STARS

SATELLITE TECHNOLOGY FOR ADVANCED RAILWAY SIGNALLING

D2.1 Specification of the Measurement Information

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1 INTRODUCTION

1.1 EXECUTIVE SUMMARY

The purpose of this document is to present the results of all information collected by WP2 members for the definition of the STARS WP2 measurement campaign. This is related with the task 2.1 defined at the WP2 project planning. It should also be taken into consideration that the decisions taken in WP2 are linked to the future development of WP3 and WP4.

Section 2.1 identifies the possible techniques to characterize the local phenomena that cause GNSS performance degradation and PVT errors. The analysed local phenomena are the multipath, RFI, and GNSS signal visibility and attenuation. In addition, section **Error! Reference source not ound.** identifies the techniques to assess the GNSS position estimation error using a ground truth or reference. Moreover, a characterization of environmental conditions and the choice of GNSS signal acquisition chain that may influence the GNSS navigation solution are presented in section 2.3. Finally, section 3 summarizes the measurements to be recorded.

1.2 DEFINITIONS AND ACRONYMS

Acronym	Meaning
AC	Alternate Current
ADC	Analog to Digital Converter
ATO	Automatic Train Operation
CRP	Carbon fibre Reinforced Plastic
GRP	Glass Reinforced Plastic
CMC	Code Minus Carrier
COM	Communication
DC	Direct Current
EDAS	EGNOS Data Access Service
EKF	Extended Kalman Filter
EMC	ElectroMagnetic Compatibility
ETCS	European Train Control System
FE	Front End
FTP	File Transfer Protocol
GDOP	Geometric Dilution Of Precision
GEO	Geostationary Earth Orbit
GNSS	Global Navigation Satellite System

GT	Ground Truth
HDOP	Horizontal Dilution Of Precision
ID	Identity
IF	Intermediate Frequency
IGS	International GNSS Service
IMU	Inertial Measurement Unit
LHCP	Left Hand Circular Polarization
MDB	Minimum Detectable Bias
MEDLL	Multipath Estimating Delay Lock Loop
MIB	Magnetic Identification Balise
MP	MultiPath
NAGU	Notice Advisory to Galileo Users
NANU	Notice Advisory to Navstar Users
OBU	On-Board Unit
PE	Position Error
PDOP	Position Dilution Of Precision
PPD	Personal Privacy Devices
PPK	Post-Processing Kinematic
PSD	Power Spectral Density
PVT	Position, Velocity, Time
RAIM	Receiver Autonomous Integrity Monitoring
RF	Radio Frequency
RFI	Radio Frequency Interference
RFID	Radio Frequency Identification Device
RHCP	Right Hand Circular Polarization
RMS	Root Mean Square
RPS	Record and Playback System

RTK	Real Time Kinetic
RX	Receiver
SBAS	Satellite Based Augmentation System
SBF	Septentrio Binary Format
SNR	Signal to Noise Ratio
SQM	Signal Quality Measurement
SW	Software
TDOP	Time Dilution Of Precision
TX	Transmitter
VDOP	Vertical Dilution Of Precision
VSA	Vector Signal Analyser
WLS	Weighted Least Squares

2 Railway Line Characterization of Local Phenomena Related to GNSS Signal Reception in Railway Environment

According to the description of work of STARS Grant Agreement [1], the train environment needs to be characterized in terms of local phenomena:

a. Multipath both from trackside objects and from objects near locomotive roof mounted antenna

b. Electromagnetic RF properties and interference sources both from external sources and locomotive

c. Sky visibility due to trackside obstacles in terms of elevation masking angle versus sky area and satellite LOS visibility (number of GNSS satellites in view as a function of time)

2.1 Techniques for Assessment of Local Phenomena

All possible techniques to assess such local phenomena will be presented in the following table with the pros and cons of each technique in order to help choose in the appropriate measurements to be carried out in the STARS project. For a better understanding of such techniques and avoiding any confusion related to terminology, a simple schematic of the GNSS receiver chain is drawn in **Figure 1** showing the GNSS signal from reception by an antenna to the end of its processing. The RF samples relate to the sampling of a down-converted GNSS signal at RF frequency in GHz whereas I & Q correlator outputs are GNSS specific, and GNSS raw data comprehends code and carrier phase measurements which estimate the distance between the GNSS RX and the GNSS satellite. Finally the PVT data is relative to the position, velocity and time estimates of the GNSS RX.

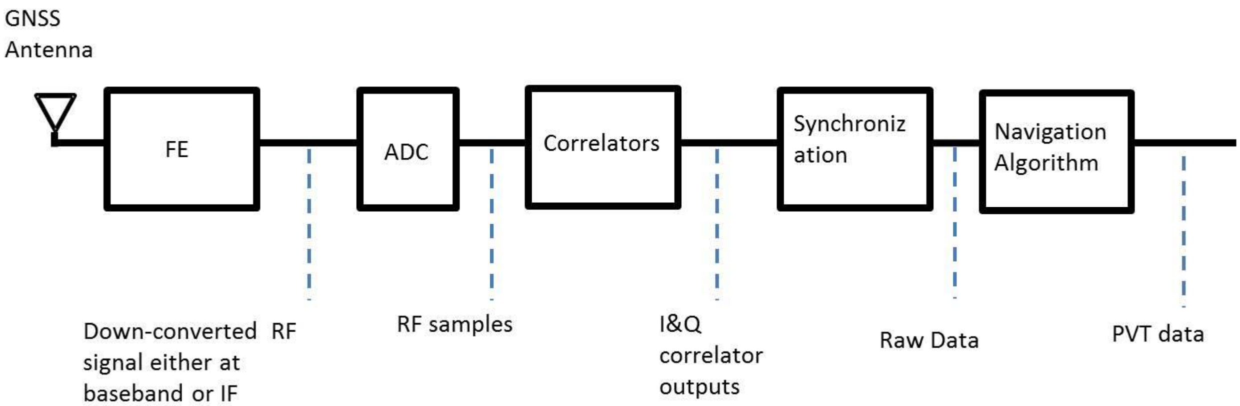

Figure 1: GNSS receiver chain

Local phenomenon	Technique and Measurement	Technique description	Notes (~) Pros (+) Cons (-)
2.1.1 Multipath (MP)	2.1.1.1 Code minus Carrier (CMC) technique uses one frequency code phase measurement and two-frequency carrier phase measurements	CMC technique is a simple way for GNSS measurement assessment from multipath perspective. The technique supposes one code and two-frequency carrier phase measurements [4]. Two frequencies are generally needed to remove most of the ionosphere delay error. As its name indicates, the technique is based on following combination of code and carrier observables: $\rho - \varphi = 2\, I\rho + MP\rho - const.$ (The multipath contribution on carrier phase measurement MPφ is neglected). The ionosphere contribution Iρ has to be estimated by two-frequency measurement and the nuisance constant bias has to be filtered out (the multipath contribution MPρ is supposed to be zero-mean). Actually, the combination contains not only the multipath contribution MPρ (which is an objective of this technique) but also the thermal noise contribution (multipath and thermal noise are inseparable by this technique). The combination after bias removing represents an instantaneous value of the multipath error. Usually, the RMS value is computed over a moving fix-length window. The technique is a part of several SW for GNSS measurement post-processing, e.g. teqc [5].	~ multipath error is assessed in directions (azimuths/elevations) of actually processed satellite signals + generally available technique for all multi-frequency receivers with raw data output - actually, CMC combination consist of a sum of multipath error and thermal noise error contributions

