, as well as the possibility to check the position of the train via remote access it was fairly easy to just catch the train wherever it operated to perform manual measurements.

To record data, sufficient data storage volume has been installed on the train to limit the need for a frequent manual download to around once every two or three weeks. For some analysis work a data download was possible via the UMTS remote connection; for larger data sets, such as the pictures taken by the camera, this was however not possible, and data had to be collected manually at certain intervals.

Generation of Ground Truth

As mentioned above, the generation of Ground Truth data was a major task for the measurements performed in Switzerland, as the entire network of 3'000 km of lines with approximately 5'000 km of track had to be covered.

As a starting point, SBB provided us with surveyor quality track geometry data, which included the position and identities of all Eurobalises. The data is structured as a graph model, with nodes typically representing points, and edges the track sections, which connect the nodes. Nodes are also used to mark the end of a track (e.g. buffer stops), or they are used to split long edges into more manageable sections, e.g. at interlocking boundaries. Each node is described in Swiss National Grid coordinates (CH1903+/LV95), each edge by a length, as well as a sequence of absolute coordinates with a distance of approximately 10 m between them. The position of balises is described as being on a specific edge, with the distance from one end of an edge. A sample of the track data is shown in the figure below:

Figure 24: Sample of track data, including balises (yellow)

The track geometry data had to be converted from CH1903+/LV95 to WGS84 format using an algorithm supplied by the Swiss Federal Office of Topography (swisstopo), before being used as input for the Ground Truth generation. By using this proven algorithm, it could be ensured that conversion errors were minimal, without requiring additional checking.

The actual generation of Ground Truth data had to be done for each trip as described in the following steps, using a set of tools which have been specifically adopted for the STARS project from a number of already existing tools.

First, all GNSS and environmental data, as well as data used to produce the Ground Truth had to be recorded synchronized against the same time reference. This was done by using a data recording system from National Instruments. Data required to produce Ground Truth included odometry information from wheel tachos and radar sensors, as well as the balises read by the ETCS equipment installed on the train. This is shown in the figure below, where the yellow points represent balises in the area, and the red dots the balises the ETCS has read during this specific trip. Note that the read balises are shown with an offset from the position represented by the yellow dots, as the offset between the GNSS antenna and the balise reader antenna on the train has been compensated in this step.

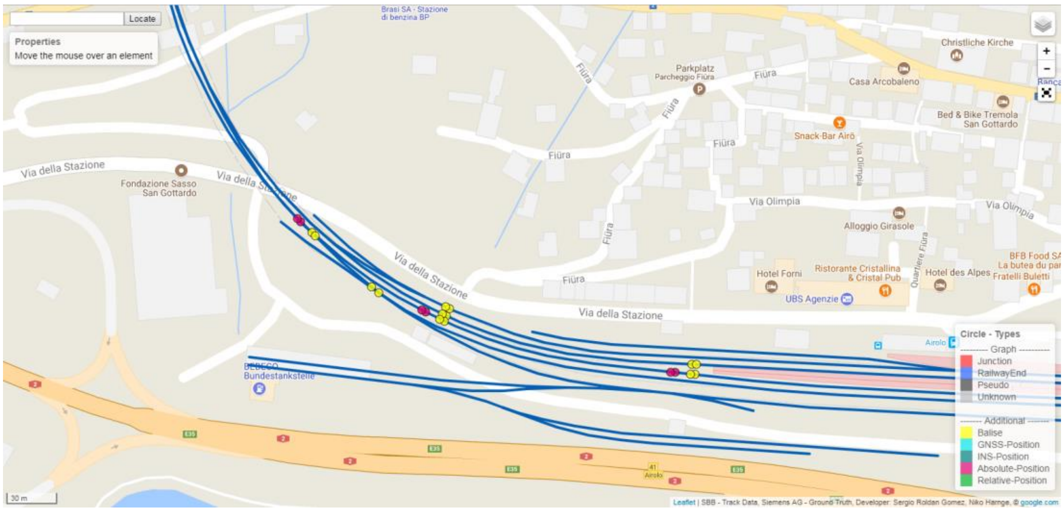


Figure 25: Example of track data with the recorded balise marked in red

A complex algorithm specifically developed for the STARS project then determines the path taken by the train during the test trip. The algorithm then uses odometry data to produce intermediate positions between the recorded balises, mapping them to the geometry of the track. The algorithm also compares the true distance between the balises derived from the track geometry data with the distance measured by the odometry sensors and corrects the error. Below an example of the route generated between the above shown, read balises, with intermediate positions marked in green.

Figure 26: Example of track data with the route and intermediate positions

Unfortunately, there are sometimes multiple routes between subsequent balises, or balises are not correctly positioned in the track database. An example of a case of multiple routes is shown in the figure below, where the algorithm selected the wrong route.

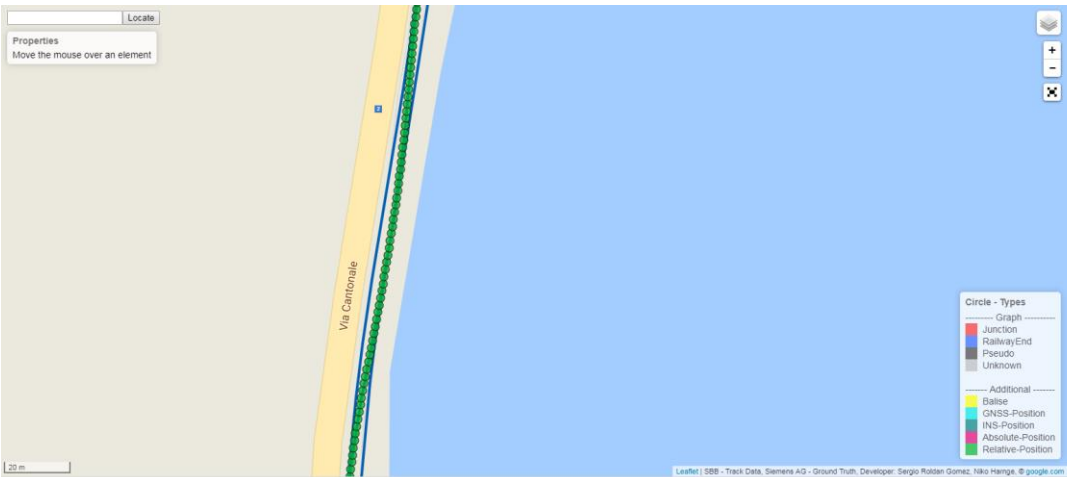


Figure 27: Example of a wrong route determination, requiring manual correction

Each trip therefore had to be checked manually, using the pictures taken from the cab every second to verify whether the tool had determined the correct path. If not, then the correct route could be enforced in the tool by selecting the correct track edges. In case of wrongly placed balises the tool generated a warning as it would detect an unusually high odometry error, in which case the ground truth tool could also be told to ignore he respective balise ID.

As a result of the process, a Ground Truth file was generated for each trip, which is time-synchronised with UTC, and contains a true, GNSS referenced position every approximately 100 ms.

3.3 WP4, Data Post-Processing

3.3.1 Pre-Processing of measured data

Pre-processing of recorded data required development or selection of suitable methods and software, as different outputs from data pre-processing were required for subsequent analysis. A request for values such as the Ground Truth (coordinates of reference position of a train), coordinates of the reference position of GNSS antenna on a train, extracted parameters of GNSS measurements, PVT for different signals and constellations calculated by different post-processing software, extracted RF samples from data recorded by RPSs and extracted figures from video data of panoramic camera had to be met.

To obtain some of the requested outputs generally available open source or commercial software scripts and software tools were selected. Examples are PP-SDK (Septentrio, commercial software) and RTKLIB (open source software), which were used for PVT calculations, RxTool (Septentrio, free software for registered users) was used to extract parameters of GNSS measurements. For the rest of the outputs it was necessary to develop appropriate methods and software.

Data processing was split among the three WP4 partners responsible for measurement. Each partner processed data from his measurement campaign.

All the outputs were stored in the database located at Google Cloud, to be available for all the WP4 partners for subsequent analysis.

3.3.2 Analysis of pre-processed of data

Once recorded data has been pre-processed to conform to common formats it was analysed by various methods. Each method attempted to identify the presence of negative phenomena (multipath, RF interference and limited sky visibility), and its impact on the GNSS signal at specific locations or at a specific time.

Different methods were used in this analysis, not only for distinguishing which phenomenon was presented but also for achieving reliable results by applying multiple methods to identify each phenomenon.

One or more of the selected methods were assigned to each of the WP4 partners, which then developed appropriate script for automated processing. An important task in analysing data was the evaluation of the outputs. It consisted in defining a threshold, or multiple thresholds identifying the degree of influence of the respective phenomena on the GNSS signal and assigning a scalar value to the output value with respect of the thresholds.

The results of the analysis were stored in the Google cloud, together with the developed software scripts and a description of how the method was applied. This will allow future analysis if data from the measurements performed, or from future measurements in the frame of follow up projects.

Note that not all methods originally defined were applied due to the time available, it was however ensured that those methods applied covered the analysis in regard to each negative phenomena with sufficient redundancy.

3.3.3 Railway environment characterization

The basic idea how to characterize the railway environment consists in the use of some evaluating indicators. The three indicators MPL, RIL and SFV were introduced for this purpose. They represent a degree of influence (and predicted impact) of particular negative phenomena on GNSS signal (or its reception) for given place on a track. They are defined as follows:

- MPL (MultiPath Level) – indicates influence of multipath
- RIL (RF Interference Level) – indicates influence of RF interferences
- SVF (Satellite Visibility Factor) – indicates influence of reduced sky visibility.

Outputs of the particular methods mentioned in the previous section contribute to these indicators in dependence on a weight assigned to each method.

Explanation of basic principles and complete guide how to proceed for achieving the characterization of railway environment is provided in the respective deliverable [5].

The script for the calculation of the indicators was developed and stored in the Google cloud, again for future use.

From the analysis of mass data, the cases with the highest value of horizontal error HNSE in each typical railway environment e.g. clear sky, mountains etc. were selected. They were then analysed in more detail by the use of both the calculated indicators and the outputs of the individual methods, both to identify the cause of high horizontal error HNSE and to test the developed methodology and the script for the characterization.

Note that some of goals set in the beginning or when defining the various methods of analysis had to be redefined during the process for a number of reasons. Some lie in the complexity of some of the tasks, but also in the incoherence of measured data, the reassessment of the original goal due to the analysis of data etc.

An example is the correlation in the position domain. The correlation was done only for a sample of data with SVF and figures from the panoramic camera in order to check if the measurement system works well. Originally it was expected that this correlation could result in some useful statistics reflecting the different conditions (e.g. satellite constellation) for the same place at different times. However, too many measurements would have had to be carried out for the same track at different times, and huge amounts of measured data processed in order to get sufficient data for relevant statistics. Also, the train with the measurement system installed was running according a regular schedule, so worst and best case conditions for each location along the line would probably have been missed. The same is valid for random RF interferences from e.g. moving sources, or sources which are only active temporarily.

On the other hands, it was revealed during evaluation of the indicators calculated from analysed outputs of the various methods that the SVF indicator calculated only from the camera figures strongly correlates with the MPL indicator. Because SVF is nearly constant over longer time it could therefore partially substitute statistics of MPL. Some occasional multipath may however not be detected, so this will have to be analysed further. It can be assumed that next development of the camera-based technique could result in fast railway environment characterization from perspective of the sky visibility and multipath by using only a pair of camera measurements.

Another example of a change of goals during the project is the tuning of the weights of the various methods in characterising the environment. It was proposed to use different, tuned weights for the different methods for the calculation of the MPL and RIL indicators. This approach would permit to e.g. set the weights according to the efficiency of each single method. But due to complexity of iterative analysis and the tuning of these weights, a basic setting with all weights equal to one was finally used. It could be analysed in a future project whether the tuning of the weights could improve the accuracy of identifying environmental influences.

A third example is the processing of only a limited amount of the recorded data, and integration of all applied methods in the characterization process. Some of the methods, especially RF I/Q sample data processing, are extremely time consuming, thus only selected measured data could be processed. Full integration of the outputs of all the methods was also not achieved since only results from methods, whose performance could be demonstrated, were allowed to contribute the values of the indicators.

3.3.4 Manual Data Analysis using Siemens Ground Truth Visualisation

Due to the complexity of producing ground truth for many different lines, which could not be equipped with position references required for all possible routes, Siemens had developed a visualisation tool to verify whether the Ground Truth data was correct for each measurement run. By overlying recorded GNSS PVT data from the low cost ublox reference receiver onto the Ground Truth data a simple method resulted to detect locations with reduced GNSS performance. This method could therefore be used to quickly identify locations with environmental conditions which significantly impact GNSS signals

One example of such a location in the station of Renens, VD, is shown in the figure below.

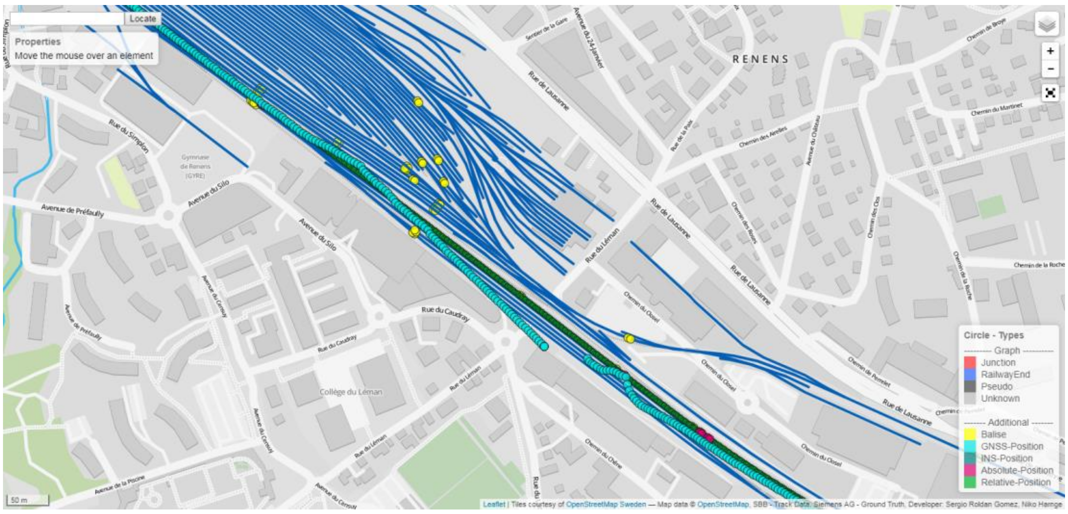


Figure 28: Example 1 of GNSS data overlaid onto Ground Truth data

Once a location was identified a more detailed look could be taken at the raw data recorded with the Septentrio receiver. This was done using the SBF Analyser tool supplied with the receiver. In the above case the data revealed that the number of visible satellites dropped to nearly zero in that area, as shown in the figure below:

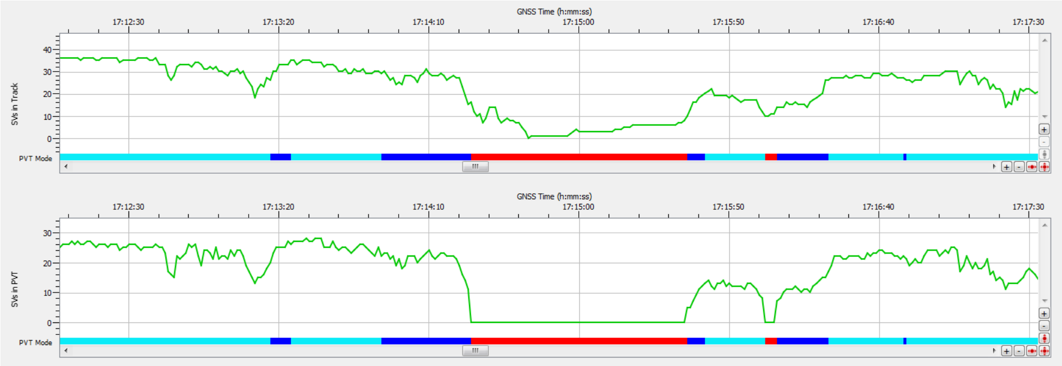


Figure 29: Number of visible Satellites / number of Satellites used

The multipath indicator shown in the figure below does not reveal any significant anomaly; however the loss of visible satellites can be seen again.

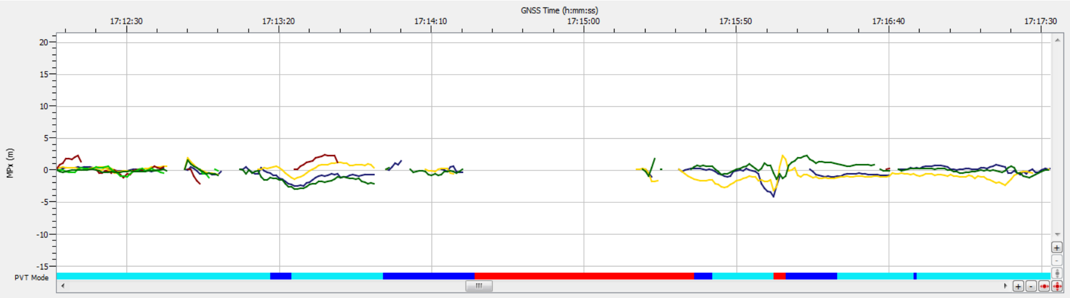


Figure 30: Multipath Indicator

The planimetric plot below shows that the PVT algorithm of the Septentrio receiver does not produce any position within around 1.3 km of what can be considered open terrain. It can therefore be assumed that either the ublox receiver uses some extrapolation functions to continue delivering PVT data even where GNSS signals are lost, or the Septentrio receiver applies methods to identify signal distortions, which are then used to eliminate specific signals from the calculation of PVT.

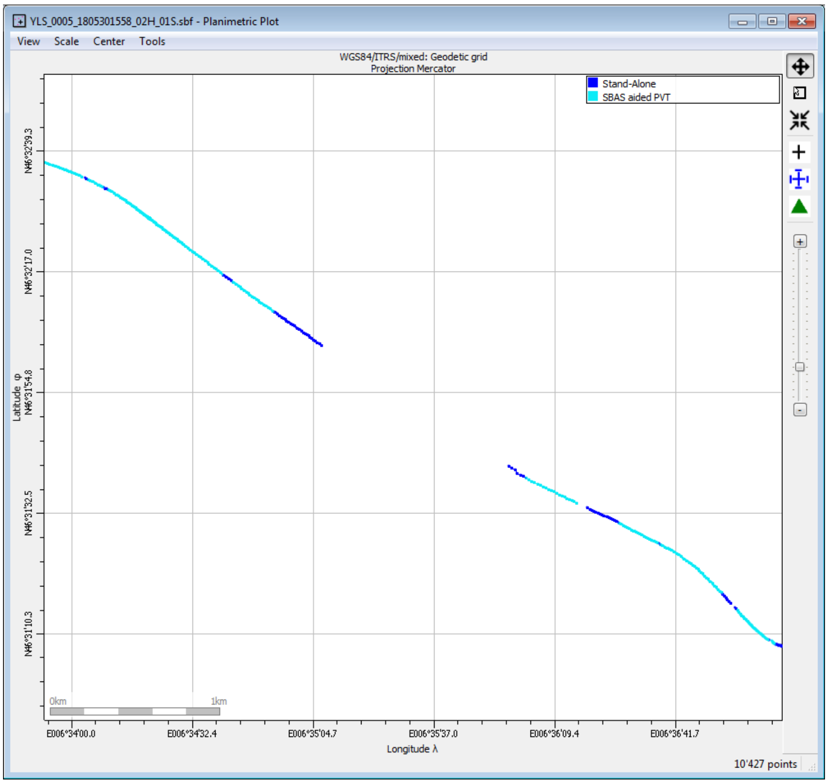


Figure 31: Planimetric Plot

When looking at the environment using the online mapping tool from Swipos, the area in this particular example looks fairly open. Such an environment should never result in a loss of position over such a long distance, marked red in the figure below:

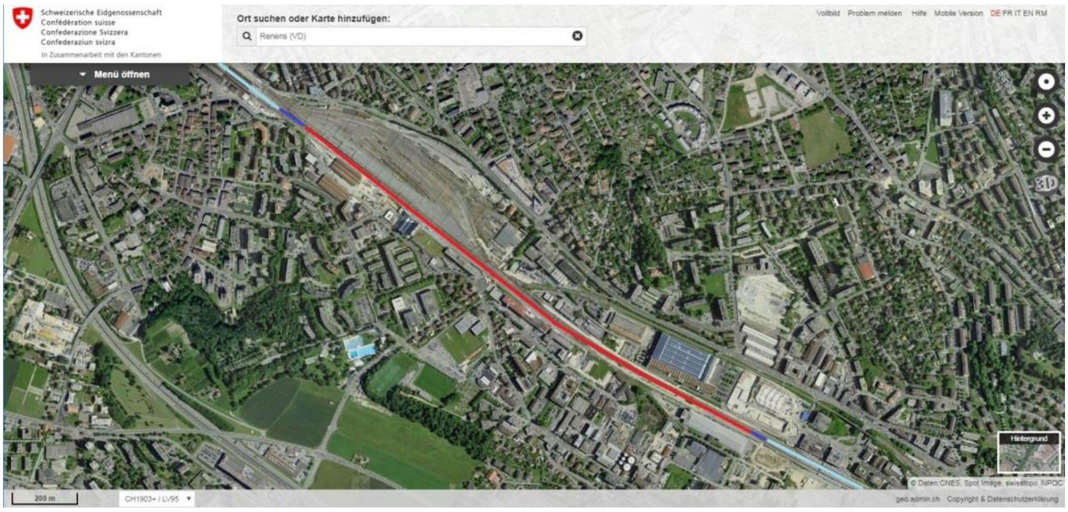


Figure 32: Swipos map

3.4 WP5, EGNOS Technology Feasibility Study

3.4.1 General

This work package was addressing the following tasks:

Tasks 5.1: State of the Art

The objective of this task was to review the existing navigation augmentation systems (ground or satellite based) and services in terms of performances achieved and applicative environments, and to analyse the experimentations and projects already performed in railway applications related to the use of these systems and services.

A report has been generated highlighting the level of performances achieved, the existing limitations and their applicability to the railway context and constraints. In addition, the suitability of the concept of integrity monitoring (developed for aviation) has been analysed in terms of applicative added-value and technical feasibility for the railway environment.

Task 5.2: Assessment of EGNSS service performances in the Railway Environments

The aim of this task was to evaluate the EGNSS performances achievable in railway environment based on the data collected during the on-field data collection campaign and the railway environment characterisation done on WP4. The assessment of these performances has been realised using a set of qualified tools (used in EGNOS program) that allowed to predict the EGNSS performances considering the error budgets applied in aviation environment versus specific ones more suitable to model the railway environment.

On the other side, a dependability analysis was conducted as part of tasks 5.3 and 5.4 to evaluate the safety performances achievable for EGNSS services in terms of integrity, continuity and availability which are dimensioning for railway applications.

Task 5.3: Definition of EGNSS target key performances to satisfy the ETCS L2 and L3 safety requirements:

The objective of this task was to define the EGNSS performances necessary to achieve the ETCS L2/L3 safety requirements. For this purpose, reference architecture of the ETCS system has been defined including the contribution of EGNSS services and considering the NGTC project outputs.

A functional hazard analysis has been performed on this architecture to assign the Tolerable Hazard Rate (THR) values to each function involved on the train positioning. These values were defined as the key target performances to be achieved by the EGNSS services.

Task 5.4: Definition of EGNSS Services evolution to meet the performance and safety requirements in railway environment and identification of ERTMS/ETCS possible impacts

From the assessment of GNSS performances achievable in the railway environment and the target performances requested by ETCS L2/L3 the objective of this task was to identify the deltas between both and propose the possible evolutions that could be implemented on EGNSS and ETCS systems to converge.

3.4.2 Analysis using the SPRING tool

To analyse the EGNSS service performance in railways environment, the SPRING software receiver tool was used. The analysis was then completed using specifically dedicated MATLAB functions to cope with certain limitation of SPRING (lack of interface, lack of tuning capability).

The complete analysis performed is therefore the following:

1. Run the SPRING software tool on the receivers' binaries files. SPRING is used to first decrypt the binaries files, then to reprocess the train position using the EGNOS information. The outputs of SPRING are ASCII files containing different information such as UDRE, UIRE, Receivers and satellites positions etc…
2. Run the MATLAB functions on the output of SPRING and the reference ground truth files to determine the Horizontal Protection Level (HPL) and Horizontal Navigation System Error (HNSE) at each point of the survey.
3. The MATLAB function is also in charge of generating the different figures, the log files of the analysis and the KML file to interface with Google earth.

This tool chain is run in an automatic way in order to cope with the number of surveys to analyse. The tool will provide the following figures for each of the analysed receiver captures in railway environment:

- For accuracy characterisation of the following results will be provided: figure featuring navigation error versus distance to origin of the receiver survey (point 0=first point coherent between provided ground truth and receiver capture), logs of errors that exceed a fixed threshold with corresponding epochs and distance to the starts of the survey. A log file will present the statistical values of the receiver position error (average, max, 95 %...).
- For integrity characterisation the following figures will be provided: horizontal Stanford diagram that shows protection level with respect to the navigation error. The tool will log all the detected non-integrity events (non-integrity state is declared when HPL<HNSE).
- For availability characterisation the following figures will be provided: Stanford diagram, instantaneous availability as a function of distance to track start.
- To link the performance to the local train environment a KML file will be processed. This file allows the display of the trains positions (receiver and reference) in Google Earth and Open Street maps.
- To facilitate the post processing, a text files with all the important values will also be generated by PLR tool.

An example of these outputs is provided hereafter based on a Sardinia run (SAR_4250_1706141453_01H_10H).

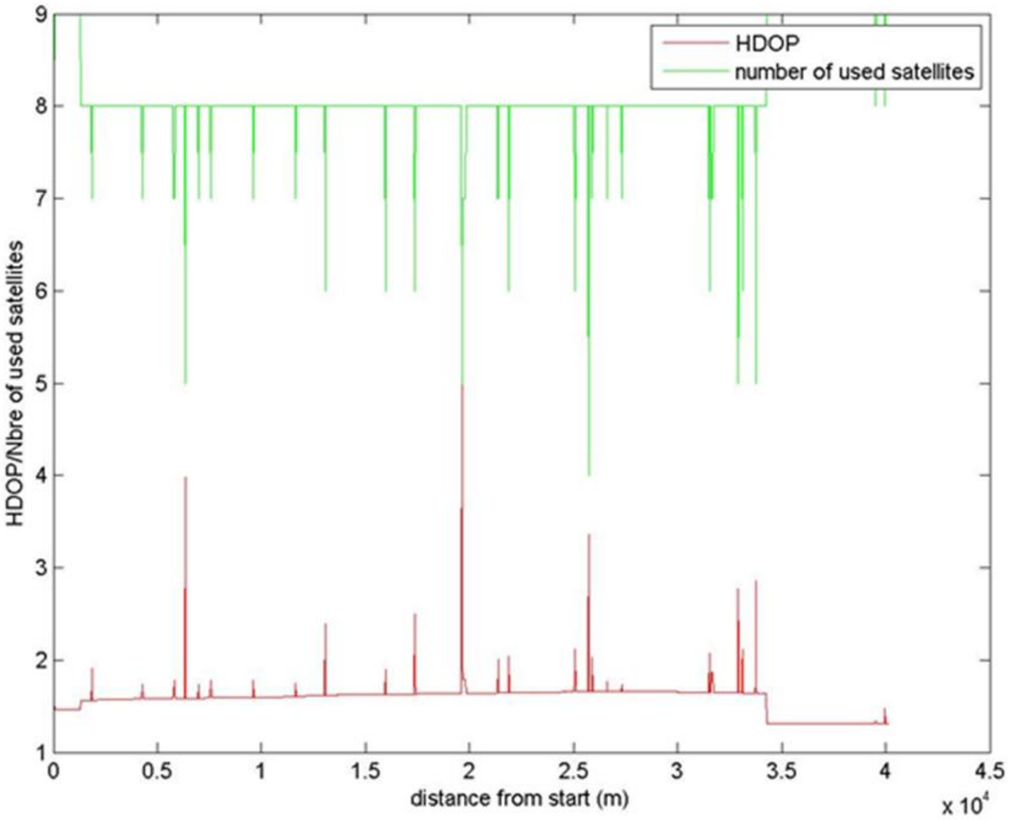


Figure 33: Number of used satellites and HDOP values

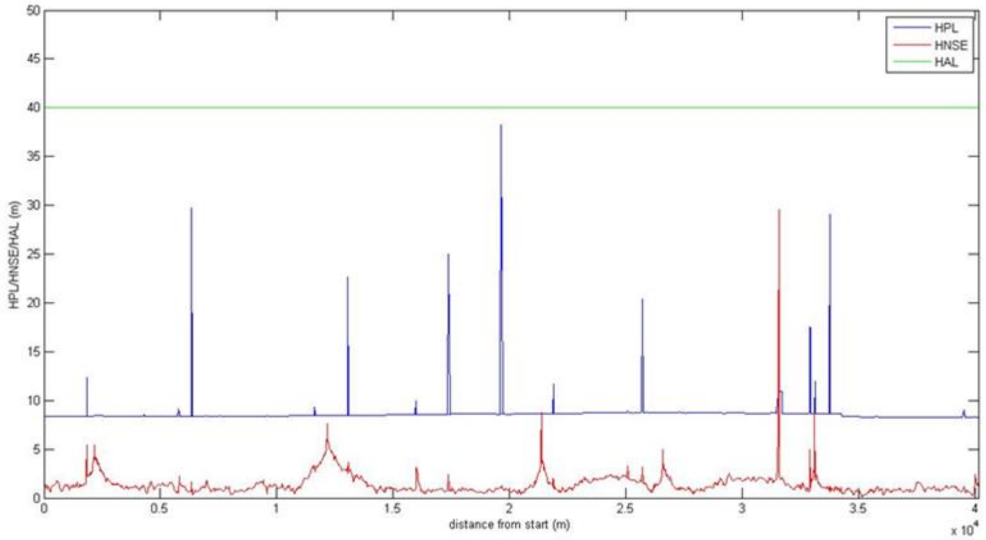


Figure 34: HPL and HNSE values

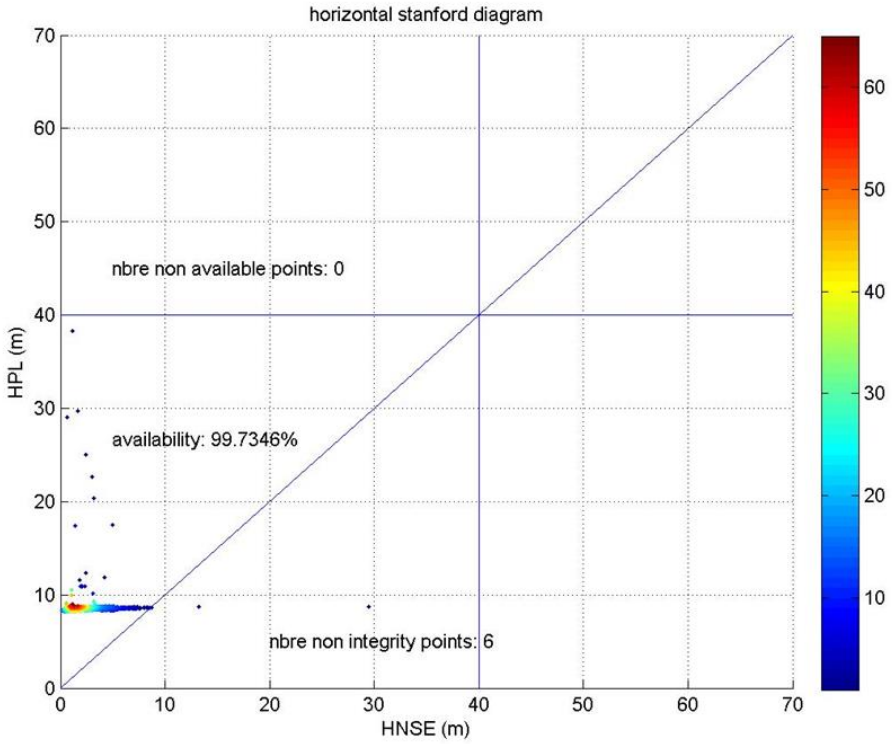


Figure 35: Horizontal Stanford diagram

Additional analyses are then proposed based on the result obtained by analysing the trajectories and comparison with WP 4 characterisation of the railway environment.

Below an example is shown of the study of an event based on a google earth analysis (red dots are the reference position and blue dots are the receiver trajectory)

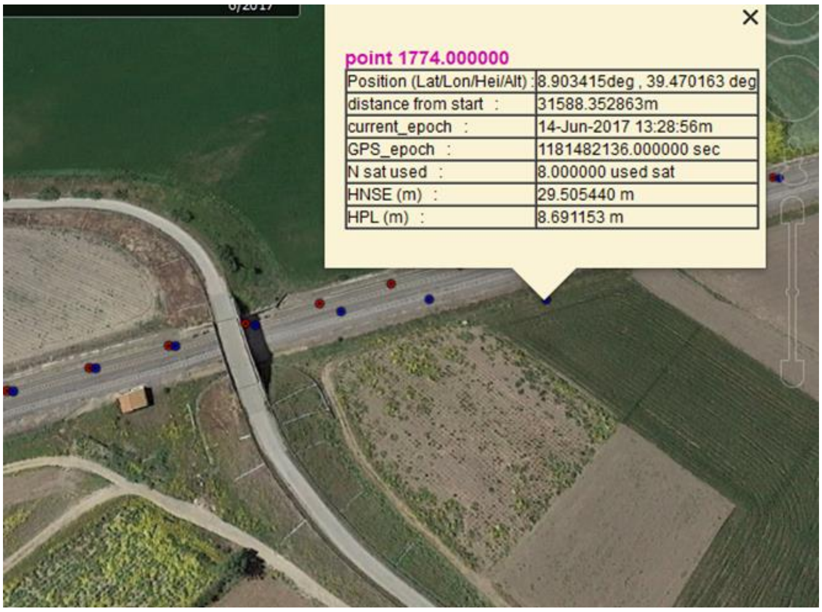


Figure 36: Example of event study based on google earth analysis

Details on all the analysis performed for the whole campaign can be found in [09]

3.4.3 Analysis using the Septentrio SBF Analyzer

Using the Spring tool required quite significant work effort. Siemens therefore proposed a much simpler, but also more efficient method to generate EGNOS coverage statistics for different lines. It was based on using the SBF Analyzer software, which was supplied together with the main GNSS receiver used on all three test sites.

Note: This method is less accurate than the one using the Spring tool, as the percentage of each mode does not reflect the coverage in % of track kilometre, but in % of measurement time as PVT fixes are produced at regular time intervals, rather than distance intervals. Sections of track where the train has run at low speed, or even stopped, are therefore weighted more than sections where the train has run at line speed. On most of the analysed runs the train has however run at a more or less constant speed and not stopped at most stations, or only for brief times. The resulting distribution should therefore still give a fairly good indication of the quality of EGNOS coverage. Where this has not been the case it is indicated.

Example: Erstfeld – Göschenen – Bellinzona Line

The trip analysed below is a journey across the old Gotthard route from Erstfeld, which lies on the north end of the line to Bellinzona, which lies on the south end. The terrain is very mountainous, and includes many tunnels, including 7 spiral tunnels and the old, 15 km long Gotthard Tunnel.

The following figure contains the statistics on the active PVT modes for the trip along the line.

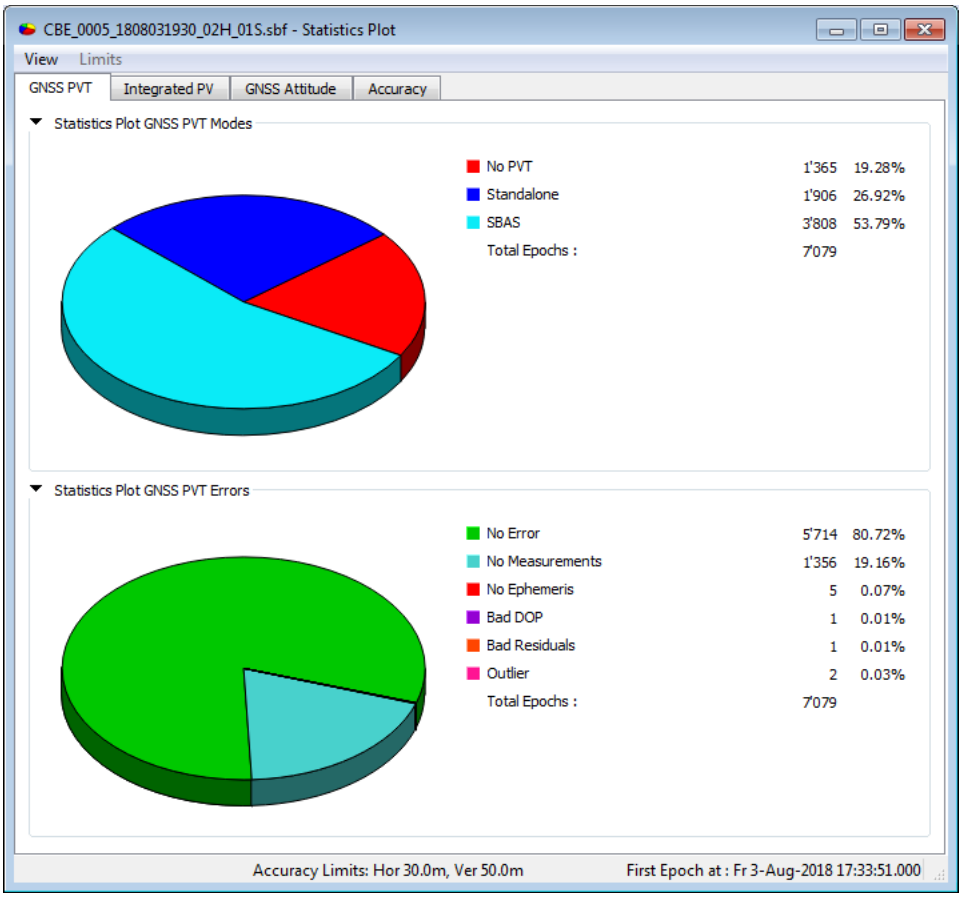


Figure 37: Erstfeld – Göschenen – Bellinzona, PVT Mode Statistics

The high percentage of measurements where no PVT could be produced (19.28%) can be explained by the 15 km long Gotthard Tunnel, as well as the many other tunnels, including seven spiral tunnels of each around 2 km in length.