Local phenomenon	Technique and Measurement	Technique description	Notes (~) Pros (+) Cons (-)
	2.1.1.2 Multipath mitigation algorithm output of GNSS receiver technique. The measurement is the multipath estimate of the GNSS receiver	Many contemporary GNSS receivers, especially high grade receivers, contain some advanced multipath mitigation algorithm. One possible approach of mitigation algorithms is based on the discrete multipath model. A receiver then tries to estimate the model parameters to fit receiving signal disturbed by multipath. Such model parameters, if available on receiver output, provide useful information concerning actual multipath situation. The work [6] shows how the NovAtel receiver was used to apply the MEDLL multipath mitigation technique and modify it to an equipment which works as a multipath meter. In fact, correlator outputs (real and imaginary parts) with symmetric code phase delay spacing (SQM, Signal Quality Measurement) around the tracking correlator, allow to detect and quantify multipath by SQM point symmetry. Same principle is applied by MEDLL technology. Furthermore, Septentrio receivers provide a value “multipath correction applied to the pseudo range” as an item in MeasExtra SBF block available through receiver’s interface [7].	~ multipath error is assessed in directions (azimuths/elevations) of actually processed satellite signals + indicates directly multipath error (thermal noise is not included) - since the mitigation algorithm in a receiver is proprietary, the performance is generally unknown (the receiver output should be calibrated on a known multipath distorted signal) - requires a receiver which has the described capability, i.e. which provides the information concerning multipath distorted signal identified by its internal algorithm - requires I&Q correlator outputs
	2.1.1.3 GNSS Post-processing technique of GNSS RF samples	GNSS RF samples, if compared with raw data, carry more information and act on a lower level and thus offer bigger potential to identify and analyse any local phenomena. RF samples can be processed with an algorithm with multipath detection and/or analysis capability (the algorithm can be derived from appropriate software receiver). The big advantage of post-processing approach is a fact that the same data can be processed by different algorithms to extract as much multipath related information as possible. The RF samples have to be recorded with appropriate large bandwidth; otherwise the potential for multipath analysis is degraded. For GPS L1 C/A signal, i.e. signal with BPSK (1), the bandwidth should be greater than 10MHz. The multipath analysis is not too demanding on RF sample width, 2 bits per sample seem appropriate [22].	~ multipath error is assessed in directions (azimuths/elevations) of actually processed satellite signals + post-processing enables huge variability in utilized multipath algorithm + implemented algorithm is known (open) and its performance is either also known or can be determined from the algorithm itself + the RF sample width for multipath analysis is not too demanding, 2-bit samples are appropriate - recording of RF samples produces huge volume of data (possibly, the technique cannot run through entire campaign) - the RF samples have to be recorded with appropriate bandwidth; for BPSK(1) the bandwidth should be higher than 10MHz

Local phenomenon	Technique and Measurement	Technique description	Notes (~) Pros (+) Cons (-)
	2.1.1.4 Post processing of raw data simultaneously measured with RHCP and LHCP antennas	GNSS signal broadcast from satellite has Right Hand Circular Polarization (RHCP). The signal polarization can turn to Left Hand Circular Polarization (LHCP) if signal is reflected. This technique is based on simultaneously reception of the same signal (signal coming from the same satellite) with two antennas but with opposite polarizations. Antennas are placed as close to each other as possible. It is supposed, that raw data of both antenna inputs will be further processed to identify the multipath. E.g., multipath environment can be indicated if signal with significant C/N0 from LHCP antenna is received. Mutual comparison of measurements (code measurements) from RHCP and LHCP antennas can be used to determine the reflected path delay.	~ multipath error is assessed in directions (azimuths/elevations) of actually processed satellite signals + can effectively indicate odd number of reflections - requires a two-RF-input receiver - requires two antenna (one unusual with LHCP)
	2.1.1.5 Utilization of 3D environment model	Digital 3D model can provide comprehensive information concerning local environment and has a potential to be used for prediction of all local phenomena. Utilization of 3D model is a common approach for terrestrial communication (mobile network) planning, especially in urban environment. Concerning GNSS, there are several tools available for such work as SE-NAV from OKTAL or SPRING developed by CNES and Thales [10]. Such 3D models can be used to perform statistical multipath estimation [11]. The difficulty lies in developing 3D models of the track. For this technique to be applicable for GNSS multipath phenomenon prediction, the 3D model has to carry information concerning surface reflection and also diffraction on obstacle edges. Such extended information for 3D model is not supposed to be available and perhaps requires a dedicated study.	~ multipath error can be assessed in arbitrary directions (azimuths/elevations) + provides complete description of terrain and buildings which can be used not only for multipath phenomenon prediction - availability of 3D terrain model cannot be supposed for all railroad tracks - providing of 3D model is generally expensive (LiDAR + successive data processing) - the assignment of reflection and diffraction coefficients to particular surfaces and edges is not easy and probably requires a dedicated study - estimation of multipath error from 3D model requires developing 3D models of the track - estimation of multipath error from 3D model requires a special software

Local phenomenon	Technique and Measurement	Technique description	Notes (~) Pros (+) Cons (-)
	2.1.1.6 Utilization of 360° camera	Panoramic figures taken from the GNSS antenna position can be used for identification of obstacles (their surfaces or edges) which cause multipath phenomenon. This technique can be considered auxiliary, because the value of multipath error of signal coming from specific direction cannot be easily deduced from the obstacles in an image. Ray tracing tools should be used to accomplish that task. The advantage of this technique is its low requirements in terms of the device capabilities, i.e. 360° camera, which is now widely available and cheap device. For advanced multipath analysis based on images the appropriate algorithm has to be proposed and implemented. This step probably requires another dedicated study. Note that elevation angle detection using image processing has already been studied [12].	~ has a potential to indicate a multipath error source in arbitrary directions (azimuths/elevations) ~ provides rough information concerning obstacles, which can cause reflections or diffractions ~ the size of data volume depends on picture quality ~ camera should be regularly checked and cleaned within WP3 as camera usability can decrease due to dust, rain, fog, icing… + low requirements to the device (360° camera) + can be used for Non-Line Of Sigh (NLOS) signal detection in raw data - mapping camera pictures to values of multipath errors is complicated (requires an appropriate algorithm and/or has a pure performance)
	2.1.1.7 Utilization of orthophoto map	Based on obstacle types, density, their mutual positions the location can be very roughly assessed from multipath perspective. The advantage of this technique lies in general availability of orthophoto maps. The technique can be used for rough identification of locations, which can be then analysed in detail with some advanced technique.	~ has a potential to indicate a multipath error source in arbitrary horizontal directions (azimuths) ~ provides very rough information concerning environment tendency to multipath + availability of orthophoto map can be supposed for all railroads and it is available for free - mapping of orthophoto map to values of multipath errors is impossible

Local phenomenon	Technique and Measurement	Technique description	Notes (~) Pros (+) Cons (-)
2.1.2 RF interference (RFI)	2.1.2.1 Post processing of RF samples (utilization of high frequency digitizer)	RF samples, if compared with raw data, carry more information and thus offer bigger potential to identify and analyse any local phenomena. Concerning utilization of RF samples for RF interference analysis, the simplest approach is to estimate Power Spectral Density (PSD) over the floated fixed-length window of samples. Interference signals then can be identified in spectral domain. Further, the significance of identified interference can be evaluated by comparison of the PSD with the allowed spectral mask, e.g. from [8]. The same data can be processed with different algorithms (algorithms can differ in complexity and capability to provide additional information about interference sources). Requirements on RF samples for interference analysis can be very demanding, both in bandwidth (sampling frequency) and RF sample width. If the goal is to identify and evaluate the urgency of out-of-band interference (by verifying that the computed PSD meets the spectral mask from [8]) the bandwidth could be in the order of 100MHz and sample width approximately 16 bits (corresponding to dynamic range of 96dB). These requirements have an unpleasant consequence of large volume of recorded data.	+ post-processing of RF samples enables huge variability of algorithms for RF interference identification and analysis - recording of RF samples produces huge volume of data (possibly, the technique cannot run through entire campaign) - the technique is very demanding concerning recorded signal bandwidth and sample width (for the verification of spectral mask from [8], the bandwidth of 100MHz and 16bit samples seem appropriate)