EGNOS was not available on another 26.92% during the trip, which can be explained by the mountainous area, so only 53.79% of the measurements produced positions in SBAS mode (GPS plus EGNOS).

The figure below shows the track generated by the Septentrio receiver, with pale blue indicating SBAS Mode (GPS plus EGNOS), and dark blue indicating Standby mode (GPS without EGNOS), as well as No PVT Mode.

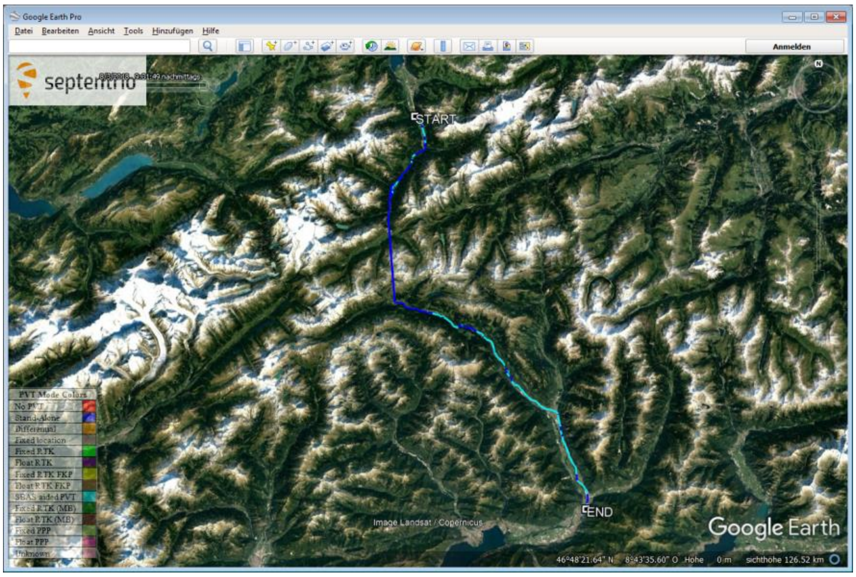


Figure 38: Erstfeld – Göschenen – Bellinzona, EGNOS coverage

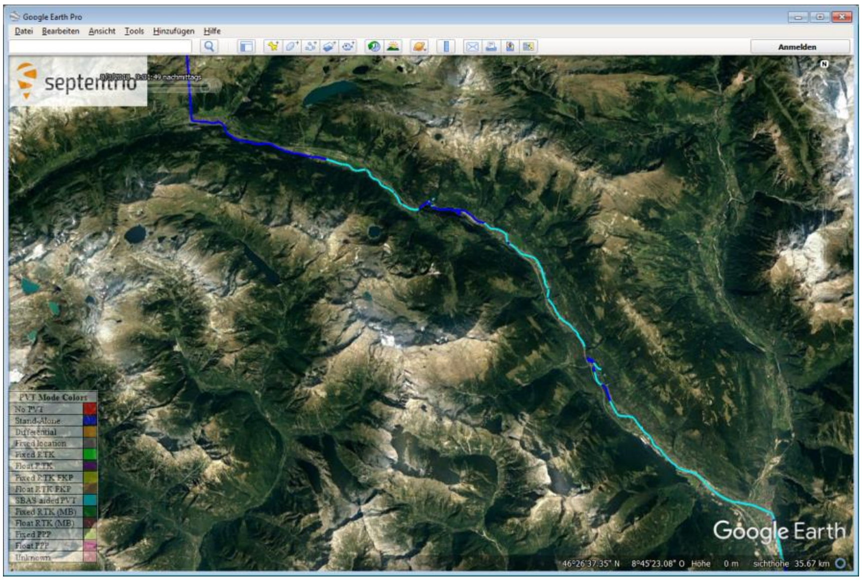


Figure 39: Erstfeld – Biasca, EGNOS coverage

Detailed data on all lines analysed can be found in [03].

3.5 WP6, Impact Analysis

Work Package 6 contained four independent elements:

Task 6.1: Economic model and scenarios

This task built on the methodology for the economic evaluation of the introduction of EGNSS technologies into the ETCS train control system.

At first, it defined the methodological approach, describing the cost-benefit analysis framework and the indicators that have been used for the evaluation of the projects, such as ENPV/NPV (Economic - Net Present Value), ERR (Economic Rate of Return) and BCR (Benefit Cost Ratio). Then, it defined the characteristics, in term of technological architecture, of the so-called project scenario, that is the scenario envisaging the implementation of an EGNSS-based technological solution, and of the so-called baseline scenario, that is the alternative one envisaging the traditional balise-based technological solution. Finally, it defined the case studies that have been analysed.

Due to the antitrust statement, no cost items assumptions could be exchanged among partners. For this reason, the analysis has been carried out on the basis of UBOC's expertise and assumptions.

Task 6.2: Cost-Benefit Analysis

This task deals with the economic evaluation of the project solution from the community point of view. The CBA applies the economic model at the case study level via UBOC's own assumptions on unit costs that are not disclosed in accordance with the Antitrust agreement of the STARS Consortium, and investigates the public convenience of the project, by means of techniques complying with the EC Guidelines and producing aggregate indicators such as the ones defined in D6.1. The analyses have been applied to the nine case studies defined in D6.1 and completed by sensitivity analyses that investigate the impact of the variability of some of the initial assumptions concerning unit cost items or parameters that affect the overall comparison of costs and savings.

Task 6.3: Impact analysis

This task aims at quantifying the economic effects for each stakeholder involved. Collecting input from previous Work Packages, the analysis defined the relations among stakeholder in terms of supply of hardware and services and identified the impact in terms of investment costs, operating costs and savings along a determined time horizon.

The focus has been on players such as not only infrastructure managers and railway undertakings but also the satellite sector.

Task 6.4: Implementation plan

This task deals with the definition of a possible implementation plan by identifying the major milestones and investment cost items that are relevant to the EGNSS service for ERTMS. With the aim to outline strategic guidelines for the implementation of the system, the main positive and negative factors has been defined. Addressing threats such as the current delay in the implementation of the ERTMS program at the European level (e.g. by introducing innovative financing solutions and business models which include mechanism for balancing risk- and benefit-sharing between operators), is the main sample of the roadmap of the project.

The task 6.4 also includes the expansion of the Cost Benefit Analysis results, as from D6.2, to the European level in order to assess the general impact at this level of the introduction of the EGNSS innovative technologies in the railway domain.

4 PROJECT RESULTS

4.1 WP 2, PREPARATION OF CAMPAIGN

The measurement specification has been carried out according to a well-defined methodology. The sources of error or influence on GNSS measurements can be identified based on different processing techniques with pros and cons of each technique, which require a set of GNSS measurements and need to be referenced to a train position reference, based on both absolute and relative distance measurements with respect to a track database.

It has been concluded that the measurements to be acquired are of different nature and each would be required to respect a certain data rate and resolution. The measurements needed have been divided into measurements related to the GNSS signals and European augmentation system, measurements related to the local environment, measurements related to the train itself and its dynamics as well as the train position reference in time.

The above-mentioned activities carried out in this task reached the assigned objectives, to give a clear indication for the following task of identifying the relevant measurement equipment and measurement procedures.

The minimum common set of measurement equipment and configuration consisted in multi-frequency multi-constellation GNSS antenna and receiver, real-time spectrum analyser, and record and playback system.

Centralized and distributed measurement equipment arrangement were possible with different data synchronization procedures. The procedures, setup and configuration of each measurement equipment has been deemed crucial to have comparable results.

In addition, Ground Truth (GT) estimation techniques have been identified using different technologies than GNSS to reliably estimate GNSS position error. Moreover, GT performance criteria and preliminary requirements have been set to fulfil the objectives of the STARS project, after explaining the methodology defined to derive such requirements.

It has been concluded that measurement procedures are complex to define and need careful tests to ensure comparability of results.

The above-mentioned activities carried out in this task reached the assigned objectives, to create the basis for completing the field measurements, and data collection for data post-processing and EGNOS technology feasibility study in the remaining WPs.

The description of criteria used for identification of representative test lines has been carried out as well as the description of identified lines / areas managed by ASTS, AZD, and SIE.

The identification & negotiations with infrastructure manager / operator of three different test lines has been carried out.

It has been concluded that such negotiations can be really time consuming as it has proven the case with the railway operator in Czech Republic.

The above-mentioned activities carried out in this task reached the assigned objectives, to create the basis for completing the field measurements, and data collection for data post-processing and EGNOS technology feasibility study in the remaining WPs.

4.2 WP3, FIELD MEASUREMENT, DATA COLLECTION

Significant amounts of raw data were collected in the three test sites from November 2017 to June 2018.

4.2.1 Czech Republic

General Description

The vehicle 814/914.114 with installed STARS system operated almost daily the same line Číčenice-Volary. Occasionally, it continued up to Nové údolí station located 14 kilometres south of the Volary station or left this line for a service in a depot in České Budějovice.

The line Číčenice-Volary was operated by this DMU up to two runs per a day in both directions, at lower speeds due to this line passage through rugged terrain and corresponding maximum speed limit of 50kmh-1.

The schedules of the three-day regular cycle and the one-day extra service for this DMU is presented in figure below.

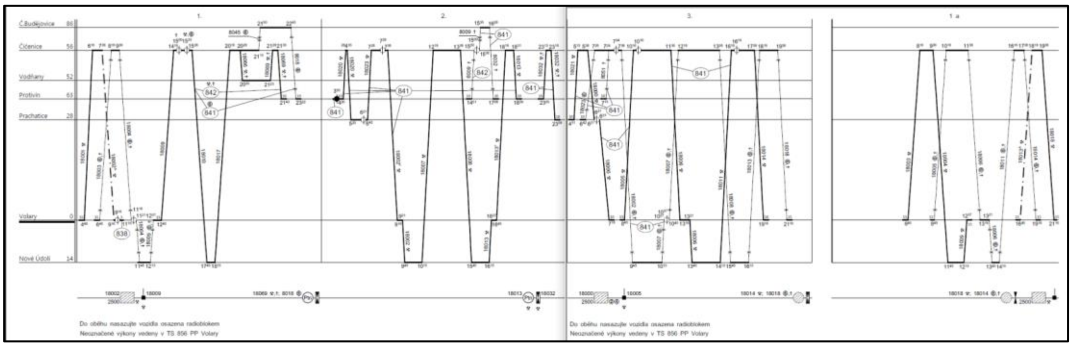


Figure 40: Číčenice-Volary, Typical Daily Schedule

Such frequent service of this line by this DMU bearing the STARS system provided great opportunity to collect a lot of data from this line.

Data Collection

The measured data of the STARS and odometry systems was recorded at common hard disk.

The concept of the measurement system has been proposed unattended. The measurement was automatically carried out and data was recorded whenever the on-board power supply was turned on. This allowed the collection of high volume of measured data and the saving of human resources because only the hard disk full of data required a visit to the DMU.

On the other hand this approach brought some difficulties. The files of measured data were mostly of very large size sometimes including the measured data outside the selected line without position reference. Exchange of such data was time consuming, the data processing also required higher effort mainly due to remove useless data and split of data according to individual train runs.

The RF I/Q samples (high volume data) were recorded on the internal hard disk of the RPS Spirent. Turning this instrument on/off and start/stop of data recording was done manually to record only useful data from Číčenice-Volary line. New separated file was created for each train run in particular direction.

Ground Truth

The Ground truth was calculated from recorded data of the onboard sensors such as odometer, accelerometer and microwave Doppler radar, from the time markers and RFID tag numbers obtained from RFID reader and from the track axis map. Some internal checks were implemented in the algorithm for ground truth calculation to mitigate unexpected travelled distance errors originated by different causes e.g. delayed reading of RFID tag due to possible buffering.

But unusual errors may still occur in the ground truth, caused mostly by processing (splitting and merging) of data files due to e.g. their very large size, exclusion of the recorded data during train stop etc.

4.2.2 Italy

General Description

The results of field measurement and data collection performed from Ansaldo STS have been uploaded inside the STARS CLOUD (“Ansaldo-stars project”) according to the defined guidelines.

The complete upload has been performed within December 2017 and documented in the related data inventory file.

Data Collection

ASTS personnel had be present on-board the train in order to set up the portable equipment and to supervise the measurements performed during commercial service train runs, agreed with the railway and train operators.

In order to provide, for each train run, the collection of the complete set of data, Ansaldo STS faced the need to manage a huge amount of data (especially the ones RF components such as Spirent RF recorder, Tektronix and Aaronia Spectrum analysers, video camera outputs), collecting them on high capacity hard disks.

Below an example of the train time tables for collecting STARS data on Cagliari-San Gavino line is shown (reference period for this time table: October and November 2017 data collection sessions).

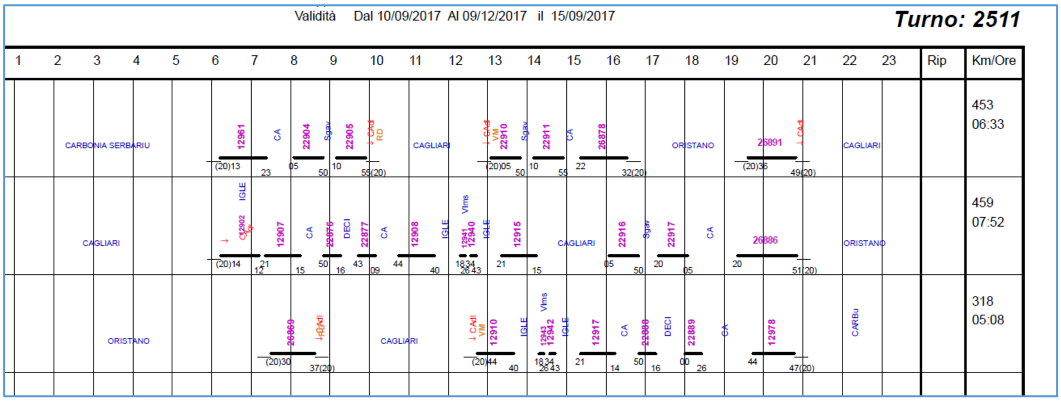


Figure 41: Cagliari - San Gavino, Typical Daily Schedule

Ground Truth

Ground Truth data collection has been performed during train runs by collecting the BTM output logs, reporting physical balises detection, tagged with GPS timestamp.

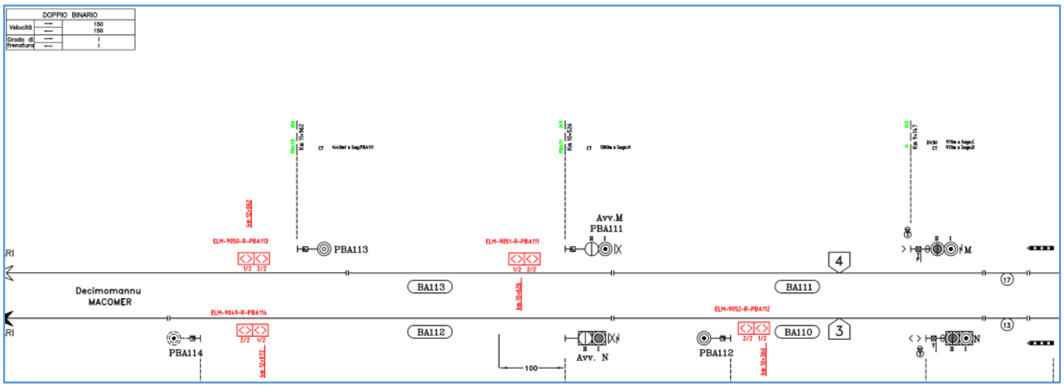


Figure 42: Scheme plan with a small subset of Cagliari-San Gavino physical balises

The train runs Ground Truth elaboration has been realised by using these GT collected data and knowing the exact position of balises (in term of ECEF coordinates and offset from the starting point of the track database) through the line survey campaign.

4.2.3 Switzerland

General Description

Swiss Federal Railway SBB operates rolling stock as fleets of identical units, which can be assigned anywhere where the respective fleet is being used. Individual vehicles typically also operate over multiple lines, rotating between lines on a daily basis. This resulted in data being collected on many different lines over the duration of the project.

Data Collection

Data collection was largely performed by remote access to the test system via a UMTS modem. Due to the limitation that data could only be collected running in the forward direction, the number of lines on which the train operated even within a single day, as well as the desire to visually analyse data, the data was collected on a trip by trip basis. For that reason, the data files from the Swiss measurements are significantly smaller than those from e.g. the Czech test runs, where data files typically contain a full day of measurements including multiple runs back and forth over the same line.

Performing remote measurements on a trip by trip basis required detailed information about the daily schedule of the train, which we could download from SBB's rolling stock scheduling system. This input looks as follows, with the trips in forward direction marked in red:

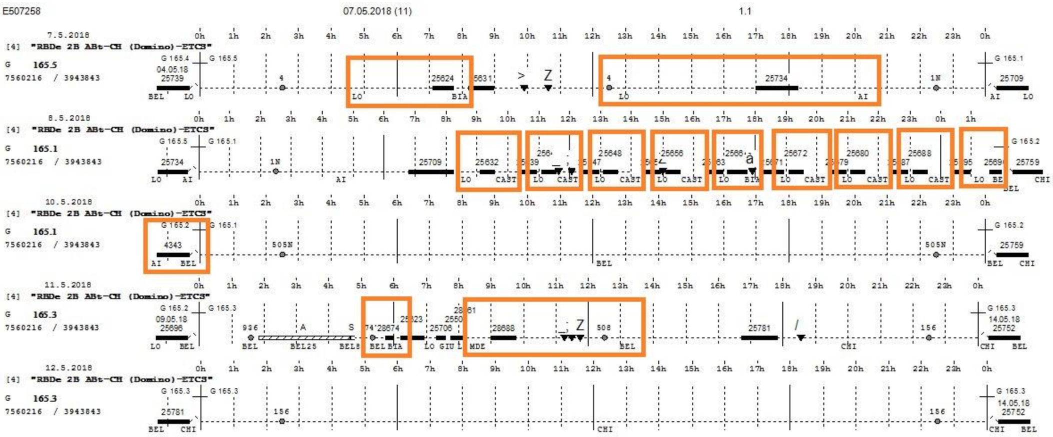


Figure 43: Domino, Typical Weekly Schedule

Measurements were then started and stopped manually for each run via remote access.

Manual measurements with staff on the train were only performed for those trips where RF data was recorded, as the TeleOrbit receiver requires some manipulations which cannot be done via remote access.

Generation of Ground Truth

Ground truth had to be produced manually for each trip, including verification of whether the tool always considered the correct route. Where this was not the case the route had to be forced manually. Where the tool reported an unusually high difference between the distance between balises calculated from the track data and the distance measured using odometry sensors, it had to be assumed that the respective balise was wrongly placed in the track data. These balises were subsequently omitted from the ground truth generation.

4.3 WP 4, Data Post-Processing

4.3.1 Introduction

The purpose of WP4 was to perform a number of analytical analyses on a large number of data sets to detect the presence of environmental factors along the track which degrade GNSS performance, such as multi path, electromagnetic interferences etc. This would then permit a characterisation of the railway environment.

This complex analysis consists of multiple steps of data processing, including an evaluation of the results of each step. The analysis consists of the following steps:

- Selection of methods and software tools to perform the data analysis
- Processing of raw data
- Post-processing of he data
- Detection, identification and possibly quantification of the negative phenomena
- Characterization of the railway environment

As multiple partners carried out the various steps of the analysis, and as large data volumes were processed it was necessary to ensure a fast and efficient data handling and exchange. To achieve this specific solution have been developed, which are described in the following section. The actual steps of the analysis are described later.

4.3.2 Data exchange, reference data set

First a common repository had to be established to ensure that all partners within the STARS project had efficient access to the recorded data, and to store results for further processing and subsequent analysis. Google Cloud was selected for this purpose. A structure of the database was agreed, and a file naming convention defined to keep order in the stored data and to allow deduction of basic information on a measurement data or results from the file name.

The basic structure of STARS repository is created by three projects representing the three measurement campaigns. Each project comprises three buckets, each of them is dedicated for different type of data.

The first of them named as company-large-files is the coldline type of bucket and contains files of large size, which are only occasionally accessed. The files of recorded RF I/Q samples are typical example. An example of this bucket directory structure is presented below.

```
/
|--...
|--config
|   |--...
|   |--2036
|   |   |--STR_2036_STB.rc
|   |   |--STR_2036_CVO.rc
|   |   |  `--...
|--CTB
|--CVO
|   |--170727
|   |   |--spirent
|   |   |   |--CVO_2016_1707271046_01H_NOA.L1.dat
|   |   |   |--CVO_2016_1707271046_01H_NOA.L5.dat
|   |   |   |--CVO_2016_1707271046_01H_NOA.txt
|   |   |--Z4341
|   |   |   |--...
|   |   |--Z4342
|   |   |--Z4343
|   |--170817
|   `--...
|--...
```

Figure 44: Large Files, Cloud Directory Structure

The second bucket named as *company-normal-files* is the nearline type of bucket for frequent access to the data. It includes directories intended for storage of:

- files of configurations of different devices or instruments
- files of recorded raw data and analysed outputs of all measurements of given test line
- data inventories providing an overview on availability of both the measured data and the analysed outputs
- software tools for particular method-analysis (This directory is presented only in AZD project because the identical software tool is used for data from all three campaigns in each analysis. This was made possible by specifying a unified data format).

The structure of this bucket is presented on following example.

```
/
|--...
`--config
|   |--...
|   |--0005
|   |--0995
|       |--0995_septentrio_config.txt
|       `--0995_septentrio_description.docx
|   |--2008
|   |--2998
|   |--...
|   `--...
|--CVO
|   |--170128
|   |--170129
|   |   |--gtruth
|   |   |--vivotek
|   |   |--septentrio
|   |   |   |--...
|   |   |   |--CVO_0995_1701291100_01H_10Z.SBF.GZ
```

```
|   |   |   |--CVO_0995_1701291200_01H_10Z.SBF.GZ
|   |   |   |--CVO_0995_1701291300_01H_10Z.SBF.GZ
|   |   |   `--...
|   |   |--javad
|   |   |--ublox
|   |   |--Z4230
|   |   |   `--CVO_4230_1701290000_01D_01S.PVT.GZ
|   |   |   `--...
|   |   `--...
|   |   |--Z4337
|   |   |   |--CVO_4337_1701290000_01D_01S.L1.TXT.GZ
|   |   |   `--CVO_4337_1701290000_01D_01S.L5.TXT.GZ
|   |   `--...
|   |   |--Z4337
|   |--170130
|   |--170131
|   |--170201
|   `--...
|--...
|--Data_inventories
|   |--WP3
|   |   |--20180619 STARS Data Inventory_AZD.xlsx
|   |--WP4.3
|   |   |--WP4.3_Data_Inventory_AZD_180914.xlsx
|--sw_tools
    |--Z4230
  |--...
    `--Z4370
```

Figure 45: Normal Files, Cloud Directory Structure

The last bucket named as *company-support-data* is the nearline type and includes two directories with supporting data from EDAS and IGS servers. An example of this bucket directory structure follows.

```
/
|--...
|--IGS
|   |--ionos
|   |   `--170130_030
|   |--tropo
|   |   `--170130_030
|   `--gnss
|       `--170130_030
|--EDAS
|   `--170130_030
`--...Log_Latest_Updates.txt
```

Figure 46: Support Data, Cloud Directory Structure

The figure below illustrates one of interface to Google Cloud Platform.

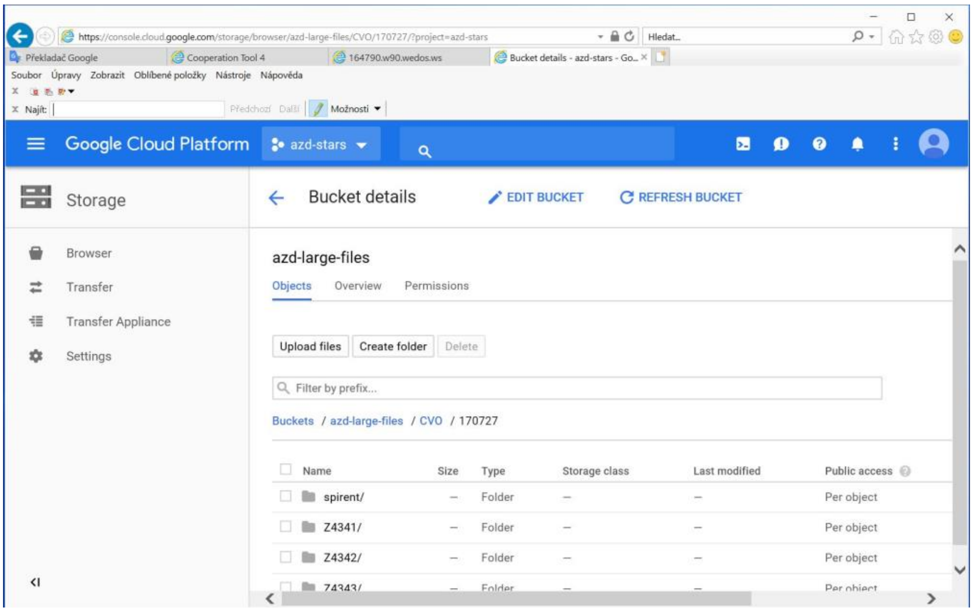


Figure 47: Google Cloud Interface

More detailed information on repository structure and file naming convention can be found in [2], [6]. A guide how to access data stored in the reference data set is available in the D4.2 document [7].

The achieved results:

The reference data set was created. It included proposal of the principle and the structure of the database together with file naming convention, search and contracting suitable provider of the repository, establishing and accessing the database, uploading of different data such as the measured data, the GNSS support data, the calculated outputs for each level of the whole analysis in frame of Task 4.3, the configuration files of all devices and instruments, data inventories and software tools for all particular analyses.

Apart from that, many supporting documents had to be elaborated to ensure e.g. the common file format for reference position of a train, the same process of PVT calculation by each responsible partner, the same approach in calculation position error by different partners, the proper file naming etc.

4.3.3 Selection of methods and software tools for data analysis

In the beginning of the solution of WP4 the suitable methods for different parts of the analysis had to be selected.

Then, it had to be checked for selected methods of each stage of analysis if appropriate tool exists and is available for the use or has to be developed.

The results achieved:

The suitable methods were selected for following levels of analysis: the raw data processing, the data post-processing, the detection and identification of the negative phenomena. A proper method had to be developed for the last level of the analysis, i.e. the railway environment characterization.

Available software tools were only identified for the raw data processing and partly for the data post-processing. Appropriate scripts or software tools had to be developed for the rest of methods in the data post-processing and in the remaining levels of the analysis.

An overview and description of the selected methods and software tools for the analysis is provided in the D4.1 document [8].

4.3.4 Raw data processing

Once the raw recorded data from the measurements was available the analyses aimed to the railway environment characterisation could be launched. The first step in this process, is the raw data processing. The aim of this activity was to provide verified measured data in a suitable format into the next stage of the analysis, i.e. the data post-processing.

The recorded data from different sensors and devices had to be firstly checked, cleaned and properly split or merged to have only useful data. During the measurements, in the case of AZD, the train moved on lines outside the line where GT based reference position of the train is available. Because AZD measurement system starts to record data once the power is on much data from measurements outside the selected line is recorded. Thus, removing this useless data represents the data alignment in raw data processing.

The data was also aligned within the next parts of the analysis, i.e. in the data post-processing and the detection and identification of negative phenomena. The different subsystems or devices started or finished providing the measured data in different time, e.g. in the case of Siemens and Ansaldo the GNSS receivers were mostly switched on before odometry system switch on to ensure their initiation before train run. To have the same time range for data of all the systems or devices for different comparison the data alignment was carried out with respect to an initial and final time of odometry system measurement under the available position reference. The figure below illustrates data alignment principle.

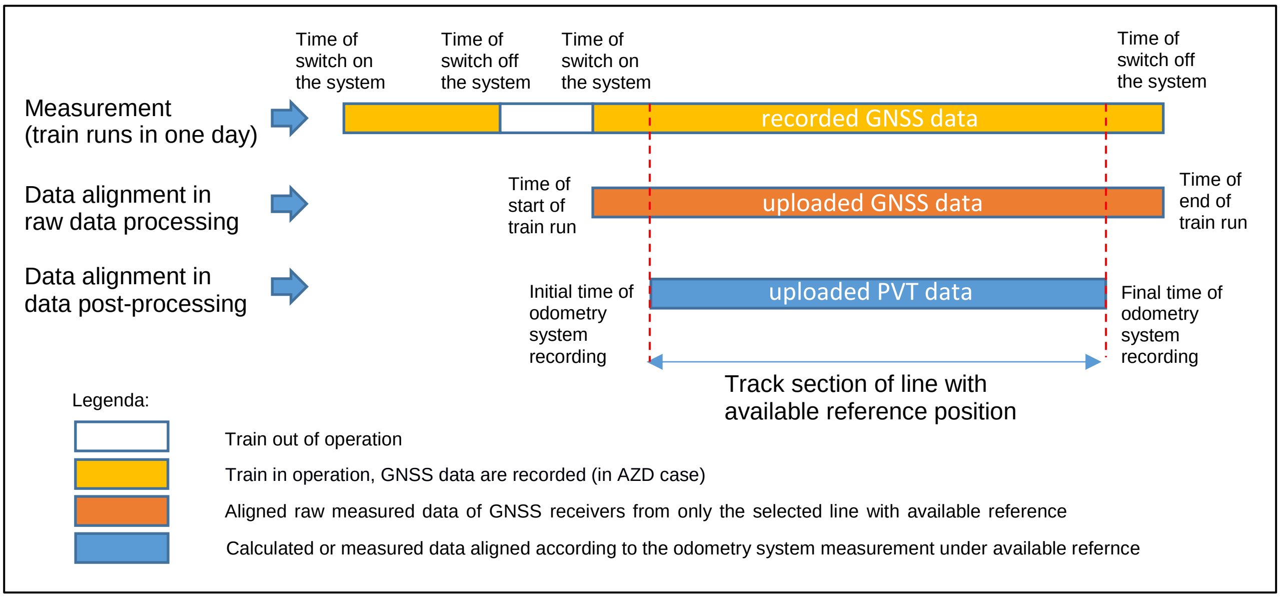


Figure 48: Data Alignment Principle

After the alignment the files with the binary format of data from some devices had to be converted by the partners responsible for the measurement campaign into the specified format for a reason that some software tools are not capable to read binary (or ascii) format of output data files of such devices. An example could be conversion of the binary data file of GNSS Javad receiver (*.jps) by RTKLIB into the RINEX ascii file then converted by Septentrio convertor into the Septentrio binary data file (*.sbf) SBF necessary for PVT calculation in Septentrio PPSDK software tool.

Different software tools were used for these purposes e.g. Septentrio RxTool for check and conversion of Septentrio receiver's data, Teqc for splitting and merging GNSS data, RTKLIB for conversion of file formats, own developed scripts for conversion of odometry sensors data, data alignment etc.

The results achieved:

The files of measured data of suitable size for further processing were prepared by splitting of original files of large size (especially in AZD case, due to long time of some measurements consisting of multiple trips of a train). The useless data were removed from these files.

Different binary data files coming from sensors or devices of the system were converted by the use of different software tools into the files of the specified formats, applicable by different partners in next stage of the analysis.

Appropriate software scripts were developed for conversion of data from individual sensors of odometry system (in AZD case) and RPS Spirent[1], other scripts were prepared for automatic processing of stored raw data files.

4.3.5 Data post-processing

This part of the analysis included two activities. The first one was a calculation of the ground truth-based reference position of a train[2]. The different approaches were applied by the partners responsible for the measurements as different odometry systems were employed in the campaigns. The calculated reference position was checked for random errors and their cause analysed to allow removing the error. A common format for reference position files was proposed and implemented to be applicable to the methods for the detection and evaluation of degraded GNSS performance.

The second activity consisted in the calculation of PVT. The different software tools such as RTKLIB, PPSDK or SPRING were used. The PVT calculation was carried out for different combinations of the constellations (GPS, EGNOS, Galileo), the GNSS signals (GPS L1, L2, L5, Galileo E1, E5a, EGNOS L1) and the position solution modes (standalone, differential EGNOS SIS, differential EGNOS EDAS, carrier phase differential).

The results achieved:

The reference position of a train was provided for each measurement in the files of the data format according the proposed specification [4].

The files of differently calculated PVT were created according the prepared methodology [5]. Data in files was aligned according to the time range of reference position as described in previous chapter.

4.3.6 Detection and Identification of the negative phenomena

In this part of analysis, the files prepared in above described activities were used by different methods selected within previous dedicated activity for detection and identification of the local phenomena (multipath, RF interference and limited sky visibility) negatively impacting GNSS performance.

Generally, the methods could be sorted in the following groups:

- methods providing general information about disturbance of GNSS signal without cause (phenomena) determination
- methods for detection of RF interference
- methods for detection of multipath
- methods for determination of sky visibility mask

[1] Specification of the Spirent native data format is not public thus conversion in a proposed format, opened to STARS partners, had to be done.

[2] While the ground truth position is related to the antenna of the balise or RFID readers, the reference position of a train is related to the GNSS antenna position.

However, some of methods belong to more groups as they are able to detect more than one phenomenon. Therefore, the more practical distribution of the methods is presented:

- methods for identification of degraded GNSS performance based on comparison in position domain. EGNOS differential solution and standalone solution modes were employed in comparison with both the ground truth-based reference position and the position from carrier phase differential solution. These methods are not capable to identify particular negative phenomenon. The list of these methods follows:
    - comparison of position from the standalone solution (GPS L1) and ground truth-based reference position
    - comparison of position from the standalone solution (GPS L1) and position from carrier phase differential solution
    - comparison of position from the EGNOS solution and ground truth-based reference position
    - comparison of position from the EGNOS solution and ground truth-based reference position
    - comparison of (standalone) position solutions from different satellite subsets
- methods for identification of degraded performance or identification of factors disturbing GNSS signal and positioning solution based on raw data or specific features of receivers. Most of these methods, listed below, are capable to indicate occurrence of particular phenomenon from receiver parameters:
    - deviation of pseudo ranges in time
    - comparison of pseud0ange and distance between satellite position and reference position of a train
    - C/N_0 analysis
    - code-minus-carrier analysis
    - multipath detection and mitigation by algorithm built-in receivers
    - Rf interference detection and mitigation by algorithm built-in receivers
    - AGC analysis,

    The last method belonging to this group is SSE method which without ability to identify the particular phenomenon.

- methods for identification of factors disturbing GNSS signal and position solution based on analysis of recorded RF I/Q samples. Following three methods were selected for detection of multipath and RF interference:
    - Analysis based on software receiver implementation
    - Evaluation of RF I/Q sample histogram
    - Evaluation of power spectrum density
- method for evaluation of impact of different constellation on GNSS signal and solution availability
- method of sky visibility assessment based on panoramic figures

The figure below presents some pictures from the image processing in frame of solution of the sky visibility assessment from panoramic figures.

Figure 49: Sky Visibility Processing

Within each method the suitable solution process was proposed and described by responsible partner. The appropriate script for automatic data processing and solution was developed.

Two parameters were specified and implemented for evaluation of outputs of all the methods. The APV (Analysed parameter value) is the first parameter which is a scalar value and is either calculated by the use of the particular method or is directly provided by a device. In a case of methods evaluating the individual observables so called combined APV had to be introduced to get one scalar value for one instant. The combined APV takes into account influence of the satellite elevation on signal propagation by introduction of correction factor $\sin(El_i)$. The original value of analysed parameter is multiplied by this factor for each observable. Combined APV is then scalar value obtained by the maximum or minimum function (depending on given parameter) on a set of the corrected values of the analysed parameter (i.e. products of multiplication).

Some methods without possibility of quantification of analysed parameter do not provide APV (e.g. 4.3.3.7 RF interference detection and mitigation algorithm built-in receiver). In this case, the local phenomenon impact is only indicated by a discrete value that corresponds to the second parameter ES.

The second parameter, ES (Evaluation Symptom) indicates the impact of the local effects. In each method one or more thresholds were introduced for ES in order to distinguish how much impact was detected at any moment. The setting of thresholds was dependent on judgement of the partner responsible for solution after the evaluation of results of the corresponding analysis performed by this partner.

The table below provides overview of the selected methods, they purpose and the responsibility of partners.