Local phenomenon	Technique and Measurement	Technique description	Notes (~) Pros (+) Cons (-)
	2.1.2.2 Snapshots of spectra (utilization of spectral/ vector signal analyser - VSA)	The technique is based on spectrum estimation by a spectrum analyser and identification of interference in spectral domain. Further, the spectrum can be compared with the allowed spectral mask. The technique is more effective, if compared with "post processing of RF samples", since it directly provides the spectrum (without a need to store wideband and high-dynamic range samples). The natural drawback of this technique is the fact that a spectrum analyser supposes stationary signals (the sweep time of spectrum analyser can be several seconds depending on set span and resolution bandwidth). Thus, for on-board spectral analyser, there is no issue if interference is coming e.g. from a constant interference source on the locomotive engine but can lead to misleading results if interference is coming from trackside (e.g. converter station). Vector Signal Analyser (VSA) can provide additional useful information (constellation diagram, demodulated data stream, etc.) which can be helpful for the identification of interference sources (interference source has to be digital communication equipment in this case).	+ provides ready to use technique which can determine the spectrum over large frequency span with sufficient dynamic range + VSA equipment provides, apart from spectra, the additional information of digital communication signals, which can be helpful for identification of interference sources - the interference signal source has to be stationary otherwise there is a risk of misleading results - even if the interference signal source is on the locomotive engine, if it varies in time depending upon motor load and oscillations at certain frequencies, there is a risk of misleading results
	2.1.2.3 Information provided by interference mitigation algorithm in a receiver	Most contemporary receivers contain some unit for suppression of RF interference. An example can be low-cost uBlox receiver, which contains a bank of digital filters under software control [9]. The bank can be tuned to blank out interferences before the signals are fed to the tracking loops. The setting of the filters, if available as a part of the receiver interface would provide the valuable information concerning actual RF interference. Probably only several receivers make the RF spectrum available at its output (e.g. Septentrio AsteRx4 OEM).	+ provides information concerning actual RF interference as is recognized by receiver - till now, we don't know any receiver providing this type of information

Local phenomenon	Technique and Measurement	Technique description	Notes (~) Pros (+) Cons (-)
	2.1.2.4 Analysis of signal quality indicator(s) in raw data (C/N0, SNR, I&Q correlator outputs)	RF interference can cause either performance degradation (demonstrated as noisy measurements) or can lead to the synchronization loss (receiver does not measure). In the first case, when receiver is still capable to track interfered signals, the presence of interference can be apparent from signal quality indicator: signal to noise density ration C/N0 [dB-Hz] or signal to noise ration SNR [dB]. Such values are commonly available in raw data and even in NMEA messages ($GPGSV). Some receivers provide other additional information which can be useful for interference identification. E.g., Septentrio receivers provide correlator outputs in “CorrI” and “CorrQ” items of CorrChannel datagram. Further, baseband signal samples (I&Q) intended for signal quality monitoring are available in BBSamples datagram [7].	+ signal quality indicator as C/N0 and SNR are commonly available in raw data or even in NMEA messages + some receivers can provide other useful quality indicator (I&Q correlator outputs) or even baseband samples - lowering the quality indicator can have also other reason than interference (signal shadowing, lower antenna gain for low elevations, etc.)
	2.1.2.5 Identification of RF interference sources in a map	Many large stationary sources of RF interferes (cellular phone BTS, terrestrial TV/radio transmitter, converter station) can be identified in a map. Their distance to the track together with other auxiliary information (frequency band, modulation type, broadcasted power) can help to predict their potential impact on GNSS performance. The technique can be used for rough identification of locations, which can be then analysed in detail with some advanced technique.	+ availability of map can be supposed for all railroads - the available information should vary per site and as such make it difficult to quantify its general effect - the level of interference can be (probably) estimated very roughly - Exhaustivity may not be guaranteed (It is questionable that RFI sources are fully listed in maps. Normally, they are only identified in a map, if separate buildings belong to this facility. Information on BTS (GSM) position is available in internet)

Local phenomenon	Technique and Measurement	Technique description	Notes (~) Pros (+) Cons (-)
2.1.3 GNSS Signal attenuation, sky visibility	2.1.3.1 Analysis of signal quality indicator(s) in raw data (C/N0, SNR)	Signal attenuation due to shadowing demonstrates as lowering of signal quality indicator(s) (C/N0, SNR). Signal blockage, or also strong signal attenuation, is expressed as synchronization loss, so the receiver doesn't provide measurements (raw data) to blocked satellite(s). These have to be compared with satellite elevations (e.g. computed from ephemeris). First, a satellite can be below the horizon (this is a natural signal blockage by the Earth, and not an objective of this analysis). Second, the signal can be tracked with lower C/N0 due to lower gain of antenna radiation pattern (this is a consequence of the utilized antenna and also not an objective of this analysis). The technique itself has not potential to distinguish the cause, i.e. among the signal attenuation/blockage, multipath and RF interferences.	~ evaluates sky visibility/signal attenuation only in directions (azimuths/elevations) of actually processed satellite signals; "evaluation" means to assign GNSS signal attenuation to particular direction + signal quality indicator as C/N0 and SNR are commonly available in raw data or even in NMEA messages - degradation of quality indicator can have also other reasons then signal attenuation due to shadowing (RF interference, lower antenna gain for low elevations, etc.)
	2.1.3.2 Utilization of 360° camera	Panoramic pictures taken from the GNSS antenna position can be used for determination of sky visibility and identification of obstacles which can cause signal attenuation. In principle, the identification of clear sky directions (in azimuth x elevation coordinates) is straightforward. An issue could be the assessment of obstacles from GNSS signal attenuation perspective (assignment the attenuation in directions of identified obstacles in figures). Probably, a dedicated study with calibration measurements is needed to determine the lens distortion. Further, an appropriate algorithm has to be proposed and implemented for autonomous image processing (note that satellite elevation angle identification from image processing has already been performed in [12]).	~ evaluates sky visibility/signal attenuation in all directions (360°/180°); "evaluation" means to assign GNSS signal attenuation to particular direction ~ the size of data volume depends on picture quality ~ camera should be regularly checked and cleaned within WP3 + simple requirements of device capabilities (360° camera) + in principle, straightforward identification of directions with clear sky - the assignment of attenuations to identified obstacles (e.g. vegetation with different mass) is feasible but can be challenging, and requires a dedicated study for specific image processing - for autonomous processing of figures the appropriate algorithm has to be proposed and implemented [13]

Local phenomenon	Technique and Measurement	Technique description	Notes (~) Pros (+) Cons (-)
	2.1.3.3 Utilization of 3D environment model	Digital 3D model can provide comprehensive information concerning local environment and has a potential to be used for prediction of all local phenomena. The sky visibility/signal attenuation can be determined using line-of-sight signal rays and their possible intersections with obstacles in 3D model (it is an easier task than in the multipath assessment case, where reflected and diffracted signal rays have to be considered). The only issue could be the assignment of materials to obstacles and consequently their attenuations for GNSS signal. This additional information has to be a part of 3D model. Also, it should be considered using a 3D simple real model in which multipath is intentionally induced by reflecting surfaces and noise is injected in order to calibrate the receiver and be able to better understand the measured data.	~ evaluates sky visibility/signal attenuation in all directions (360°/180°); "evaluation" means to assign GNSS signal attenuation to particular direction + provides complete description of terrain and buildings which can be used not only for sky visibility and signal attenuation assessment - availability of 3D terrain model cannot be supposed for all railroad tracks - providing of 3D model is generally expensive (LiDAR + successive data processing) - the assignment of attenuations to materials of obstacles is not easy; probably the knowledge from other field of branch can be utilized - evaluation of sky visibility/signal attenuation based on 3D model requires a special software
	2.1.3.4 Utilization of orthophoto map	Based on identified obstacle positions, their types (materials) the location can be very roughly assessed from sky visibility/signal attenuation perspective. The advantage of this technique lays in general availability of orthophoto maps.	~ has a potential to identify obstacles which can restrict sky visibility or can cause signal attenuation; the determination in elevation can be done very roughly based on the supposed height of obstacles and the distance from the location + availability of orthophoto map can be supposed for all railroads and it is available for free - technique has no potential to provide accurate (numerical) directions of visible sky or directions with attenuated signals

Table 1: Techniques for assessment of local phenomena

Note: all local phenomena are supposed to be weather and/or season dependent but not only. The level of dependency is a subject of the study in WP4. Examples for justification: a) MP: reflection of a surface can change if wet or covered by snow; b) RFI: when an overhead line (catenary) is covered by ice the sparks could be more often and intensive which can result in more intensive interference; c) signal attenuation/satellite visibility: in summer period the signals can be more attenuated due to foliage. As a consequence, weather info including the season has to be also recorded (see section 3.3).