Task No.	***Resp. partner***	***Group***	***Output***	***Com. APV***	***Task name***
4.3.2	Identification of factors disturbing GNSS signal and positioning solution based on comparison in position domain				
4.3.2.1	BT	G	APV,ES		Data analysis based on comparison of pseudorange based receiver antenna position estimation and GT based reference antenna position
4.3.2.2	CAF	G	APV, ES		Data analysis based on comparison of pseudorange based receiver antenna position estimation and reference antenna position based on PPK

4.3.2.3	TTS	G	APV,ES		Data analysis based on comparison of receiver antenna position estimation based on differenced pseudoranges and reference antenna position based on GT
4.3.2.4	ALS	G	APV,ES		Data analysis based on comparison of receiver antenna position estimation based on differenced pseudoranges and reference antenna position based on PPK
4.3.2.5	ZCU	G	APV,ES		Data analysis based on comparison of position solution from different satellite subsets
4.3.3	Data analysis and identification of factors disturbing GNSS signal and positioning solution based on raw data or specific features of receivers				
4.3.3.1	ZCU	G	APV,ES	C	Data analysis based on deviation of pseudoranges in time
4.3.3.2	ZCU	G	APV, ES	C	Analysis based on comparison of measured pseudorange and distance between SV and reference antenna position
4.3.3.3	AZD	M,V,I	APV,ES	C	C/N_0 data-based analysis
4.3.3.4	ALS	M	APV,ES	C	Code minus carrier-based analysis
4.3.3.5	AZD	M	APV,ES		SSE based analysis
4.3.3.6	CAF	M	APV,ES	C	Analysis based on multipath detection and mitigation algorithm built-in receivers
4.3.3.7	RADLBS	I	ES		Analysis based on RF interference detection and mitigation algorithm built-in receiver
4.3.3.8	RADLBS	I	ES		Analysis based on AGC level evaluation
4.3.4	Identification of factors disturbing GNSS signal and position solution based on analysis of recorded RF I/Q samples				
4.3.4.1	TASF	M	APV,ES	C	Analysis based on GNSS SW receiver implementation
4.3.4.2	TUBS	I	ES		Analysis based on evaluation of RF sample histogram
4.3.4.3	RADLBS	I	(APV),ES		Analysis based on power spectral density evaluation
4.3.4.4	AZD	I	APV,ES		Analysis based on measured power spectral density
4.3.5	TUBS	V	ES		Evaluation of impact of different constellation on GNSS signal availability
4.3.A	AZD	V	APV,ES		Sky visibility assessment based on panoramic figures

Table 2: Applied Data Analysis Methods

The output file format had to be specified to enable further comparison and processing the outputs of the methods. The first part of the output format including the most important data e.g. GPS time, APV, ES etc. was obligatory for all the partners, the second part is optional and include parameters according to the responsible partner's consideration.

Simple comparison of the outputs of the methods was carried out to check if significant difference indicating possible error in solution is presented. If it is found, the solution was revised, and outputs compared once again.

The results achieved:

The proper solution was proposed for each of the selected methods

The solution description consisting of description of the method, the solution process, the required input data (parameters), the output data (parameters), the used software tool and a justification of set thresholds was provided for each method.

The appropriate scripts for automatic data processing and calculation of the solution output were developed within solutions based on selected methods.

The output data aligned to the time range of reference position was provided in output files according to the format specified in the description.

4.3.7 Railway environment characterization

The last part of the analysis provides information on the railway environment along a track from perspective of local negative phenomena. The basic principle of the solution consists in putting together of all the outputs obtained in particular solutions corresponding to the selected method.

The three indicators MPL, RIL and SFV already mentioned in Chapter 4.4.3 **Error! Reference source not found.**have been proposed to describe the railway environment from viewpoint of the impact of the multipath, RF interference and sky visibility masking on the GNSS signal distortion and the position solution.

As presented in Chapters 5.4.6 different methods can detect one or more local negative phenomena.

The MPL and RIL indicators are then a product of combination of the outputs of solutions of the methods related to the given phenomenon and generally focused methods (e. g. the comparison in the position domain)

The SVF is only determined from the outputs of the method based on image processing of the figures from the panoramic camera.

The scheme of the principle of the railway environment characterization is provided in figure below.

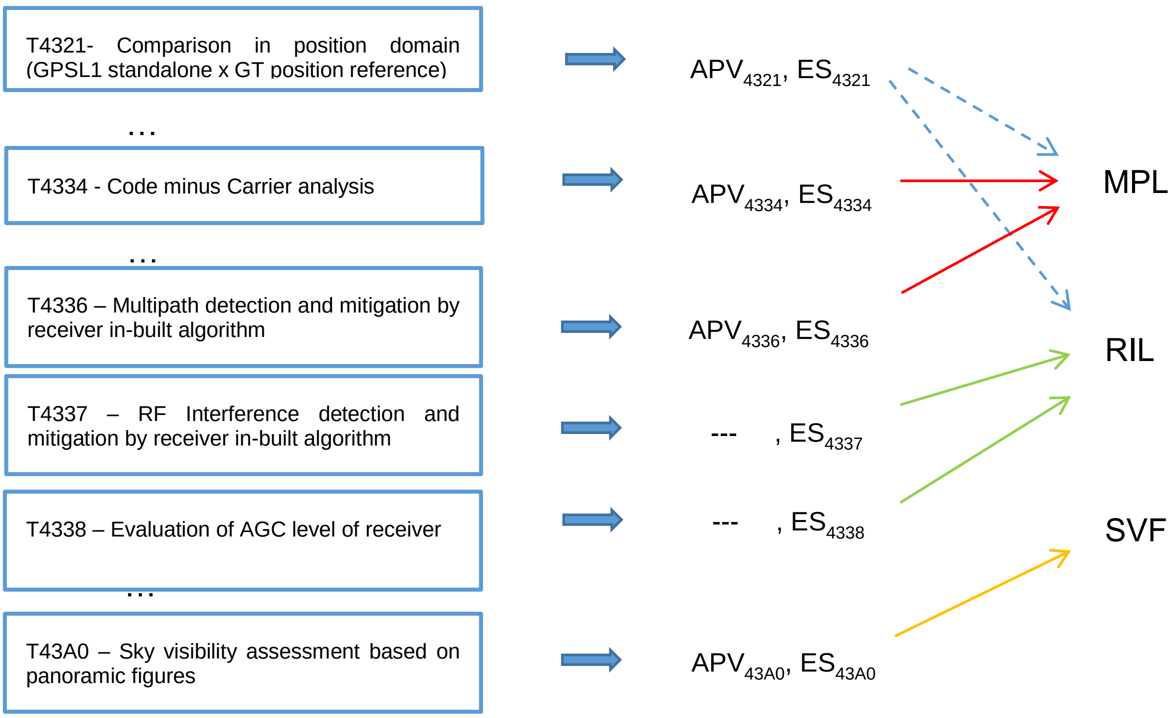


Figure 50: Environment Characterisation Principle

Taking into account the possible difference in the efficiency of individual methods as well as possibility to implement future research results the approach weighting methods' outputs has been adopted when determining MPL and RIL.

Based on the proposed methodology for the railway environment characterization the typical railway environments (scenarios) listed below were selected for the analysis:

- Clear sky view (ASTS, Sardinia test track)
- Clear sky view in the station (ASTS, Sardinia test track)
- Odd case in vicinity of a military airport (ASTS, Sardinia test track)
- Forest, normal case (AZD, South Bohemia test track)
- Forest, extreme case (AZD, South Bohemia test track)
- Mountain (SIE, Switzerland test track)
- Acceleration from the station (SIE, Switzerland test track)

A special case was a camera measurement, which is not really a scenario. It is a supplement of measurement scenarios, which do not include a camera tool.

- Camera measurement (AZD, South Bohemia test track)

The outputs coming from individual solutions of the part of the analysis concerned the identification and detection of negative phenomena were processed for each above listed scenario and results evaluated from perspective of the local negative phenomena impact.

The results achieved:

The principle of the railway environment characterization was proposed. The methodology considering this principle was elaborated. The appropriate MATLAB script was developed for automatic processing of the outputs provided by the solutions of the selected methods.

Based on preliminary analysis of HNSE provided for measured data from different lines, the worst cases (the highest values of HNSE) for each of above listed scenarios were selected for further analysis. Such selected data was analyzed, and each environment was characterized by at least two dedicated indicators MPL and RIL. The SVF indicator was calculated for AZD data due to availability of panoramic figures.

With respect to the prevailing environment along each test line, the description of results is split in following sections:

4.3.7.1 CLEAR SKY VIEW, ON LINE AND IN STATION (ASTS, SARDINIA TEST TRACK)

The line Cagliari – San Gavino is mostly of clear sky view. The figure below illustrates real situation of the clear sky view scenario (below upper) and the train in a station scenario (below lower).

Figure 51: Sardinia Sky Conditions

Figure 52: Sardinia Sky Conditions

Mostly, the low impact of the local negative phenomena on the position solution has been indicated and low value of HNSE (horizontal error in position) observed. The strong multipath has only been indicated in a vicinity of occasional obstacles along the track such as e. g. bridges, the roofs of platforms and higher buildings. However, the impact of the multipath in such areas was found highly dependent on the satellite constellation and the sky visibility given by character of the obstacle and its distance to the train. Mostly, the multipath impact was found low under suitable conditions, the values of HNSE of EGNOS solution have not exceeded 20 meters. However, some obstacles can occasionally bring a high multipath impact with high value of HNSE, when sky visibility is significantly reduced and the signals of the low number of satellites are received. The figures below present indicated multipath for GPS L1 signals and the impact of multipath on HNSE of EGNOS solution for the clear sky view scenario (the figures left) and the train in a station scenario (the figures right). In upper figures the MPL used for multipath indication is in the range of 0 - 4, the threshold equal to 1 indicates middle level of multipath. In the case of the train stop in a station the medium and higher multipath is indicated, but the horizontal error is not too high considering some inaccuracy of the ground truth reference position (several meters in this case).

In the figures below the different courses of HNSE corresponding to the different software tools used in position solution or even to the different position reference are provided.

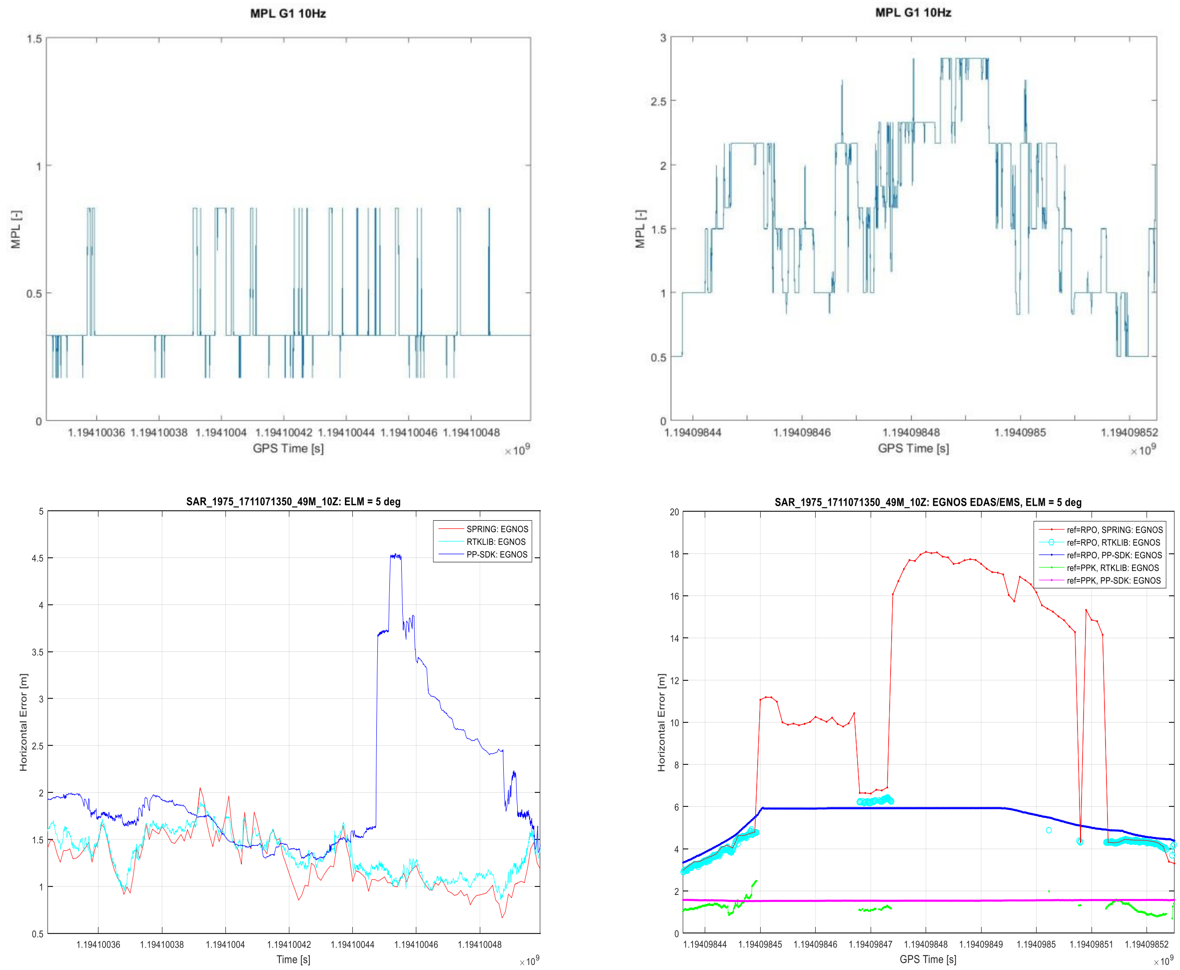


Figure 53: Sardinia

The figures below then provide information on the train speed profile (the figures up) and the number of satellites (the figures below) for these both scenarios (clear sky view – left, the train in a station - right).

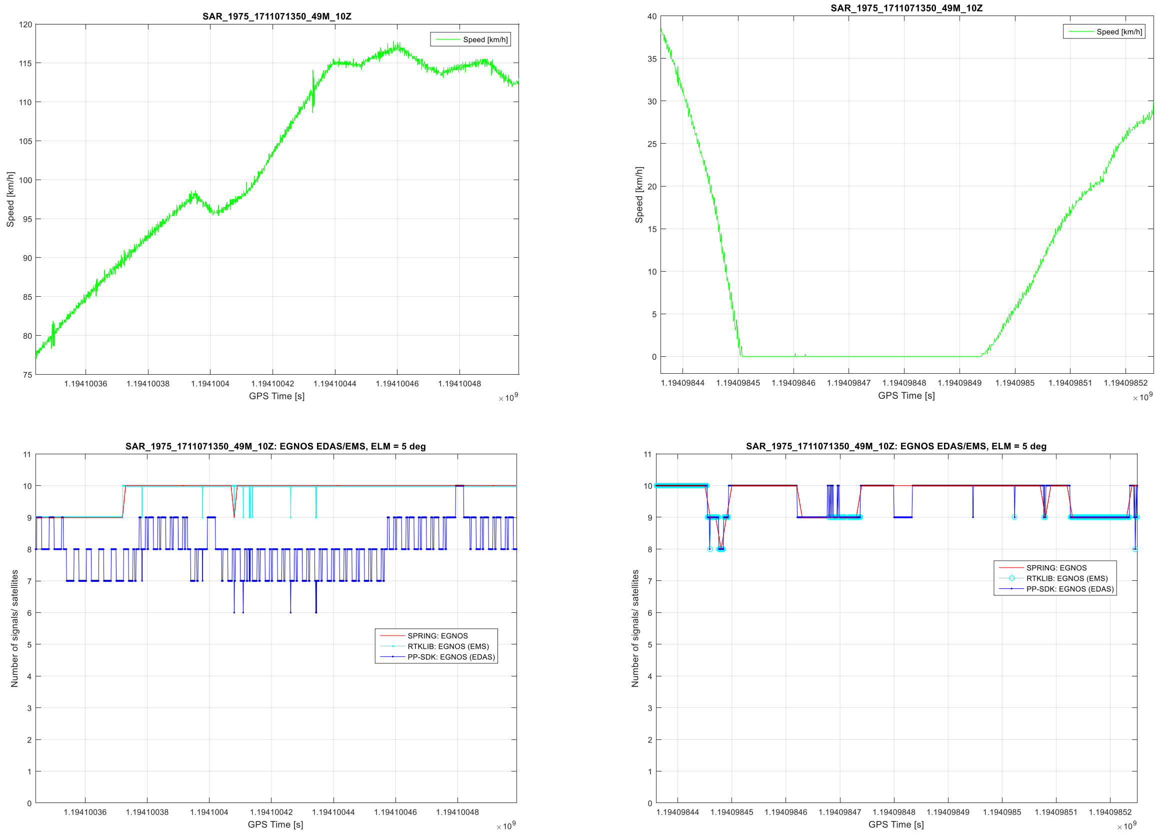
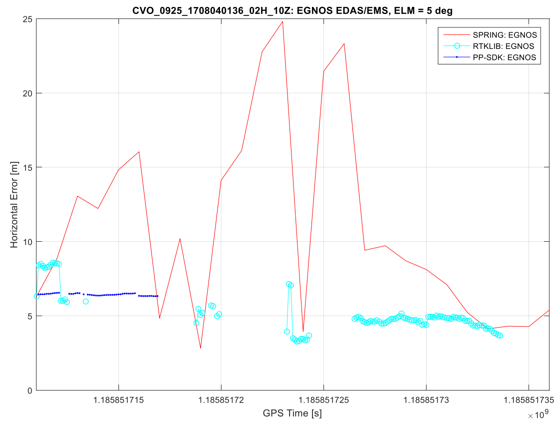


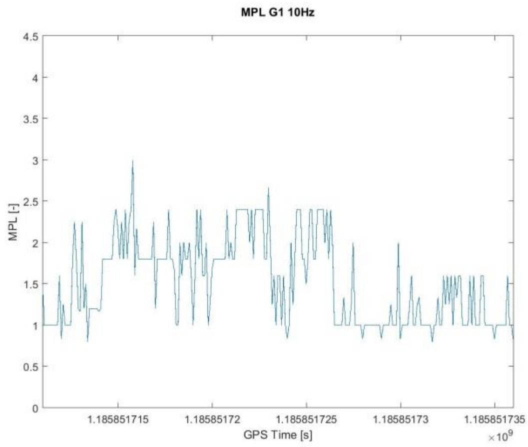
Figure 54: Sardinia

4.3.7.2 Forest, normal and extreme case (AZD, South Bohemia test track)

The line Číčenice – Volary passes through the hilly or flat terrain and the forest is the typical environment prevailing along this line. The middle impact of multipath was observed on the horizontal error achieving up to several tens. Similar to the ANSALDO scenario with obstacle, the size of the horizontal error is highly dependent on the sky visibility and the number of the satellites. When stopping the train in a station the impact of the multipath has been found much stronger. RF interference was observed in the second half of the campaign. As revealed from the analysis the source of the interference was present onboard. Probably a new device has been installed on the train or an already installed device has been modified or replaced. The higher susceptibility of the receiver to the multipath was observed under RF interference.

The figures below present values of MPL (left), HNSE of EGNOS solution (right) and speed profile (in the middle below) of the forest normal case.