2.2 GROUND TRUTH AS A POSITION REFERENCE

The ground truth is to provide a position reference to the GNSS measurement system under test. The ground truth is a position estimate itself, but typically based on a different technology independent of GNSS to satisfy metrology society best practice rules and avoid common cause errors. Details on ground truth techniques are provided in [2].

To determine the ground truth on the railway tracks on which the train is travelling, three elements are needed:

1. Track data base
2. Absolute reference measurements
3. Relative distance measurements

2.2.1 Track data base

Compared to other vehicles in the automotive or aviation domain, trains can only move along rails and a change of tracks can only occur at specific points. When the position of the train along the track is known, the cross track accuracy of the GNSS PVT can be determined directly. For this at least the following information is needed:

TDB_1. position coordinates of geo referenced track data points expressed in terms of (longitude, latitude, height above sea level) where position accuracy is expressed in statistical form (a value with given probability)

TDB_2. geo reference system in which the position coordinates are expressed

TDB_3. position accuracy of track data points (position accuracy should be expressed in statistic form (a value with given probability).

TDB_4. which track data points belong to the intersection of multiple tracks

Additional information could help increase the accuracy of relative distance measurement and to assess the GNSS PE:

TDB_5. gradient of track

TDB_6. Superelevation or cant (tilt of track)

TDB_7. position of tunnels

TDB_8. position of railway stations

TDB_9. other mileposts

2.2.2 Absolute reference measurements

To determine the track on which the train is moving, the train must detect absolute reference points along the track. The absolute reference allows recalibrating the relative reference measurements. The absolute reference points which could be detected along the track will vary between different countries and railway lines. For this purpose the following techniques and/or combinations of them shall be chosen:

ARM_1. Eurobalises

A Eurobalise is a specific variant of a balise which is a transponder placed between the rails of a railway. These balises constitute an integral part of the European Train Control System, where they serve as "beacons" giving the exact location of a train as well as transmitting signalling information to the OBU in a digital telegram.

Figure 2: Balises along the railway track

ARM_2. Magnetic Identification Balise (MIB)

MIB provides the absolute reference position for the on-board unit of ATO system. MIB is a part of the national CRV&AVV (Centrální Regulátor Vozidla Automatické Vedení Vlaku) system for Automatic Train Operation (ATO) in Czech Republic.

MIB consists of a set of 8 permanent magnets which are arranged in the beam located inside a track. Orientation of the magnets (i.e. their polarity) in the beam enables to achieve coding with Hamming distance H=8 and more than 30 000 different combinations.

MIBs are located with a density of approximately 2-3 MIBs per kilometre.

The principle of operation is similar as Eurobalises in ETCS: a train passing a MIB obtains the MIB ID and time-stamp using train's MIB reader. The technique is especially suitable for tracks/trains which are equipped with this technology.

Figure 3: MIB along the railway track

ARM_3. Milestone camera

The basic idea is to record the passing of milestones alongside the tracks with a camera. Therefore a camera with line of sight orientated orthogonal to the movement direction of train with high frame rate will be needed.

Figure 4: Milestone along the railway track

No matter the chosen technique and / or combination of different techniques, the following information is needed:

ARM_4. geo reference (longitude, latitude, height above sea level) of absolute reference points and their unique ID coding where position accuracy is expressed in statistical form (a value with given probability)

ARM_5. geo reference system in which the position coordinates are expressed

ARM_6. position accuracy of absolute reference points (position accuracy should be expressed in statistic form (a value with given probability).

ARM_7. detection accuracy of absolute reference points (detection accuracy should be expressed in statistic form (a value with given probability).

ARM_8. signal processing latency

Note: By post processing two consecutive detected absolute reference points the setting of course along the track, which is depended by the setting of the points, can be determined.

2.2.3 Relative distance measurements

To determine the position of the train on the track, after it has passed absolute reference, sensors to measure the relative distance will be needed. To obtain high accuracy a suitable combination of sensors shall be chosen which is more or less vehicle specific. This could be:

RDM_1. tachometer at wheel / rail system

When a free running wheel is available, this means it is not driven (no slip can occur) and / or braked (no slide could occur), a high accuracy (<1% uncertainty) could be reached. When the wheel is driven and/or braked the accuracy will be decreased (up to 30%), and additional sensors will be needed. Therefore, information about the train status (braking info, free running wheel) shall be collected.

RDM_2. optical correlation sensor

Non-contact optical correlation sensor offers a direct measurement of a rail vehicle velocity and direction of movement, using the railhead surface as a reference.

The accuracy of speed and distance measurement should be provided.

RDM_3. radar sensor

The Doppler radar is a type of radar which measures velocity information and relative distance using the Doppler Effect. This is a contactless system which normally also produces direction of travel as the validity and quality of the measured values. The working principle is based in the bouncing of a microwave signal (beams at 24 GHz) off a desired object and analysing how the object motion has altered the frequency of the returned signal. The microwave module of the flat-beam antenna provides highly accurate measured values that reveal very small systematic measuring errors by rotating and tilting. The microwave module of the steep-beam antenna provides a robust measurement signal that ensures that the radar sensor continues to function even under difficult conditions when the flat-beam antenna fails. The Doppler signals of both antennas are evaluated by means of digital signal processing in parallel and independently with different algorithmic methods. The evaluated speed values are output at the appliance connector via a serial interface and a pulse output. The radar sensor will be mounted on the vehicle body with undisturbed line-of-sight of the antenna beams toward the ground. The Doppler radar provides a high accuracy speed and distance measurement (< 2.5%).

RDM_4. Inertial measurement unit

A 6-axis inertial measurement unit with 3 axis accelerometer and 3 axis gyroscope could provide, by means of integration relative speed and distance information to bridge or detect slip and slide of tachometer. Due to drift, temperature dependencies and gradient / tilt of track the confidence interval will increase more or less rapidly while compared to optical correlation sensors. On the other hand, IMU sensor could be added easily into the measurement rack and hence be foreseen if it is affordable.

No matter the chosen technique and / or combination of different techniques the following information is needed:

RDM_5. validity (if applicable e.g. for CorRail sensor)

RDM_6. accuracy (position accuracy should be expressed in statistic form (a value with given probability).

RDM_7. latency

RDM_8. calibration (if applicable e.g. for wheels)

RDM_9. wear (if applicable e.g. for wheels)

2.3 CLASSIFICATION OF SOURCES OF INFLUENCE ON GNSS NAVIGATION SOLUTION

In order to facilitate railway operator decisions to provide the best local railway environment, it is useful to classify the sources of influence on GNSS navigation solution according to whether or not these sources of influence can be affected by human decision making. For that matter, two tables are presented in the following listing the sources of influence on GNSS navigation solution. The first table considers the sources that can be partially affected by human decision making while the second focuses on the sources of influence that are outside human decision making.

2.3.1 Sources of Influence partially affected by human decision making

Sources of influence that can be partially affected by human decision making

Source of influence	Reasoning (Pros and Cons)	Measurements Recommendation
2.3.1.1 RFI coming from train on-board line / equipment	Depending on the type of RFI, the GNSS impact can range from PVT errors to complete loss of GNSS signal tracking These interferences are mainly caused by the pantograph and the electrical equipment functioning.	- pantograph status should be monitored - Record received signal power density for all GNSS bands - Record received signal power density for frequency bands adjacent to GNSS - GNSS RF samples - GNSS signal quality indicators in terms of carrier to noise ratio (C/N0) and SNR - GNSS I & Q correlator outputs - Interference indicator of GNSS RX - PPK information to be compared to GT estimation
2.3.1.2 Multipath due to train type and railway environment-infrastructure (pantograph, catenary…)	The multipath phenomena considered herein is mainly caused by the pantograph and the electrical equipment functioning. Depending on the type of multipath, the impact on GNSS PVT errors can vary between a couple of meters to tens of meters.	- pantograph status should be monitored - GNSS RF samples - GNSS raw data with carrier phase measurements on at least two frequencies - Multipath estimate of GNSS RX - A posteriori PVT residual, w-test statistic and MDB of all measurements used in the PVT solution together with RAIM information - PPK information to be compared to GT estimation

Source of influence	Reasoning (Pros and Cons)	Measurements Recommendation
2.3.1.3 Type of train	Characterize the parameters which define a type of train, that affect the GNSS measurement. Determine which are influencing more in the quality of the GNSS measurement.	Characterize types of trains with respect to GNSS behaviour. Most of the parameters, which could affect the quality of the GNSS signal, are detailed in this document. Also D2.3 explains the available trains for the measurement campaign. In any case, a summary list is included herein: - Identification of the train (model, manufacturer, etc.). - Physical structure of the train, both roof shape (geometry), roof material (reflectivity) and painting/coating's details: metal, glass or carbon fibre reinforced plastic (GRP or CRP)" (it could affect the multipath and absorption assessment) - Speed of the train. Has to be determined which are the available sources to measure the train speed (tachometer, radar, others) and which is the maximum speed supported. - Type of engine - Power supply - Train family. It is a regional train, - Installed equipment. It is important to know the sources of interferences Other information

Source of influence	Reasoning (Pros and Cons)	Measurements Recommendation
2.3.1.4 Electrified/non-electrified line	RFI caused by the high voltage electrified line of the train, especially when the pantographs are mounted on the roof of the train might cause an impact. Diesel engines would not cause RFI on top of the roof, where the GNSS antennas are mounted and therefore it is assumed that they do not have a significant influence. It is still not clear which types of power supplies are affecting on a major scale the GNSS signals or if they are really affecting. The idea is to use different kinds of power supplies and identify which are more suitable.	Use of trains with different kind of power supplies: AC and DC. Diesel trains are also desirable to be able to better understand the sources of interferences and have a bigger diversity of train types. Could be helpful to consider the types of test of the EN50155 norm.
2.3.1.5 Position of the antenna at the train	The position of the antenna is affecting the satellite visibility and multi-path. A curve antenna mounted atop the bogies will have nearly no lateral influence compared to mounting positions in the middle of two bogies. The objective is to understand which is the best physical installation position for the GNSS antenna equipment.	Determine which are the best suitable antenna mounting positions. Analyse if different antenna positions are suitable and are interesting for the measurement campaign. As an example if three antennas are used, they could be arranged in triangle, horizontally or vertically on the train rooftop. Moreover, when more than one antenna is planned to be used it has to be precisely determined how the set of antennas should be installed. Detailed drawings are necessary for the installation.
2.3.1.6 Superelevation or cant (Tilting of the track) in curves	Tilting will result in additional lateral errors: however, if satellites visibility is not affected by the tilting, GNSS performance should not be affected. Lateral error due to lateral displacement could be corrected if	Track database info is needed. The characteristics of the track database would depend on the train operator and could be that in some test

Source of influence	Reasoning (Pros and Cons)	Measurements Recommendation
	appropriate info is available.	operations, they are not even available or not validated. Regarding the tilting, it is also interesting to know the gradient of the track. The distance between the provided track points should be also obtained (or calculated).
2.3.1.7 Tilting trains	These are specific types of trains which round a curve at speed. It is expected that tilting of the train will result in additional lateral errors and changing the visibility of satellites but has to be measured.	It is recommended to include tilting trains during measurement campaign. The tilting information of the train should be obtained (if available) from the already information available at the train, or an attitude measurement equipment (gyroscope).
2.3.1.8 Stand still, acceleration and speed of the train	Stand still, acceleration and speed could have an influence on the accuracy of the navigation solution (user dynamics affect GNSS receiver tracking loops). When leaving a tunnel, these factors affect the time delay for a new navigation solution to be provided.	Design a test campaign where different speed (low, medium, high) and acceleration / deceleration are used at different position types (tunnels, open sky, low visibility). Perform specific test at standstill. It is necessary to have the information of the speed and acceleration synchronized with the rest of the data. A typical suitable frequency rate for train speed measurements would be between 200 ms and 1 sec.
		After booting of train protection systems, during stand still, track selective position would be useful (avoiding cold movement detection).

Source of influence	Reasoning (Pros and Cons)	Measurements Recommendation
2.3.1.9 Type of Antenna	The antenna type selection is one of the key decisions affecting the final GNSS data measurement.	The use of different kinds of antennas is desired in the measurement campaign to understand the behaviour and benefits of the different family types. Different antenna types are optimized for different applications like antenna gain and multipath rejection to improve the data measurements. The antennas could be tested in a lab scenario to calibrate the behaviour and allow a better understanding of the campaign data. A list of data to be measured and general considerations about the antennas is included: - Record received signal power density for all GNSS bands using a high resolution bandwidth in order to distinguish GNSS signal low power from noise floor density. - Record information on multipath rejection, antenna gain, antenna bandwidth. - Record carrier to noise ratio of each GNSS and SBAS satellite signal received by GNSS receiver - Record pseudo range/phase measurements, pseudo range rate, and Doppler frequency for each GNSS satellite in view - GNSS RF samples - Gain LNA - Noise figure

Source of influence	Reasoning (Pros and Cons)	Measurements Recommendation
		- Antenna impedance (reference 50 Ohm real) - Radiation efficiency (reference more than 40%) - Radiation pattern (10 dB beam width in Hemispherical) - Polarization - XPD in coverage region (reference > 10 dB) - Environmental tests followed - Performance is low elevations - Physical characteristics of the antenna (weight, height, diameter) - Electrical and mechanical interface - Temperature supported (reference -40º C to +70º C) - Vibrations tests followed (EN 61373)
2.3.1.10 Wideband antennas	Are prone to RF interference as compared to narrowband antennas. Accommodate for multiple constellation multiple frequency GNSS signals. Evaluate interference performance and compare to narrowband antennas.	See general comments related to antennas. Detailed information will be provided in [2]. Wideband omni-directional antenna covers the required 900-1800 MHz for out-of-band interference monitoring.
2.3.1.11 Narrowband antennas	Are less prone to RF interference as compared to wideband antennas. However, they accommodate for single constellation or cover a small portion of the entire specific GNSS frequency band. Evaluate interference performance	See general comments related to antennas. Detailed information will be provided in [2].