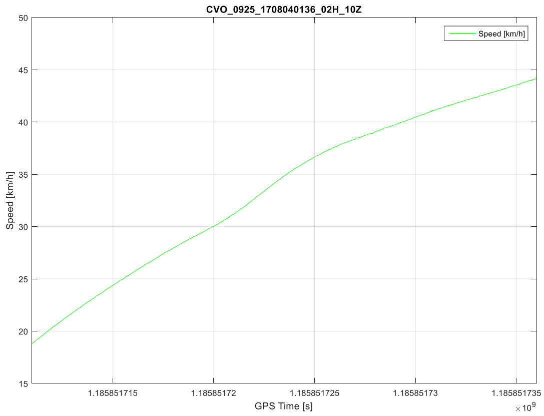
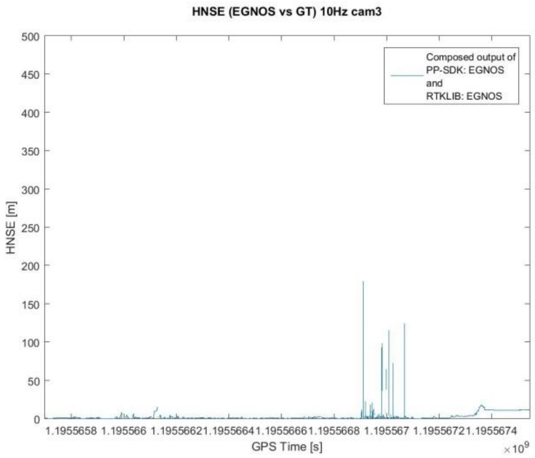
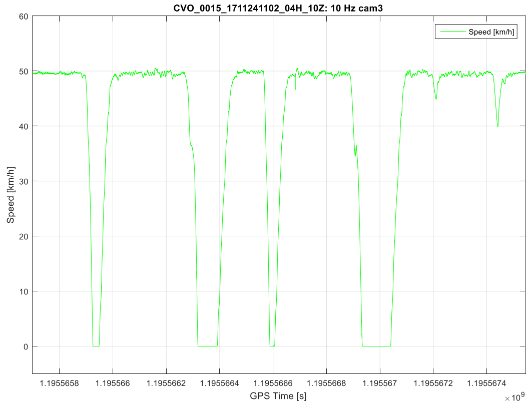


Figure 55: Czech Republic

The figures below present the HNSE of EGNOS solution (left up), speed profile (right up), MPL (below left) and SVF (below right) for another (longer) track section.





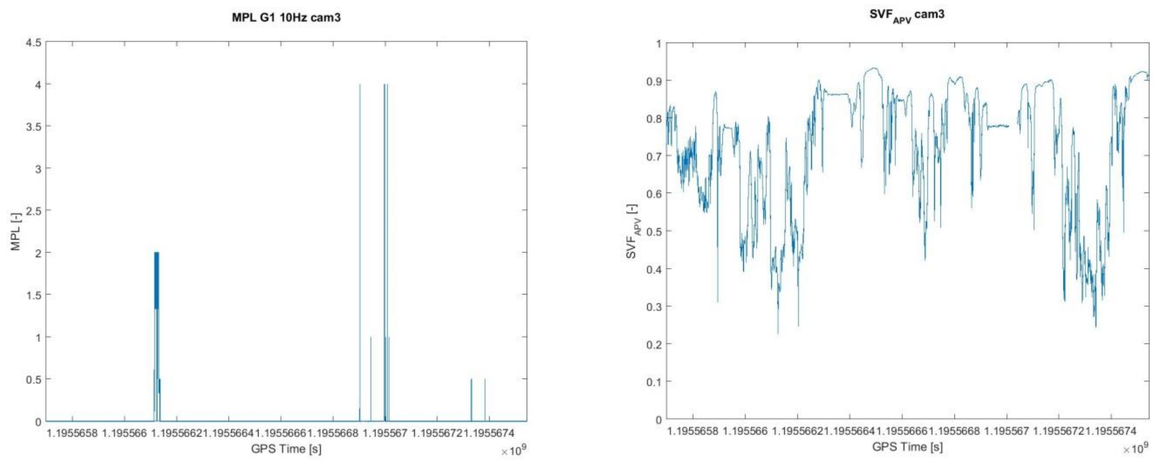


Figure 56: Czech Republic

It is worth to note that MPL values oscillate while train stopping in a station and reach more than hundred meters. It can also be noted that MPL and SVF match well, a larger multipath is indicated for the lowest values of SVF. The SVF also well indicates train stopping. It seems that the analysis of the figures from the panoramic cameras could be employed for not only the determination of the sky visibility but also for multipath prediction.

4.3.7.3 MOUNTAIN SCENARIO (SIEMENS, SWITZERLAND)

A section of the line Biasca - Airolo – Göschenen was selected for analysis due to detected high value of the horizontal error HNSE (EGNOS solution) in mountain area. Surrounding terrain relief with steep slopes along the track (see figure of real situation) and interruption in GNSS signal reception by tunnels will negatively impact the sky visibility. In this analysis only the medium multipath is indicated by the MPL and values of HNSE of EGNOS solution reach up to 30meters. Thus, the limited sky visibility resulting in a low or even insufficient number of the satellites and poor constellation (geometry) is the main reason of such HNSE values and represents the main limitation in position solution at such environment.

Figure 57: Switzerland

In the figures below the horizontal error HNSE of EGNOS solution (figure left), satellite number (figure right) and MPL (below in the middle) for this scenario are presented.

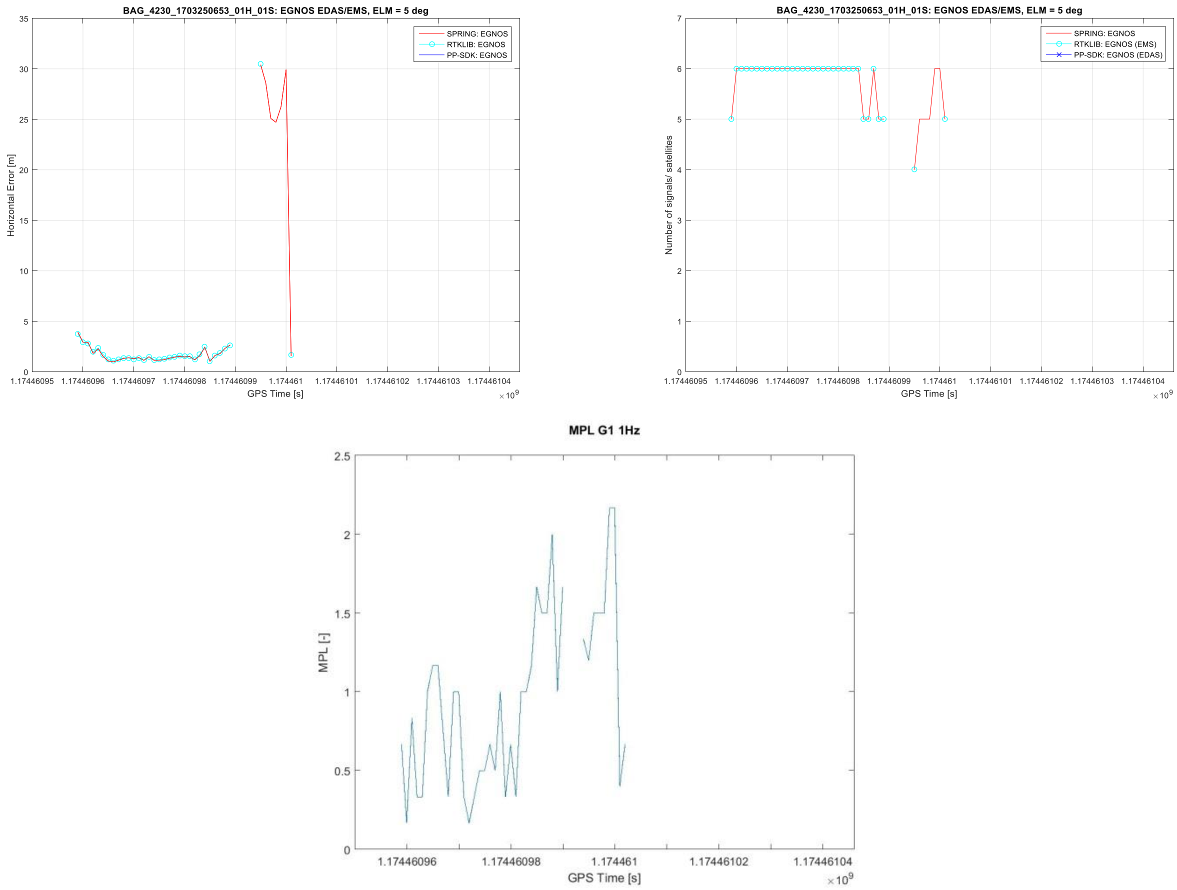


Figure 58: Switzerland

4.3.7.4 ACCELERATION FROM THE STATION SCENARIO (SIEMENS, SWITZERLAND)

The electrified line Genêve Cargo - Genêve – Coppet represents the lines passing the urban environment. The significant values of the HNSE of EGNOS solution, MPL and RIL were obtained in the analysis of this case during train acceleration from the station. The situation in a vicinity of the station is presented on figure below to allow a comparison with situation of the station at Sardinia line presented above.

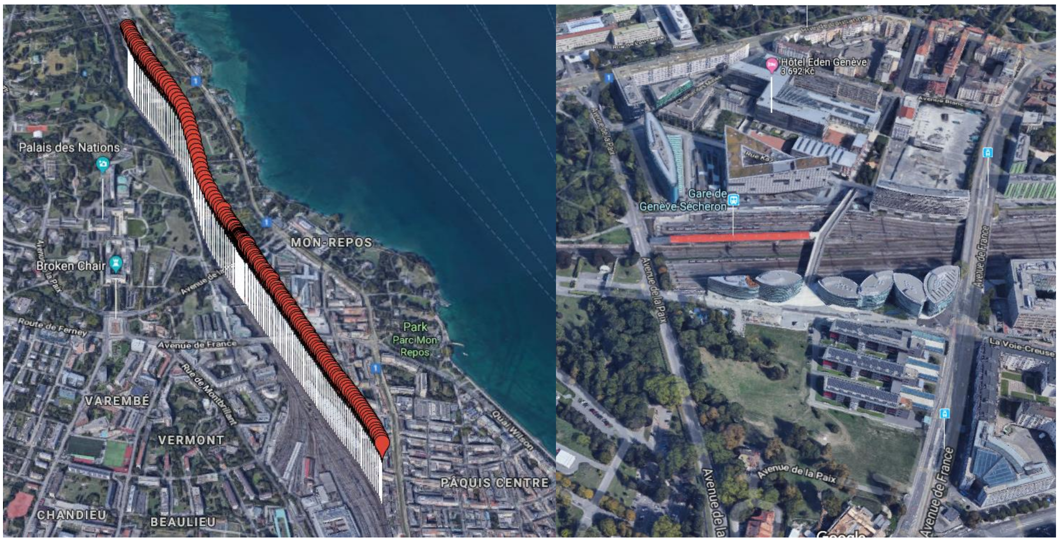


Figure 59: Switzerland

The results of the analysis carried out for selected track section in this case are presented in following figures. It can be seen that horizontal error of EGNOS solution can reach values over hundred meters under such conditions of high buildings along the track (the top left figure). A few important facts were observed in this case. The number of satellites significantly decreases during train deceleration, its stopping in the station and its acceleration (see the speed profile in the middle left figure). In the same time the horizontal error HNSE of EGNOS solution reaches high values and stronger RF interference is indicated by RIL (the middle right figure). The hypothesis on the impact of RF interference on HNSE was set and tested on other data and dependence has been revealed by many cases. The RF interference probably negatively influences noise ratios in the receiver and a consequence could be the loss off lock of the receiver on the signals of some satellites and additional noise in pseudorange measurements. The MPL is of medium levels (see the figure below) similarly to the station in Sardinia, but the horizontal error significantly differs in both cases. The reason of such high values of HNSE in this scenario consists in low number of satellites (if compared to the Sardinia station case) whose received signals (the top right figure) are strongly impacted by multipath.

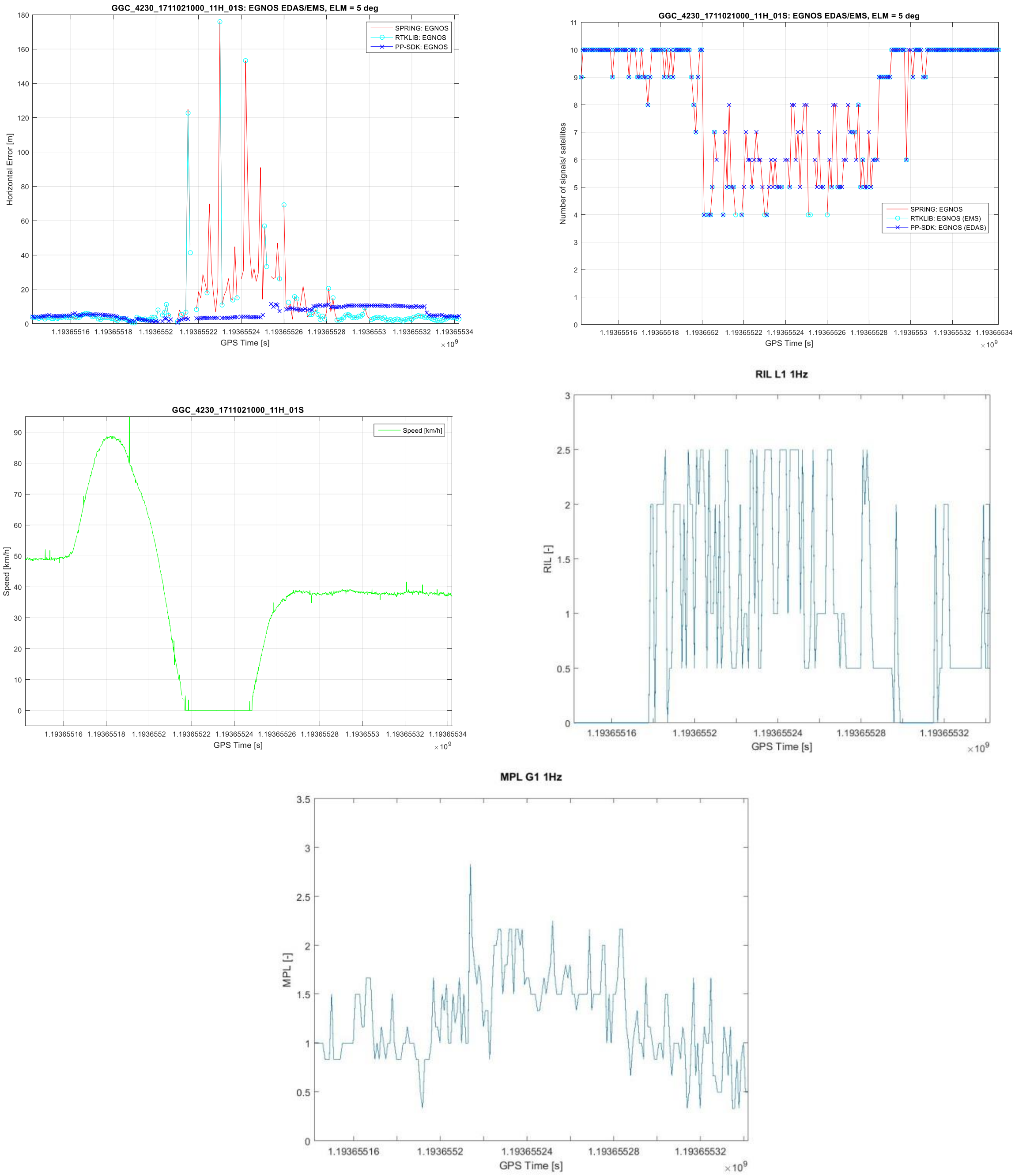


Figure 60: Switzerland

The results of the analysis of selected scenarios provided in [5] were obtained under certain conditions or limitations:

- Only L1/E1, L5/E5a signals were included in the analysis as they are primarily intended for railway safety applications. HNSE of multifrequency and multi-constellation solutions was calculated, and results were made available to the partners. But this solution has not been further analyzed. Main focus was paid only to EGNOS solution because EGNOS performance was one of the main WP5 objectives.
- The weights w1 and w2 of all methods defined in [5] were set as *w1* = 1, *w2* = 2 for calculation of MPL, RIL in all the cases by the elaborated MATLAB script. Therefore, the range of values of MPL and RIL is interval (0; 4) as individual methods provide quantized ES in range 0, 1,

2. Based on these values then influence of local negative phenomena can be considered negligible for MPL, RIL values around 0, middle for MPL, RIL values around 1, strong for MPL, RIL values above 1 and very strong for MPL, RIL values around 4.

- Only outputs of some sub-tasks have been involved in carried out analysis in dependence on their availability in the cloud in time of data processing in frame of task 4.3.7.0 Railway environment characterization. Therefore, their number can differ for each test site.
- Raw data only from Septentrio AsteRx4 receiver was included in the analysis since only this receiver was selected into the measurement set common to all three companies responsible for measurement campaign.
- Output rate of HNSE provided by SPRING is 1Hz, output rates of HNSE provided by PP-SDK and RTKLIB is 10Hz (data rate for AZD and ASTS campaigns) or 1 Hz (data rate for SIE campaign).
- MPL was calculated at output rates 1Hz and 10Hz, where 1Hz output is an extraction of 10Hz output. RIL and SVF were calculated 1Hz due to the output rate 1Hz of the source data. The purpose of 1Hz MPL output is better visual comparability with RIL and SVF parameters. The purpose of 10Hz MPL output is that some cases of high value MPL are not shown in 1Hz output.
- SVF was calculated only for AZD data since DMU operating test track in the South Bohemia was equipped by panoramic camera[3]. Data from the camera are available only for the second half of AZD measurement campaign due to camera malfunction. In presented “camera cases” the set of GNSS signals was reduced to only GPS L1 signal. The reasons are that 1) main intention is to show correlation of the SVF and HNSE data in these cases (sections) and not correlation of the SVF and MPL data, 2) only GPL L1 signal is used in HNSE calculation. On the other hand, figures with DOP parameter are included in these “camera cases” to highlight DOP and SVF_{APV} relationship.
- PVT solution in “camera cases” is provided by composition of PP-SDK and RTKLIB position solutions. Primarily, PP-SDK solution was used if available, otherwise the RTKLIB solution was used[4].
- Output of C/N_0 analysis (Task 4333) is not available for SIE and ASTS due to the method used in the analysis. This method requires data from measurements in both RHCP and LHCP polarizations of the GNSS signal. Nevertheless, values of C/N_0 parameter are available from all measurements from all the test sites in the Google Cloud.

4.4 WP 5, EGNOS TECHNOLOGY FEASIBILITY STUDY

Task 5.1 results synthesis

The purpose of this task was to review the state of the art of the EGNOS use in previous rail applications in order to highlight the identified limitations caused by the rail specificities. Indeed, EGNOS use in railway environments faces difficulties such as visibility or technical constraints but as shown in the past projects, when EGNOS is received and can be used, it shows its benefit on accuracy and integrity.

[3] Since the panoramic camera was not approved for installation on the trains used by ASTS and SIE in the measurement campaign, approved non-panoramic cameras were installed instead. Although the output of non-panoramic cameras does not allow SVF calculation, it has provided valuable information on the characteristics of obstacles along a track and helped to explain causes of higher HNSE values.

[4] Configuration of PP-SDK and RTKLIB sw tools is available in the Google Cloud (azd-stars project -> azd-normal-files -> config -> 4230)

A survey of the past project and literature has been performed. Several issues for EGNOS have been identified:

- EGNOS visibility in constrained environment is not guaranteed. This is one of the reasons of ground-based augmentation solutions developed as a complementary system in Sardinia.
- EGNOS integrity monitoring concept has been developed for aeronautics and relies on the definition of phases of flight or modes. Such phases do not exist in railways.
- EGNOS integrity monitoring concept relies on the comparison of Protection Levels with Alert Limits. Alert Limits bounds tolerable errors around the estimated position that are not defined in railways specifications.
- Propagation conditions in a railway environment differ from the open-sky environment encountered by a plane. Thus, EGNOS error models (computed for open sky environment) have to be compared to real error model in order to evaluate their suitability to the application context. Moreover, it will be interesting to evaluate the consistency of PL values regarding the true errors in order to quantify the capacity of EGNOS to properly bound the rail positioning errors.

As a consequence of the above discussion, the following points have been addressed at the end of task 5.1:

- User positioning equation needs to be specified
- User integrity equation needs to be specified.
- User local environment needs to be characterized.
- Certification process need to be addressed

And in order to request EGNOS performances that are measurable, it is highly desirable that performances required from EGNOS by ERTMS/ETCS are defined at the output of a user receiver presenting what is considered as the Minimum performances needed for railway applications.

Task 5.2 results synthesis

The aim of the task 5.2 was to analyse the E-GNSS (European GNSS) achievable performance in railway environment. In particular we have looked at the performance level assessed by the available integrity monitoring system in Europe at the time of writing: GPS augmented with EGNOS v2 (European Geostationary Navigation Overlay Service). This analysis will be mainly based on a data collection campaign performed:

- In three different European countries (Czech Republic, Switzerland, and Sardinia…)
- On railways presenting the most diverse environment possible: Open sky, forest, Mountain and City centre.
- Using two different receivers Septentrio and UBLOX for most of the captures.

The result of the survey shows that in all observed cases, most of the time the HPL is greater than the position error of the train. However, there are some localised points that present local error such that it implies very large position error. It happens even in the open sky case when in proximity of obstacles such as bridges and railways stations.

Some occurrences of miss integrities were seen in the results in particular in the city and the forest survey. The processed HPL is not always able to cope with the variations of the local environment. Indeed, HPL value is sensible to the considered geometry and satellite number but is unable to mirror complex variation of the local error budget.

To cope with this limitation the following strategies can be proposed:

1) Adapt the considered error budget. This strategy is however limited as it can never cover

error of several hundred meter. Otherwise there will be a strong impact on service availability.
2) Implement barrier to discard LOS that present large errors. This will limit the impact of local effect on availability and integrity.
3) Avoid the use of GNSS position under constrained environments. Avoid location under bridges crossing for example.

In addition to the above recommendation two other conclusions can be highlighted:

1) Direct GEO link is not usable because it severely endangers service availability and integrity.
2) Different receivers have a different behaviour with regard to the local error budget. That means it will probably be necessary to put stringent requirements on the receiver in order to avoid unpredictable behaviour. More complex environment means more stringent receiver requirements.

For future works it is proposed to:

1) Explore the trade-off between the three proposed strategies.
2) Try to apply the proposed strategies to some of the survey runs.
3) Develop a new strategy for EGNOS information broadcast compatible with railway constraint and explore the possible impact on EGNOS concepts (alarm repetition policy for example).

Task 5.3 results synthesis

In order to achieve the objectives of this task, i.e. the definition of EGNSS target key performances to satisfy the ETCS safety requirements, two possible enhanced high level ERTMS functional architectures suitable for including EGNSS in ERTMS train positioning function have been defined. The approach followed in the definition of these architectures aimed at minimizing the impact on the existing ERTMS / ETCS system and on GNSS augmented with SBAS.

A trade-off analysis between the proposed architectures have been performed and, for each architecture, the system boundaries between GNSS railway domain and railway signalling domain have been identified for the first time.

Then hazards coming from GNSS use according to the proposed reference architectures have been analysed, fault trees have been elaborated and the related THR functional apportionment between architectural elements has been performed, considering three reference railway operational scenarios (Staff Responsible, Start of Mission and Movement Authority mode), starting from fault-trees developed in NGTC WP7 but with new elements, such as (a) the identification of new gates as belonging to the functional blocks described in the reference architectures, (b) the THR allocation to the GNSS receiver type I & II and diagnostic capability according to reference architecture, (c) an initial allocation of multipath / NLOS and EMI events hazard rates at train antenna and (d) an initial allocation of FDE diagnostic probability of missed detection.

According to mission profiles and considering the above mentioned three reference railway operational scenarios, preliminary availability target figures have been evaluated.

For the analysis of the remaining performance parameters, the following consideration have been consolidated: continuity is not applicable for railways applications, while for longitudinal accuracy the preliminary values, proposed by NGTC working group, of ±20 meters for Staff Responsible and Movement Authority mode and the more restrictive and conservative value of ±10 meters for Start of Mission have been confirmed.

The above-mentioned activities carried out in this task reached the assigned objectives, to create the basis for completing the Hazard Analysis of the complete system once the agreed reference architecture will be defined and providing the preliminary performance requirements to be further investigated in T5.4 and in the context of other projects (e.g. S2R).

Task 5.4 results synthesis

The aim of the task is to provide an overview of the Evolution of the EGNSS service for the application in the railways environment with a specific reference to the ETCS architecture and operation impacts.

The analysis started from the definition of the present European SBAS service as conceived for the aviation sector.

A specific focus was put on the EGNOS performance specified in the range domain in terms of Integrity, accuracy and availability as they are expressed for the aviation application.

The analysis was then focused on the definition of the EGNOS requirements for the rail and tried to spot the main differences between the rail application and the aviation application with reference to the conception of the EGNOS service.

The assumption is that the reference signalling system for this analysis is the ETCS since it is mandated in Europe for the next decade(s)

Moreover, the application of GNSS with ETCS is limited to ETCS Level 2/3 through the Virtual Balise concept; an application with ETCS Level 1 is not considered, as Level 1 requires balises for data transmission which reduces the benefits of GNSS to a minimum.

For ETCS applications safety integrity level 4 (SIL 4) is currently required. While this does not necessarily mean that the GNSS/EGNSS system itself needs to be SIL 4 compliant, the overall application shall still maintain that safety level when using GNSS.

The analysis includes also a preliminary definition of the “EGNOS services” for railway in terms of performances requirements on accuracy and integrity (alarm limit, time to alarm, integrity level) as requested.

As a second step the analysis is focused on the convergence between ERTMS architecture and SBAS services, operational impacts and some recommendations on the implementation of the architecture to take into account some limitation intrinsic in the GNSS service (like visibility, RF propagation, fading, interference etc.).

The Application of the SBAS Integrity concept to the rail domain was then analysed comparing the possible architectures in the ETCS system that integrate the GNSS receiver and the advantages and disadvantages of the two solutions. Some recommendations were also provided to overcome the issues pointed out during the analysis.

Among the different recommendations one in particular about the continuity of the ENGOS transmission service was then further analysed with a possible solution dedicated to the broadcast of the EGNOS messages in the rail environment. EGNOS EDAS FOR RAIL was the presented where the EDAS-R was defined and analysed with a comparison to the EDAS present service.

4.5 WP 6, Impact Analysis

Task 6.1: Economic model and scenarios Definition of scenarios

The methodological approach has been defined and the CBA approach will be used for the economic analyses. When an investment has to be done and more than one options are possible, this approach helps in choosing the best solution comparing two alternative scenarios: the project and the baseline scenarios. The project scenario will be better off the baseline one if the NPV is positive and the BCR is bigger than 1.

The project scenario has been defined as the one envisaging the implementation of a satellite-based technological solution; the baseline scenario as the one envisaging the implementation of a balise-based technological solution.

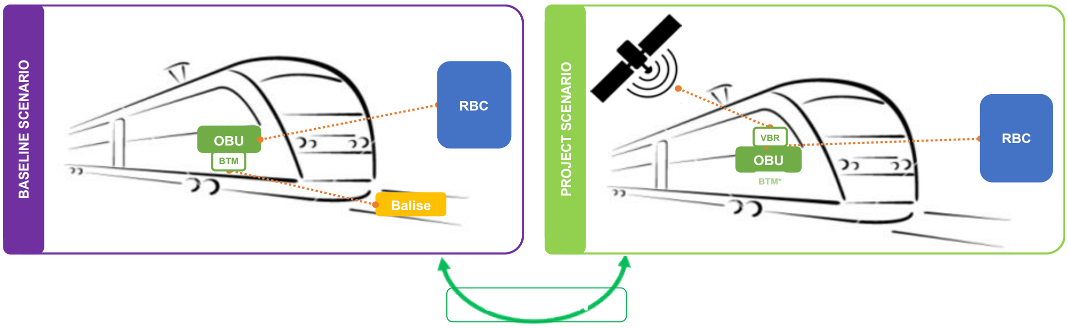


Figure 61: CBA approach and scenarios definition

Nine case studies have been defined crossing three lines type (local; regional; main) and the related localisation (dense area; medium area; isolated area).

The following table summarizes the Local, Regional and Main case studies characterisation. Defining values for the key indicators of the case studies has proven to be extremely difficult, due to huge differences in operating procedures of different operators, but the choice has been made in order to cover as much as possible the line type operating in Europe.

	LINE		VEHICLES			PRODUCTION		
	LineKm	TrackKm	Vehicles	% non-dedicated vehicles	TrKm/ Vehicle	Train/day	Train/y	Production/y (TrKm)
LOCAL	100	105	6	100%	200.000	28	10.220	1.022.000
REGIONAL	100	190	13	90%	250.000	80	29.200	2.920.000
MAIN	100	200	24	50%	350.000	144	52.560	5.256.000

	LINE		BALISES				
	LineKm	TrackKm	Balise/Km	TOT Balises	% virtualizable balises	Phisical balises	Virtual balises
LOCAL	100	105	2,5	263	100%	-	263
REGIONAL	100	190	3,0	570	90%	57	513
MAIN	100	200	3,0	600	75%	150	450

Table 3: Type of line characteristics

The values chosen for the characterisation of the case studies and the cost input assessed have obviously a critical impact on the results of the cost benefit analysis. For this reason, the methodology provides a cost benefit analysis complemented with a lot of sensitivity analyses in order to investigate the impact of the variability of some of the initial assumptions.

Task 6.2: Cost-Benefit Analysis Economic evaluations (Business Plan and CBA)

The work has proven to be more complex than originally thought, due to the antitrust statement of the project that doesn't allow the suppliers to exchange prices of components nor share or agree on assumptions for cost items. UBOC then performed the analysis using prices for components, work efforts etc. which they collected autonomously and without participation of the project partners and did not disclose them. Only total results and sensitivity analysis has been disclosed and shared.

As shown in the following table, under the base assumptions, the GNSS-based solution turns out to be convenient, for the railway system as a whole, in the Local and Regional case studies, whereas the results are negative for the case studies in the Main lines. In the main line case study, in fact, less balises can be managed as virtual and the number of trains to be equipped with the (costlier) project's OBU is higher than in the other cases.

	ENPV	Cumulated flow	BCR	Project solution convenient under the base assumptions
CUT OFF VALUE	***> 0***	***> 0***	***> 1***	
Local; Dense	420.689	567.337	2,11	**YES**
Local; Medium	442.105	607.525	2,17	**YES**
Local; Isolated	468.876	657.760	2,24	**YES**
Regional; Dense	237.839	232.895	1,16	**YES**
Regional; Medium	279.693	311.434	1,18	**YES**
Regional; Isolated	332.011	409.607	1,22	**YES**
Main; Dense	- 422.173	- 708.512	0,85	**NO**
Main; Medium	- 385.458	- 639.618	0,86	**NO**
Main; Isolated	- 339.565	- 553.502	0,88	**NO**

Table 4: CBA results summary

The solidity of the results appears to be remarkable also after the sensitivity analyses. Such analyses also show that the reduction of the number of physical balises and containing the capex of additional OBU modules for the project solution are much more critical for the economic convenience than the savings deriving from reduced maintenance of physical balises.

For the Local case study, the conditions for the project's break even (the first end of the ranges are valid for the "Dense" areas, the last for the "Isolated areas) is either of the following:

- A share of virtual balises of at least 69%-75%
- An additional cost of OBU in the project's scenario of maximum € 72'000-77'000 per unit
- A unit cost of balises of at least € 66-203

For the Regional case study:

- A share of virtual balises of at least 62%-68%
- An additional cost of OBU in the project's scenario of maximum € 40'000-45'000 per unit
- A unit cost of balises of at least € 916-1054

For the Main line case study, the initial analysis yields negative results for the project and the conditions for them to be positive are challenging, being either of the following:

- An additional cost of OBU in the project's scenario of maximum € 19'000-22'000 per unit
- A unit cost of balises of at least € 1960-2101

Task 6.3: Impact analysis

As highlighted in the D6.2, the Cost Benefit Analysis shows that - in the case studies of the Local and of the Regional line - the investment in a satellite-based ETCS technological solution, is better, under the public and general point of view, with the respect to the investment in a traditional balise-based ETCS technological solution. The case study of the Main line, instead, highlighted a negative CBA, that is, that there is no convenience in investing in the innovative solution.

The impact analysis per stakeholder is a tool helping to understand how the general benefit is allocated among the stakeholders. It is helpful because a general benefit could be the result of a benefit accrued by a stakeholder and loss suffered by another. In this case there is no alignment of incentives and, if both the stakeholders are entitled of the decision making, without any sort of compensation, no good decision could be taken.

It is what happens in the case study of the local and regional line. In both the cases, the CBA highlight a total positive impact, that is, though, the result of a big benefit accrued by the IM and a loss suffered by the RU.

In this case the impact analysis also hints at the solution: since the loss for the RU is lower than the benefit for the IM, there is a chance of aligning the incentive through a compensation from the IM to the RU at least equal to the loss RU would suffer. In this way both the stakeholder would have a benefit and decide, together, for the investment in the innovative satellite-based ETCS technological solution.

Task 6.4: Implementation plan

The report presented the progress of the development of the solution for using GNSS in ETCS, and has outlined an Implementation Plan

The issues to be solved in the future in order to reach the operating phase for an ERTMS system based on GNSS are the following:

- Definition of the expected EGNSS services performances in relation with well-defined railway mission scenarios.
- Development of a technical solution for the Virtual Balise concept (which is in the scope of the Shift2Rail TD 2.4 Project).
- Definition of a certification and qualification plan that will allow demonstrating that the overall system (ERTMS plus the GNSS Service) will satisfy the expected operational performances for the identified missions scenarios.
- Validation that the overall system (ERTMS plus the GNSS Service) fulfils the applicable safety, security and accuracy performances.
- Definition and agreement at European level of the necessary contract for the provision of the EGNOS railway service.
- Specification of the evolution of ERTMS/ETCS standards integrating the EGNSS contribution, including test specifications etc.
- Publication of the changes to ERTMS/ETCS in a future release of the TSI, in order to allow infrastructure managers to implement the concept and to require railway operators to equip their vehicles accordingly, and the supply industry to develop and certify the new products.

Based on this, a short-medium term Implementation Plan, which assumes the use of current EGNSS technology (EGNOS V2, or V3 if available), has been defined, identifying major milestones, their expected year of fulfilment, the players driving their fulfilment and the related risks. Such milestones – the first three of which especially rely on the output of Shift2Rail projects – are:

M1 Definition of System Requirement Specifications and system architecture (2020)

M2 Development and laboratory demonstration of fail-safe train positioning subsystem (2021)

M3 On-site demonstrations (2022)

M4 Development of laboratory toolchain and GNSS receiver (2022)

M5 Implementation of a terrestrial communication link standard (by 2024)

M6 System integration (by 2025)

M7 Certification and operational readiness review (by 2027)

The actual deployment plan is mainly dependent on the timeframe for the publication of the modified TSI, which is difficult to foresee; for an entry into service in 2027, it is assumed that such publication can be achieved by 2024.

As concerns the long-term evolutions of EGNSS, a similar implementation plan, with a level of detail reaching a timeframe for milestones, like for the short-medium term, cannot be produced, because the possible evolutions are not yet specified, and their availability is not ensured.

5 CONCLUSIONS

5.1 WP 2, PREPARATION OF CAMPAIGN

A solid basis for GNSS measurement characterization in railway domain has been constructed in WP2 through measurement specification and procedures specification as well as criteria for selecting representative test lines to understand the railway environment behaviour regarding GNSS signals.

5.2 WP 3, FIELD MEASUREMENT, DATA COLLECTION

Despite some issues with equipment procurement and obtaining permissions for the installation of equipment on-board the test trains all three sites have achieved full operation and have produced significant amounts of data.

Producing accurate ground truth data has been a challenge on all three test sites, and has highlighted a number of issues:

- Accurate track data will be required if GNSS is to be used on railway lines, as the position obtained from using GNSS in WGS84 format will have to be translated back into the linear world of railway coordinates by means of accurate track data.
- Track data will have to be up to date at any time, this was highlighted by discrepancies on the Swiss test site where track data updates were only received every six months, but a lot of construction work has taken place in between.
- Route information might be required to generate a true position, as GNSS positions will not always identify the correct track in multi-track layouts.

5.3 WP 4, DATA POST-PROCESSING

The railway environment characterization methodology has been developed and used for the characterization of the typical railway environment scenarios. Significant distortions of GNSS signals have been observed and documented on all of the analysed lines. The distortions are being caused by multipath effects, by limited visibility of satellites and by electromagnetic interferences.

The main findings obtained from the analysis can be summarized as follows:

Higher multipath in a forest

A higher level of the multipath was indicated by the MPL when the train passes through the forest. Strong correlation of MPL and HNSE parameters confirms multipath as one of sources of the HNSE error.

High multipath during standstill in a station

The oscillating high level multipath was observed during train standstill in a station. The known fact that stationary GNSS receiver is more susceptible to multipath then moving one has been confirmed, since the multipath indicated levels were mostly low before and after the standstill. The impact of multipath on HNSE depends on the number of received signals from satellites and degree of their distortion by multipath. It is proportional to the above-ground infrastructure in a station and in its surroundings. Appropriate techniques for standstill detection could mitigate this effect.

RF interference

Stronger RF interference mainly in L1 bands was indicated by RIL parameter in the analysis of data from AŽD and Siemens campaigns.

In Switzerland, the RF interference was often observed during train acceleration after the stopping in a railway station. A strong correlation between the RIL and HNSE parameters was found in this case. Since RF interference was detected repeatedly during the train acceleration the source of RF interference had to be present onboard the train.

In the South Bohemia, the detected RF interference was different. Stronger RF interference appeared mainly in stations during train standstill, lower RF interference during the train run. Because the RF interference was not detected in the beginning of the measurement campaign a new device installed onboard the train or modified current one probably caused it.