Source of influence	Reasoning (Pros and Cons)	Measurements Recommendation
	and compare to wideband antennas.	
2.3.1.12 Multi-purpose antennas (RX/COM-TX)	Single antenna for multi-purpose Are prone to RF interference as compared to single use GNSS antenna. Evaluate interference performance and compare to single-purpose antennas.	See general comments related to antennas. Detailed information will be provided in [2].
2.3.1.13 Single-purpose antennas	Evaluate interference performance and compare to multi-purpose antennas	See general comments related to antennas. Detailed information will be provided in [2].
2.3.1.14 Antenna elevation gain pattern	Low gain for low elevation antennas mitigate multipath. Understand the behaviour and benefits of this kind of antennas. Compare GNSS performance in terms of multipath error using different types of antenna elevation gain pattern with the same GNSS receiver and the same antenna location on the train.	See general comments related to antennas. Detailed information will be provided in [2].
2.3.1.15 Type of GNSS receiver	It is expected to measure different data depending on the receiver type. Different receivers are optimized for different applications and include SW algorithms to improve the data measurements.	It is of interest of the project to measure GNSS data with different types of receivers and constellations. It will be possible to make a final comparison and understand the main differences and benefits from each family type. A list of general considerations for the GNSS receivers is included: - Output data format. The use of standard data formats (as RINEX) is desirable but the priority is

Source of influence	Reasoning (Pros and Cons)	Measurements Recommendation
		to be able to store as much information provided by the receiver as possible. Evaluate if there are conversion tools from proprietary data formats. - Frequency rate: frequencies in the range of 5 Hz and 10 Hz are desirable but further investigation is needed. The frequency rate is dependent on the equipment, the data to be analysed, the storage capacity, the synchronization, the measurement campaign, the dynamic of the train, etc. - Code phase measurement or pseudo-ranges in meters (and its variance) - Carrier phase measurements in cycles (and its variance) - Doppler frequency in Hz (and its variance) - Carrier to noise ratio in dB-Hz - UTC time (or other time system if available) - Multipath correction information - Satellite Almanac data (when updated) - Satellite navigation message - Ephemeris data - Ionospheric delays - Position and velocity (in different systems if available) - DOP values - Augmentation information

Source of influence	Reasoning (Pros and Cons)	Measurements Recommendation
		(SBAS) - Other relevant data depending on the receiver
2.3.1.16 Multi-constellation and multi-frequency receivers	These types of receivers provide better availability and lower dilution of precision. Moreover they provide more output information like multipath correction, raw data, etc.	Analyse which frequencies GNSS receivers capability: GPS/Galileo: L1/E1, L5/E5a/E5b, GPS L2, GLONASS: L1, L2, EGNOS: L1
2.3.1.17 Multi-constellation and single-frequency receivers		Multi-constellation provides independent sources of information which improve the safety of the system. Main interest constellations are: GPS and Galileo. Analyse others if possible.
2.3.1.18 Single-constellation and single-frequency receivers		These are low-cost receivers, which could be valid for other applications.

Table 2: Sources of influence partially affected by human decision making

2.3.2 Sources of Influence outside human decision making

Sources of influence that are outside human decision making and has to be accepted as it is

Sources of influence	Reasoning (Pros and Cons)	Recommendation
2.3.2.1 Sky/Satellite visibility	The number of satellites in view changes depending on the environment and time. The rate of change of this parameter can be much higher than in the aviation case, as there is no guarantee of open sky conditions. As such, the PVT estimate is affected by a larger standard deviation.	- Record number of GNSS and SBAS satellites in view at GNSS receiver output - Record carrier to noise ratio of each GNSS and SBAS satellite signal received by GNSS receiver - Record GNSS and SBAS navigation data or ephemeris - Record pseudo range/phase measurements, and Doppler frequency for

Sources of influence	Reasoning (Pros and Cons)	Recommendation
		each GNSS satellite in view to derive info on pseudo range rate, cycle slips, carrier integer ambiguity - Record dilution of precision (VDOP, HDOP, PDOP, TDOP) based on satellites in view that are used for PVT - Suggested data rate for the listed measurements is 1 – 10 Hz - Record information about obstacles and sources of shading or blockage (such as buildings, foliage, bridges, tunnels) on the railway line with a granularity of a couple of meters - Record minimum satellite elevation for line of sight signal reception with a granularity of a couple of meters
2.3.2.2 Signal attenuation	It leads to more noise in GNSS pseudo range and phase measurements, carrier to noise ratio decreases and PVT estimate is affected by a larger standard deviation	- Record received signal power density for all GNSS bands - Record carrier to noise ratio of each GNSS and SBAS satellite signal received by GNSS receiver - Record pseudo range/phase measurements, pseudo range rate, and Doppler frequency for each GNSS satellite in view - Record IF samples of the GNSS received signal for signal attenuation analysis in post-processing mode

Sources of influence	Reasoning (Pros and Cons)	Recommendation
2.3.2.3 RFI coming from external sources	It may lead to loss of GNSS receiver tracking, decrease of measured signal strength, more noise in GNSS pseudo range and phase measurements, and increase of cycle slips in phase measurements. PVT estimate is affected by a larger standard deviation	- Record carrier to noise ratio of each GNSS and SBAS satellite signal received by GNSS receiver - Record received signal power density for all GNSS bands - Record received signal power density for frequency bands adjacent to GNSS - Record pseudo range/phase measurements, and Doppler frequency for each GNSS satellite in view to derive info on pseudo range rate, cycle slips, carrier integer ambiguity - Record RF samples of the GNSS received signal for RFI analysis in post-processing mode - Information of RF interference sources on a map - GNSS signal quality indicators in terms of carrier to noise ratio C/N0 and SNR - GNSS I & Q correlator outputs - Interference indicator of GNSS RX - RTK information to be compared to GT estimation
2.3.2.4 Multipath due to non-railway environment	The non-railway environment in terms of buildings and landscape is characterized by a high rate of change unlike the aviation case, as there is no guarantee of open sky conditions. PVT estimate is affected by a larger standard deviation.	- Record carrier to noise ratio of each GNSS and SBAS satellite signal received by GNSS receiver - Record multipath estimate of GNSS receiver

Sources of influence	Reasoning (Pros and Cons)	Recommendation
		- A posteriori PVT residual, w-test statistic and MDB of all measurements used in the PVT solution together with RAIM information - Record ionospheric estimate of GNSS receiver using at least two frequencies - Record pseudo range/phase measurements, and Doppler frequency for each GNSS satellite in view to derive info on pseudo range rate, cycle slips, carrier integer ambiguity - Record PVT estimated by GNSS receiver - Record ground truth position measurement Record multipath information on the basis of 3D environment modelling, 3D maps or environment characterization - Record RF samples of the GNSS received signal for multipath analysis in post-processing mode with various algorithms and GNSS receivers - RTK information to be compared to GT estimation
2.3.2.5 Atmosphere, ionosphere and troposphere propagation	Atmospheric impact is expressed in terms of signal attenuation and signal delays/advances. PVT estimate is affected by a larger standard deviation.	- Record carrier to noise ratio of each GNSS and SBAS satellite signal received by GNSS receiver - Record ionospheric estimate of GNSS receiver

Sources of influence	Reasoning (Pros and Cons)	Recommendation
		using at least two frequencies - Record scintillation indices estimate of GNSS receiver - Record tropospheric estimate of GNSS receiver - Record pseudo range/phase measurements, and Doppler frequency for each GNSS satellite in view to derive info on pseudo range rate, cycle slips, carrier integer ambiguity - Record meteorological information in terms of humidity, temperature, barometric pressure, and altitude above sea level - Record IF samples of the GNSS received signal for atmospheric propagation analysis in post-processing mode using different algorithms and GNSS receivers
2.3.2.6 Weather effects	Multipath impact can be different according to weather conditions. PVT estimate is affected by a larger standard deviation.	- Record carrier to noise ratio of each GNSS and SBAS satellite signal received by GNSS receiver - Record multipath estimate of GNSS receiver - A posteriori PVT residual, w-test statistic and MDB of all measurements used in the PVT solution together with RAIM information - Record ionospheric estimate of GNSS receiver using at least two frequencies - Record tropospheric

Sources of influence	Reasoning (Pros and Cons)	Recommendation
		estimate of GNSS receiver - Record pseudo range/phase measurements, and Doppler frequency for each GNSS satellite in view to derive info on pseudo range rate, cycle slips, carrier integer ambiguity - Record meteorological information in terms of humidity, temperature, barometric pressure, and altitude above sea level
2.3.2.7 Space weather	Errors can be strongly influenced by ionospheric behaviour due to space weather conditions	Check and store appropriate information from space weather forecast at http://www.swpc.noaa.gov/ [15]
2.3.2.8 Time errors of GNSS satellites	Affects pseudo range and phase measurements. It can lead to large PVT estimate errors.	Check GNSS global system of tracking stations (IGS) in post-processing mode to check if anomalous conditions have been witnessed and collect the IGS “A posteriori” precise clock corrections for the period encompassing the test. They are available at IGS after few days (See section 3.1.6)
2.3.2.9 Ephemeris errors of GNSS satellites	Affects pseudo range and phase measurements. It can lead to large PVT estimate errors.	Check GNSS global system of tracking stations (ex. IGS) in post-processing mode to check if anomalous conditions have been witnessed and collect the IGS precise ephemeris for the period encompassing the test. They are available at IGS after few days (See section 3.1.6)

Table 3: Sources of influence that are outside human decision making

3 SUMMARY OF MEASUREMENTS SPECIFICATION

A list of all the measurements to be collected is presented herein according to the information needed to assess the sources of influence on GNSS navigation solution (see *Table 2* and *Table 3*).

These measurements are classified into four types of measurements. Measurements related to the GNSS and SBAS signals processing, measurements related to GNSS and SBAS RF samples, measurements related to the railway environment, and measurements related to the train and are listed in the following sections.

3.1 MEASUREMENTS RELATED TO THE GNSS AND SBAS SIGNALS

Most of the measurements to be recorded described in section 2.3 are inspired by the list of GNSS measurements presented in [3] §3.2., however the measurements in the STARS context cover a wider spectrum and have to be performed considering aspects related to frequencies, constellations, elevation masks, sampling frequency, output format, synchronization, and auxiliary data. The motivation is to assess the integrity of GNSS receiver measurements and various sources of influence. Moreover, EGNOS data should be characterized in the railway environment to analyse the benefits provided by the augmentation and integrity monitoring functions.

N.	Measurement	Frequency	Resolution
1.	Time tag	10 Hz	Resolution in milliseconds, referenced to GPS time (including week number or date)
2.	Number of GNSS satellites in view	10 Hz	NA
3.	Number of SBAS satellites in view	10 Hz	NA
4.	Code phase measurements or pseudo ranges in meters and its variance	10 Hz	Resolution of at least 1 cm
5.	Carrier phase measurements in cycles or accumulated Doppler in meters and its variance	10 Hz	Resolution of at least 0.001 carrier cycles or 1 mm
6.	Doppler frequency in Hz and its variance	10 Hz	Resolution of at least 0.1 Hz
7.	Carrier to noise ratio in dB-Hz	10 Hz	Resolution of at least 0.5 dB-Hz
8.	Lock-time or duration of continuous carrier phase tracking without loss of lock or Loss of lock indicator	10 Hz	Resolution of at least 1 sec
9.	I and Q correlator outputs (real and imaginary parts) with corresponding accumulation interval in ms	10 Hz	Resolution of 0.1
10.	Multipath correction	10 Hz	Resolution of at least 1 cm
11.	GPS/ Galileo/ GLONASS Almanac data (only when it is updated)	upon new data	NA
12.	GPS/ Galileo/ GLONASS Navigation message or ephemeris data	upon new data	NA
13.	Satellite elevation and azimuth or satellite position and velocity 3D coordinates (PVTSatCartesian SBF block)	10 Hz	Resolution of 0.1°

N.	Measurement	Frequency	Resolution
14.	Ionospheric delays as decoded ionospheric data from the navigation message of GPS/ Galileo (the Klobuchar coefficients)	10 Hz	NA
15.	Ionospheric delay as GNSS RX estimate using GNSS raw data on frequencies	10 Hz	Resolution of at least 1 cm
16.	Ionospheric scintillation indices as GNSS RX estimate	1 Hz	Resolution of at least 0.1
17.	Tropospheric delay as GNSS/SBAS estimate	10 Hz	Resolution of at least 1 cm
18.	UTC time from decoded GPS navigation message and difference between UTC and UT1 time scales and difference between GPS and Galileo system time offsets	upon new data	Not critical
19.	Position and velocity in 3D ECEF Cartesian coordinate system	10 Hz	Resolution of at least 1 cm
20.	Position and velocity in geodetic coordinates (latitude, longitude, height above ellipsoid) with WGS84 datum	10 Hz	Resolution of at least 0.005 arcsec
21.	Position and velocity covariance matrices	10 Hz	NA
22.	DOP values (VDOP, HDOP, PDOP, TDOP)	10 Hz	NA
23.	Horizontal and Vertical PL	10 Hz	Resolution of at least 10 cm
24.	SBAS decoded data from all geostationary satellites that are currently tracked by the receiver or at least one geostationary satellite that is currently used by the receiver to compute PVT corrections expressed in message types (MT00 through MT07, MT09, MT10, MT12, MT17, MT18, MT24 through MT28). These include differential corrections (long term, fast and range rate corrections in case of SBAS HEALTHY satellites), age of applied corrections, satellite 3D orbit and clock corrections, ionospheric delay, variance of unmodelled error sources as tracking noise and multipath for XPL computations, and variance of tropospheric delay corrections.	As per SBAS specification	NA
25.	A posteriori PVT residual, w-test statistic and MDB of all measurements used in the PVT solution (PVTResiduals SBF block)	10 Hz	Resolution of at least 1 cm
26.	RAIM information (RAIMStatistics SBF block)	10 Hz	NA

Table 4: GNSS RX measurements

Note that these measurements are to be collected with the following specifications.

3.1.1 Constellations and Frequencies

- GNSS receiver measurements are preferably available for multiple frequencies and multiple GNSS constellations

- GNSS receiver will track PRN numbers that are operational and used for ranging. For example:
  - GPS PRN numbers between 1 and 32

- GNSS receiver will track frequencies that are operational and used for ranging.

- GNSS receiver PVT output for a safety of life application should consider appropriate frequencies, for example:
  - usage of L1 C/A frequency is indeed mandatory,
  - L5 frequency (or E5 for Galileo) are the natural candidates as they are in a frequency band reserved for radio navigation applications
  - Unfortunately at the time being L5 GPS full service is not yet operational as there is not enough GPS satellites capable to broadcast this frequency. So the fall-back will be the usage of L2 frequency. GPS L2C would be a good candidate but here again there is not enough GPS satellites in the constellation that are capable to broadcast L2C signal. So the only remaining capability is to record L2P(Y) with the drawback that this signal is very weak and difficult to track in codeless technique.
  - The conclusion about constellations to simultaneously track:
    - o GPS + GLONASS + Possibly Galileo
  - The conclusion about frequencies to simultaneously track:
    - o GPS L1 C/A, L2P(Y), L2C, L5
    - o GLONASS L1
    - o Galileo: L1, E5

3.1.2 Elevation Mask Angle

The data capture shall be done as soon as signal is tracked, no minimal elevation mask should be implemented in the receiver.

This will allow capturing all possible measurements. An analysis of what should be a reasonable elevation mask angle for train application could be done as part of captured data.

3.1.3 Pseudo range and Phase Measurements in RINEX 3.x Format

- Pseudo range measurements in terms of code are needed to have an unambiguous value, but phase measurements are also mandatory in order to be capable to smooth the code measurements thanks to phase measurements through some kind of filtering such as the Hatch filter.

- GNSS pseudo range and phase measurements should be raw measurements without any iono or tropo model corrections.

- All GNSS measurements should be made available in the de-facto standard RINEX 3.x. If it isn't available, an older version is also acceptable.

3.1.4 Navigation Data Messages to Record in RINEX 3.x Format

- All recorded GNSS receiver measurements should be accompanied by recording of SBAS message data stream from all available SBAS satellites and at least two EGNOS GEO satellites (if available). This is in order to maximize availability and be representative of normal user operational usage.

- It is necessary to record the GNSS navigation data messages received on the channels that are used to perform a navigation fix. These are:
    - GPS
        - o Recording of the messages on L1 C/A channel is mandatory.
    - GLONASS
        - o Recording of the messages on L1 C/A channel is mandatory.
    - Galileo
        - o Recording of the messages on E5a channel is mandatory
        - o Remark: Recording of the messages on E5b channel may also be done
- All GNSS measurements should be made available in the de-facto standard RINEX 3.x. If this is not available, an older version is also acceptable.