Deployment of GNSS technology at railway requires careful design of installation of GNSS equipment on a train from perspective of RF interference.

High efficiency of panoramic camera

The analysis has confirmed a strong correlation between higher values of HNSE parameter and minimum values of SVFAPV indicator. A strong correlation was also observed between SVFAPV and MPL indicators. This suggests that the technique utilizing the panoramic camera could evaluate the sky visibility and possibly also predict multipath.

From the measurements in the South Bohemia the HNSE parameter has been discovered to be more often impacted by limited sky visibility and poor constellation (geometry) compared to multipath (or RF interference).

The main advantage of the camera-based technique is that only one measurement run with a camera equipped train is needed to have sufficient data to produce sky visibility data, or to identify obstacles which are potential sources of multipath. This is due to the stationary nature of the track surroundings.

If the same data shall be produced from received raw data by identifying visible satellites, multiple passes are required as the constellation of the satellites changes continuously.

HNSE, MPL and RIL dependency

A strong correlation has been found between high values of HNSE, MPL and RIL parameters in most cases of train acceleration from a station in Switzerland. In these cases, RF interference seems to be the primary cause of high HNSE, either due to a loss of lock of some satellites or introduction of additional noise to the pseudorange measurements.

Reference position error

Producing ground truth based on fixed position markers and odometry has been revealed critical, as longitudinal position errors of several meters have been observed.

This fact should be considered in future analysis, because higher reference position error may overpass the error of EGNOS position solution and incorrect HNSE value can exceed the protection level and cause false alarm in the analysis.

Ground truth based on PP-SDK could also be used for verification, but this is limited to locations with sufficiently good GNSS coverage.

Techniques used in analysis

Many of the techniques applied to detect the presence of interferences show good correlation with the observed position errors.

Software tools

When using different tools to perform identical analysis some differences in the output have been observed. Some tools also sporadically produce erroneous outputs, so care has to be taken when interpreting the results.

Incorrect reading of the SBF file format comprising dual input data of the Septentrio receiver by the SPRING tool as well as TEQC was revealed.

SPRING offers the highest availability of position solutions compared to RTKLIB and PP-SDK. The PP-SDK solution is limited by the GDOP (<15), the RTKLIB solution has been found more sensitive to the presence of obstacles and multipath.

The software tools developed primarily for position calculation purpose are less suitable for detection of the local effects than the software tool developed for GNSS data analysis. However, the use of multiple software tools has permitted cross-checking of results of the various analysis performed.

Receivers in measurement campaign

Receivers used to record raw data show different behaviour, especially at standstill, probably due to some internal filtering which cannot be disabled.

Necessity of measurement

As the railway environment is not sufficiently homogenous, measurement will have to be performed to characterise the environment of each specific line.

Periodic measurements will probably be required to detect changes in the environment, especially in urban areas.

It has still to be determined whether some environmental characteristic change during seasons, especially those resulting from vegetation.

5.4 WP 5, EGNOS Technology Feasibility Study

The analysis has shown that EGNOS (as provider of GPS augmentation services) can provide significant support in achieving and proving safety, especially to cope with failures in the GNSS ground and space segments, but also wide area effects.

EGNOS coverage is however very poor on many railway lines due to the obstruction of the line of sight to the geostationary satellites used to distribute EGNOS data. The coverage also changes significantly depending on which satellite is being used. Finally, EGNOS reception is also impacted by local and environmental effects.

To use EGNOS data in the railway environment it will therefore be necessary to distribute it over other means than the geostationary satellites, such as over a terrestrial radio link. By doing this the EGNOS data can also be protected against interferences, intentional or unintentional, if that radio link can be protected accordingly. Preferably the ETCS radio should be used, to avoid having to install an extra radio system.

Achieving the necessary overall safety when using GNSS also requires measures against jamming and spoofing, where EGNOS will not provide support as they are local effects. These issues have not been considered in the aviation application of GNSS but will have to be covered in a railway application both due to the environment and to the applicable safety standards.

Note: Unrestricted EGNOS availability has been simulated in most of the data analysis by overlying EGNOS data to the GNSS signals collected during the measurement campaign.

5.5 WP 6, Impact Analysis

An economic impact analysis has been carried out for different infrastructural and operational environment.

The most important economic issues to be considered for the future implementation of the GNSS technological solution in the railway domain can be summarised as follows:

- The operational costs of balises is less important than the related investment cost, so that the share of them that could be managed as virtual becomes critical. The share that make the cost benefit ratio positive varies, depending from the case study, from 62% to 75%.
- The additional cost for adding the VBR functionality to the on-board equipment also turns out to be critical. The additional cost below which the Benefit/Cost ratio becomes positive varies heavily between the different application cases, from 19'000 € to 77'000 € per unit.
- The third critical element is the saving achieved for reach virtualized balise that, depending on the application case needs to be above a value from 66 € to 2'101 €

Note that all these figures are subject to change once the concept how GNSS is integrated into ETCS is finalised and all additional measures, such as the on-board map, or the provision of point data to the on-board unit for map matching are fully defined.

A development plan has also been defined, which includes next steps for the implementation of the GNSS technology in the railway domain.

6 PROJECT SUMMARY

The overall conclusions from the project can be summarised as follows:

6.1 LESSONS LEARNED

Thanks to the significant amount of data which has been collected on the three test sites and the subsequent, detailed data analysis, a characterisation of the railway environment in regard to impact on GNSS performance has been achieved.

EGNOS has also been thoroughly analysed, both regarding availability, if received from geostationary satellites, and possible contribution to increase performance, if available continuously.

A model to analyse cost – benefit for individual applications has been develop as well.

6.2 LIMITATION OF PERFORMANCE

The project has confirmed that the performance of GNSS in the railway environment is limited in many instances due to a number of reasons:

- Different from aviation applications, GNSS in the railway environment is not a continuously available service. Instead, safe and accurate position and speed information can only be generated intermittently due to a number of environmental conditions.
- GNSS is only available on a certain percentage of most lines, and not available at all in e.g. tunnels or under station roofs. These locations are however fairly easy to cope with, as they are easy to detect by the GNSS on-board equipment and are also at predictable locations.
- GNSS will also not be available with the required accuracy and integrity in some locations where GNSS coverage is obstructed, e.g. by buildings, overpasses, platform roofs etc., or where other effects such as multipath or electromagnetic interferences degrade the performance. GNSS might still provide position and speed information in these locations, which can however be misleading if the degradation remains undetected. Some of these locations are again fairly easy to detect or predict, for others this is however much more difficult as their causes are intermittent, time / constellation dependent or even caused by moving sources.
- Good results can be achieved where GNSS is available and where no local feared effects are present.
- The split of the cases with good/disturbed/no GNSS coverage depends on the local conditions, which can vary from full availability in open sky, rural environments to severely limited availability in urban or mountainous areas. A minimum percentage of good coverage is however required to make usage of GNSS feasible.

Detecting and managing the sections where GNSS is not available or where the position and speed provided cannot be trusted is therefore the main challenge of using GNSS in the railway environment.

There are also a number of other issues, mostly related to safety/security and to the applicable safety standards. These include the following points:

- Due to the open, unprotected interface between the GNSS satellites and the GNSS receivers it is difficult to achieve and also to prove a high level of safety in a system like ETCS where GNSS provides the safe train position, unless additional, standardised measures are implemented across the European Railway Network.
- EGNOS (as provider of GPS augmentation services) can provide significant support in achieving and proving safety, especially to cope with failures in the GNSS ground and space segments, but also wide area effects. EGNOS coverage is however very poor on many

railway lines due to the obstruction of the line of sight to the geostationary satellites used to distribute EGNOS data. The coverage also changes significantly depending on which satellite is being used. Finally, EGNOS reception is also impacted by local and environmental effects.

- To use EGNOS data in the railway environment it will therefore be necessary to distribute it over other means than the geostationary satellites, such as over a terrestrial radio link. By doing this the EGNOS data can also be protected against interferences, intentional or unintentional, if that radio link can be protected accordingly. Preferably the ETCS radio should be used, to avoid having to install an extra radio system.
- Achieving the necessary overall safety when using GNSS also requires measures against jamming and spoofing, where EGNOS will not provide support as they are local effects. These issues have not been considered in the aviation application of GNSS but will have to be covered in a railway application both due to the environment and to the applicable safety standards.

Note: Unrestricted EGNOS availability has been simulated in most of the data analysis by overlying EGNOS data to the GNSS signals collected during the measurement campaign.

6.3 MOPS FOR RAILWAY APPLICATIONS

An attempt has been made to produce some key properties of a MOPS for the usage of GNSS in safety critical railway applications, starting from the MOPS used for aviation applications.

The error budget model for aviation covers the following effects:

- Satellite ephemeris errors
- Satellite clock errors
- Ionospheric and tropospheric delay
- Multipath
- Receiver noise, interference, and biases

According to the RTCA MOPS DO-229D, the aviation error budget model is however only valid under clearly specified assumptions, such as carrier phase noise requirements, under elevation angles greater than some thresholds, exclusion of multi path from other sources than the aircraft structure etc. In addition, it clearly stated that the error models for the above listed error sources are only applicable to aircraft in flight and not to an aircraft on the ground [RTCA DO-229D Appendix A2.4, A4.2, J2.3 and J2.4).

Satellite ephemeris errors, satellite clock errors and ionospheric and tropospheric delays are associated to global phenomena and can be considered identical for railway and aviation applications (namely, evaluable in the same manner). The same applies for receiver noise and biases, if similar types of receivers are assumed.

The error budget for railway applications could therefore possibly be the same as for aviation applications, if only clear sky conditions are assumed, multipath is considered as only being caused by the railway vehicle’s structure and no significant external RF interferences exist.

A realistic error budget for railway applications must however also consider errors caused by the environment, which adds multipath caused by the environment, as well as RF interferences from external sources. Signal attenuation caused by external influences such as forests, platform roofs etc. also has to be considered.

Finally, performance degradation as a consequence of reduced satellite visibility needs to be assumed too, which is again caused by external structures, terrain etc.

A uniform error budget model for railway applications would therefore have to consider the following aspects:

- Satellite ephemeris errors (same as in aviation)
- Satellite clock errors (same as in aviation)
- Ionospheric and tropospheric delay (same as in aviation, with some possible enhancements for the tropospheric model)
- Multipath, caused by the vehicle (as in aviation)
- Multipath caused by external causes (railway specific)
- Receiver noise, ~~interference,~~ and biases (same as in aviation)
- Electromagnetic interference caused by the vehicle and by external sources (railway specific)
- Signal attenuations caused by external causes (railway specific)
- Masking of satellites caused by external structures, terrain etc. (railway specific).

There are however a number of issues which make such an error model impossible to use without additional measures:

- All of the railway specific errors causes are not present uniformly along a track or line but vary significantly to the point where each of them can cause position errors which are much larger than what an application could tolerate.
- Some error causes are location dependent, such as masking of satellites by temporary structures, many are however location-independent, such as masking of satellites by temporary structures or vehicles, RF interference caused by the train itself or by other moving or stationary sources, or multipath caused by temporary structures or other trains.
- Some errors are also time dependent, such as multipath, due to the changing satellite positions, or might even depend on the season, due to changes in foliage.
- Finally, as already mentioned, there are locations where GNSS cannot be used at all, such as in tunnels, under certain types of station roofs etc. Such locations cannot be covered by an error budget.

The approach of using the current aviation error model with error budgets adapted to cover local phenomena in the railway environment would therefore lead to a system with extremely poor availability, except probably for the case of clear sky, due to the need to cover extreme cases of local effect. The purely GNSS-based position and speed would therefore have to be excluded frequently in adverse conditions, since the a priori error model for local phenomena could scarcely represent the dynamic railway context.

In order to cope with the situation multiple alternative scenarios have been discussed.

- The first one would be based on using the aviation error budget to cope with the non-railway specific error causes, combined with receiver functions which verify that the current environment is free of multipath, electromagnetic interference and masking. If any of the effects is present then the GNSS receiver and the supporting algorithms could signal to the application that the position generated might be degraded, and therefore cannot be trusted. Note that offline functions might also be defined to identify areas where GNSS will not work at all, such as in tunnels, but such functions can never replace on-board functions which continuously monitor the environment.
- Alternatively, several location dependent error budgets could be produced, which would then be used by the on-board system according to its approximated position. It is however problematic to use the GNSS position to select the applicable error budget, as this would create common source issues. Such a solution can also not cover errors caused by location-independent sources.
- Finally, in combination with the first approach, the error budget could be made “dynamic”, either by defining budgets for the presence of different combinations of the listed

environmental effects (e.g. multi path alone, multi path plus masking etc.), or even by continuously calculating an error budget depending on the magnitude of the listed environmental effects. Such a solution could provide better availability compared to the first solution. It is however questionable whether such a solution would contribute significantly to the usability of GNSS in the railway environment if the error budget is sporadically increased significantly.

As a result, it has been concluded that, due to the intermittent working of GNSS in the railway environment, producing a single, fixed (universal) error budget model for a positioning system purely based on GNSS, which covers all degrading environmental effects and operating conditions, will not work unless it is so conservative that the achievable performance becomes unusable. It will therefore most likely be necessary to produce a solution as proposed above as alternative one. A corresponding MOPS will have to contain the error budget model for GNSS without considering railway environment specific errors, and additionally functions to cope with the railway environment specific errors, which continuously check the quality of the GNSS signals.

6.4 Other Issues

From the above listed issues which impact performance of GNSS in the railway environment, as well as from the analysis of the measured data, a number of issues have been derived which also need to be solved.

- It has been shown in the STARS project that there are locations where the current PVT and protection level calculations, as defined for aviation, do not cover train position error. Railway specific PVT and protection level algorithms might therefore have to be developed, unless on-board functions to detect local interferences causing these errors can correct the protection level.
- Such algorithms, and / or on-board functions to detect local interferences will need to be standardized, in order to achieve identical behaviour, as interoperability cannot be achieved if the behaviour of the on-board systems of different origins is not predictable.
- A way to distribute EGNOS data to the on-board GNSS equipment will need to be standardised, in order to overcome EGNOS satellite visibility issues, but also to improve safety by generating a protected data link between the EGNOS ground service and the on-board GNSS equipment.

6.5 Cost / Benefit Issues

A cost / benefit analysis has been performed for different scenarios, from secondary lines to main line. It employs the “Discounted cash flows” technique that allows the comparison of the costs and savings on a long time-horizon, discounting the items that occur in the future with a certain discount rate. A comparison has been made between the application of ERTMS based on the use of the physical balises (i.e. the baseline scenario that uses the standard ERTMS solution) and the alternative scenario based on the use of virtual balises.

In general, the analyses have shown that the GNSS-based solution has the potential to generate a positive Benefit/Cost Ratio, especially in the Local and Regional case studies even under prudential assumptions, whereas in the case of Main lines the conditions to achieve a positive Benefit/Cost Ratio are stricter, the benefits are therefore less likely (but not impossible) to cover the costs.

Another important activity that has been carried out is the sensitivity analysis associated with some key costs of the analysis. It has demonstrated that, in all the operational scenarios analysed for the different types of lines, in order to assess the economic feasibility of the GNSS-based solution, it is always more relevant to evaluate the share of balises which can be suppressed of the total number of balises and the cost of the additional module on board rather than the savings in operating costs. Moreover, the sensitivity analysis has outlined that the use of an integrated platform for the BTM and the VBR functions will surely bring to further advantages and possible to have a Benefit/Cost Ratio also positive for main lines.

In other words, the convenience of the GNSS based solution as compared to the traditional solution is less dependent on the yearly savings for the operation of balises than it is on the amount of capex born for equipping the trains and of capex saved for installing balises.

This is relevant in that it shifts the question of the economic convenience of the solution from a geographically diverse item (such as the maintenance cost of balises) towards factors that depend on the technological advancements of the solution's development.

The results of this analysis are however still to be refined, as a number of cost items will need to be included, such as those listed under the major issues section above. Also, the scenarios will need to be refined to better represent practical applications of ETCS on the Trans European Network, where an open access to all railway lines is crucial. Finally, the virtual balise concept, which has been used as the basis for the cost / benefit analysis is still under evolution, e.g. by the work done under the Shift2Rail programme, which can have a significant impact on the cost assumptions.

A solution will also have to be found to balance costs and benefits between participants, as the benefits of using GNSS lie mostly trackside, whereas most of the cost is generated on-board.

6.6 Other Findings

The technical feasibility of the virtual balise concept needs additional effort to demonstrate that it can work reliably and safely, and it becomes more and more likely that significant additional measures on top of EGNSS will be required to make it work in the railway environment. A number of such additional measures might even be required, which have so far not been evaluated in detail, nor included in the on-board GNSS architecture as well as the cost/benefit analysis. Examples are:

- the use of real balises in locations, where track selectivity is required at start up, based on defined engineering rules
- a sensor fusion of GNSS with e.g. odometry or IMUs, in order to cope with short, local interferences, with minimum performances defined for theses sensors and standardised algorithms on fusion
- an on-board track database with map matching functions, together with the necessary mechanisms to provide, maintain and update the database on-board
- possibly the provision of route information to the on-board system from the trackside signalling system, in order to support map matching, communicated by the trackside through a standardised interface.

These additional measures are currently being discussed within the Shift2Rail project. Once selected, they will have to be developed, standardised, and implemented, and made a mandatory part of the application. They will then also have to be included in the cost / benefit analysis and the rollout scenarios.

6.7 Way Forward

A number of questions have arisen from the work performed in the STARS project from which a number of work packages result, which will have to be addressed in future projects.

Some of the key topics are:

- new, standardised PVT and PL algorithms, which can better cope with the environment, but still provide high performance
- the feasibility of cost-effective on-board functions for the detection and mitigation of environmental influences to decide where the GNSS position cannot be trusted
- the use of additional sensors to complement GNSS, including the development of

algorithms for sensor fusion (addressed in Shift2Rail)
- the use of signalling information and map matching functions to support track selectivity of GNSS based positioning
- service provision for EGNOS to ensure high available and integrity, such as through a standardised interface between the EGNOS ground segment and ERTMS
- a standardised format for a track database, to be provided track geometry data to the ERTMS system. Note: Depending on the final architecture, this will either be in the form of a track database stored on-board the train, or in track to train messages containing track data for each movement authority.
- if an on-board stored track database will be used, standardised processes and interfaces will have to be developed to produce, distribute and upgrade track databases

It should also be determined what characterises an acceptable environment for the application of a GNSS based positioning system, this definition could then be mapped against sample lines to determine what benefits can realistically be achieved (e.g. percentage of virtual balises).

It should also be decided whether interoperability between different GNSS based positioning system and trackside shall be achieved by standardizing the functionality in detail, or only by testing against reference scenarios.

Finally, the advantage of using Galileo and/or GPS with multi frequency receivers needs to be investigated, as soon as a full constellation of Galileo becomes available. Both GPS L5 and Galileo E5a signals seem much more resilient against multipath than the legacy GPS L1 signal.

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