3.1.5 Auxiliary Receiver information

All other GNSS receivers' flags should also be recorded as they can be used for in-depth analysis of receiver behaviour in some specific points. Therefore, all recorded GNSS receiver measurements should be accompanied by recording of information relative to:
- RX-Status
- User Range accuracy
- Validity of measurement
- Clock update indicator (optional).

3.1.6 Auxiliary Data

In order to complement the live data recorded during the test, the following data should also be recorded for the whole duration of the test.

- IGS post processed data (precise orbits and clocks) for GPS and GLONASS satellites.
- All NANU for GPS & NAGU messages for GLONASS and Galileo, covering the experimentation period.
    - These information are available on various web sites for example
        - http://www.navcen.uscg.gov/?Do=constellationstatus
        - https://www.glonass-iac.ru/en/CUSGLONASS/
        - http://www.gsc-europa.eu/system-status/nagu-information
- All EGNOS broadcast messages obtained through the EDAS
    - See (http://www.gsa.europa.eu/egnos/edas/application-form).
    - This will allow obtaining all EGNOS messages for the two EGNOS GEO, even the messages that could not be received in real-time due to SIS blockage or interferences.
- All EGNOS RIMS data could additionally be retrieved from EDAS server
    - This could be useful if one day an analysis of EGNOS algorithms adaptation for train activity is launched.
- Effective ionospheric activity at time of test through the IONEX files available through IGS servers (see section 3.3).

- Regarding Galileo, such service centre is anticipated but not yet operational.
  - (See http://www.gsc-europa.eu/about-the-gsc/the-european-gnss-service-centre)

3.1.7 EGNOS GEO Information

Information from EGNOS geostationary satellites takes into account that:

- The receiver shall simultaneously track two operational EGNOS GEO satellites.

- EGNOS ranging function being presently inactivated, it is not mandatory to record the L1 C/A pseudo range and phases. Nevertheless, the capability to record these measurements should be planned in case GEO ranging function is re-activated in some forthcoming release.

- The data messages broadcast by each EGNOS GEO shall be recorded as well as the receiver estimated C/N0 values for GEO signal.

3.1.8 EGNOS Data Captured at the same epoch by EGNOS RIMS

In order to be in a position, if necessary one day, to adapt EGNOS algorithms to railway environment and expected service, the "STR-WP2-T-TASF- 018-001" document also proposes to capture all EGNOS information that could be needed to perform a replay with adapted EGNOS algorithms.
For this purpose, it is necessary to record during the whole period of test

- All (consolidated) GPS navigation messages received by EGNOS RIMS
- All "raw measurements" made by all EGNOS RIMS A and RIMS B. This includes L1 C/A, L2P(Y) pseudo ranges as well as phase measurements, plus associated C/N0, plus other information
- All EGNOS generated corrections messages

All this info shall be recorded at 1Hz and is to be retrieved from the EDAS FTP service. More detailed information is provided in [2].

In order to be able to perform some replay, it is necessary to leave the necessary time for EGNOS algorithms to converge. For this purpose it is necessary to start the EGNOS data capture at least 2 days before the experiment.

3.1.9 GNSS Receiver Measurements Sampling Frequency

The sampling frequency shall be at least 1Hz. If the receiver is capable to sample at a higher rate, it could be useful to sample at least pseudo range and phase measurements at this higher rate (5Hz or even 10Hz) but this is not considered mandatory for the time being. Recommended sampling frequencies are presented in Table 4. Higher sampling rates could be considered depending on the maximum speed of the train vehicle (10 Hz sampling rate on a 350 km/h running train can deliver measurements for every 10 m and this can still be not enough if PVT Information is needed at a higher spatial rate).

3.1.10 GNSS RF samples

GNSS RF samples shall be recorded with a bandwidth covering the whole frequency plan of the considered GNSS band (of the order of 20 to 24 MHz). The motivation is to consent the experimentation at RF samples level with various algorithms and receivers to characterize interference and multipath affecting GNSS signals in railway environments. If the motivation is to characterize both multipath and interference, there should be at least 16 quantization bits for each sample, on the other hand, if multipath is to be characterized while it is enough that interference be detected from the GNSS RF samples, then 2 quantization bits for each sample should be good enough.

3.1.11 RTK information for kinematic differential GNSS in post processing

Generally, the RTK operating range in terms of baseline length or distance separation between base and rover does not have an upper limit, but accuracy degrades and initialization time increases with the range from the base [16]. The typical accuracy is given by 10mm + 1ppm* (1σ horizontally and twice that for vertical) in case of single baseline RTK solution [17]. This means that for a baseline of 30km the resulting accuracy is 40mm horizontally, 80mm vertically.

To improve positioning accuracy the network RTK solution is recommended. It enables to model distance dependent errors (ionosphere, troposphere delays and sat. orbits influence) and almost eliminate the ppm component [18].

On the other hand some novel approaches appear for long range single baseline RTK solution to provide similar accuracy as short range single baseline RTK solution provides [19].

PPK should provide the same or better results than RTK.

* Different sources (e. g. [20], [21], etc.) give different accuracy e.g. 10mm+1ppm (1σ horizontally) under 10km and 20mm +1ppm (1σ horizontally) over 10km for single baseline RTK solution or 5mm +1ppm (1σ horizontally), but the difference is not significant.

3.2 *MEASUREMENTS RELATED TO THE GNSS RF SAMPLES*

These are samples of the GNSS signal down-converted either at baseband or to IF (frequency in MHz) which specifications are described in 3.1.10.

3.3 *MEASUREMENTS RELATED TO THE ENVIRONMENT*

Cartographic information has to be georeferenced to WGS84 geodetic system (the coordinate reference system used by GPS) or alternatively to a reference system that consents conversion of its coordinates into WGS84 geodetic system.

N.	Measurement	Frequency/Period	Resolution
1.	Information about obstacles and sources of shading or blockage (such as buildings, foliage, bridges, tunnels) on the railway line	5-10 meters	NA
2.	Minimum satellite elevation for line of sight signal reception with a granularity of a couple of meters	5-10 meters	1 degree
3.	Received GNSS signal power spectral density for all GNSS frequency bands (1140 MHz to 1630 MHz) using a high resolution bandwidth in order to distinguish GNSS signal low power from noise floor density.	1-10 seconds	NA
4.	Received signal power density for frequency bands adjacent to GNSS using a high resolution bandwidth in order to distinguish RFI signal power and GNSS signal power from noise floor density (900-1800 MHz frequency range).	1-10 seconds	NA
5.	Meteorological information if possible in terms of humidity, temperature, barometric pressure, and altitude above sea level	30 minutes	NA
6.	Ionospheric activity in terms of IONEX files on IGS servers **Error! Reference source not found.**	NA	NA

Table 5: Environment related measurements

3.4 MEASUREMENTS RELATED TO TRAIN

In the following, general measurements related to the train structure, operation and movement are reported. More detailed information is expected in [2]

N.	Measurement	Frequency/Period	Resolution
1.	Static information of the train characteristics (train model, type of engine, installed equipment, wheel diameter, physical characteristics, etc.)	Static information. The only measure that needs to be updated during maintenance is the wheel diameter	NA
2.	Characteristics of antenna installation	Static information	NA
3.	Information of the train status (for example if applying braking or if it is stopped)	1 sec	NA
4.	Train speed	200 ms – 1 sec	m/s (or km/h)
5.	Train acceleration/deceleration	200 ms – 1 sec	m/s2
6.	Relative distance	200 ms – 1 sec	meters
7.	Absolute distance	200 ms – 1 sec	meters
8.	Absolute position	200 ms – 1 sec	Coordinate system
9.	Tilting of train	200 ms – 1 sec	Degrees
10.	Train direction	200 ms – 1 sec	NA
11.	Pantograph status (The information can be provided by the vehicle or can be extracted from camera pictures)	1 sec	NA

Table 6: Train related measurements

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