Local GNSS Threat Detection Methods for Virtual Balise Placement in Railway Applications

Omar Garcia Crespillo
Andriy Konovaltsev
Institute of Communication and Navigation
German Aerospace Center (DLR)
Oberpfaffenhofen, Germany
{Omar.GarciaCrespillo,Andriy.Konovaltsev}@dlr.de

Juliette Marais
Univ Lille Nord de France, IFSTTAR, COSYS, LEOST,
F-59650 Villeneuve d'Ascq, France
juliette.marais@ifsttar.fr

Salvatore Sabina
Innovation & Satellite Projects Portfolio, Business Development & Innovation
Ansaldo STS
Genoa, Italy
salvatore.sabina@ansaldo-sts.com

Alessia Vennarini
Andrea Coluccia
Alessandro Neri
Radiolabs
Rome, Italy
{alessia.vennarini,andrea.coluccia, alessandro.neri}@radiolabs.it

Antonio Águila
INECO S.M.E. M.P. S.A.
Madrid, Spain
antonio.aguila@ineco.com

Elena Razzano
Francesco Ranauro
Massimiliano Ciaffi
Italian Railways Infrastructure Manager (RFI)
Rome, Italy
{e.razzano,f.ranauro,m.ciaffi}@rfi.it

***Abstract*—The introduction of the GNSS positioning technology into the evolution of ERTMS/ETCS is based on the concept of virtual balise to minimize the impact onto existing ERTMS solutions. The detection of virtual balises is foreseen by using GNSS in combination with odometry information or other kinematic sensors. However, the presence of local GNSS threats (e.g, multipath, NLOS or interference) may lead to errors in the pseudorange measurement that cannot be neither corrected by local or wide-area augmentation systems nor properly bounded, and will lead ultimately to an error in the virtual balise position that cannot be bounded with the required integrity. In order to a priori prevent the risk of this hazardous situation, virtual balises must be logically located in areas where there are not local threats that may lead a Virtual Balise Transmission System on board the train to dynamically estimate unbounded virtual balise position errors. This paper summarizes the initial work performed in the H2020 GSA Project ERSAT-GGC with respect to the different techniques that can be used to detect local GNSS threats and that can support a later classification of railway areas as suitable or not suitable for placing virtual balises.**

Keywords—global navigation satellite system, local feared event, multipath, radio frequency interference, non-line-of-sight propagation, Railway signaling

I. Introduction

The introduction of the Global Navigation Satellite System (GNSS) positioning technology into the ERTMS/ETCS specification evolution roadmap is based on the concept of Virtual Balise (VB) to minimize the impact onto existing ERTMS solutions and to guarantee the backward compatibility, protecting existing and planned investments around ERTMS and its related deployment plans.

The main Virtual Balise Transmission System (VBTS) functions are to compute the position of the train front-end to safely detect VBs and to dynamically estimate the maximum VB position error associated with the above computed train front-end position. This position error must be computed so as to bound the residual errors due to GNSS local and global environments.

When possible, the VB must be located in track areas where the area environmental permanent properties with respect to sky visibility, multipath, NLOS, in-band near-band and out-of-band interference do not lead to hazardous or unbounded threat events. The smart choice of these areas will guarantee that the Error Models used in a VBTS will bound the VB position error in accordance with the required Tolerable Hazard Rate (THR=10^{-9}/h).

In the context of the European ERSAT-GGC project, the goal of work package 4 is to develop a standard process to classify railway track areas as suitable for placing VBs or not, so as any On-Board ETCS subsystems, complied with the possible new ERTMS/ETCS specifications that include the GNSS technology, can guarantee the SIL 4 Train Position function.

From a research point of view, the challenges for the track area classification process are numerous and of various nature. First, the classification process shall be applicable on any track area by using a simple and cost effective solution. Every solution that should embed costly equipment or complex procedures or even require long-term measurement campaigns shall be excluded. Second, the state of the art for the detection of GNSS local effects often rely on mitigation techniques more than detection because they are designed for being implemented in the end-user Position Navigation Timing (PNT) platform. In the context of our objective, as the Railway MOPS has not been defined yet, the local threat events (multipath, NLOS, etc.) shall be detected independently of a specific embedded GNSS algorithm and of an on-board PNT equipment whose properties would be complied with such a Railway MOPS in the future. To this end, the decision logics defined to classify the areas have to be parametric and adaptable for enabling their future setting in accordance with the expected oncoming international recommendations and with the measurement equipment (GNSS antenna, GNSS receiver, etc.) used for the track area classification process itself. Last but not least, as GNSS constellation is moving, the process shall take into account the spatial and temporal changes of the signal reception. This introduces a great complexity in the classification process due to the needs of reducing the field measurement campaigns for logistics and cost reasons even though the process must be suitable for SIL 4 railway applications.

In this paper, we first present the different local GNSS threats relevant for the identification of railway track areas where the VBs can be logically placed. We then review relevant detection techniques and we comment on their suitability for the track area classification process. Finally, we give indications on the further necessary steps so that these techniques can be used for the later classification of railway areas as suitable or not suitable for placing VBs.

II. LOCAL GNSS THREATS

Augmentation systems mainly rely on the measurements of reference stations capable of modelling global or common mode errors such as satellites orbit and clock corrections, satellite faults, signals delays in ionosphere. The receivers of the reference stations are located in free of obstacles environments and this enables them to perfectly monitor the quality of the available GNSS signals. These systems are not designed to handle errors caused by local phenomena which are, by definition, too local to be detected by augmentation systems and to be shared by a large number of end-user PNTs.

In land transportation applications, GNSS signal often suffers from different sources of local threats that cannot be corrected by an augmentation system. In the following we detail the different local threats relevant for the track area classification: multipath, NLOS and interferences.

A. Multipath

Multipath is characterized by the reception of multiple echoes of a same signal, each of them being delayed compared to the direct path. The length of their delay depends on the distance from the obstacle. The received power depends on the surface reflection coefficient. With multipath, the received signal is a sum of signals written as:

$$s(t) = \sum_{l=0}^{N-1} A_l . D(t - \tau_l(t)) . C(t - \tau_l(t)) \exp(j\varphi_l(t)) + n(t) \quad (1)$$

With

$$\varphi_l(t) = \varphi_l(0) + 2\pi \int_0^t f_l(u) du \quad (2)$$

where N is the number of echoes and index 0 represents the direct path.

The frequency fl results of the Doppler effect caused by the relative movement of the satellites and the GNSS antenna.

Interference caused by multipath can be constructive or destructive and these characteristics will modify the output shape of the correlation used by the receiver to extract the pseudo-range information. The impact of multipath on the positioning error will depend on the distortion of the correlation.

B. Non-Line-Of-Sight (NLOS) signals

On the contrary, NLOS represents the case where the direct signal cannot be received because of the presence of a masking obstacle.

For NLOS, the correlation output is always characterized by a delay on the pseudorange estimation caused by the absence of the direct path. Attenuation of the signal power depends on the delay but also on the reflecting surface material and its coefficient of reflection.

C. Interferences

Due to the low power level of the GNSS Signal In Space (SIS) received by conventional hardware, Radio Frequency Interference (RFI) plays an important role in the definition and characterization of the EMC GNSS Receiver environment.

The impact of RFI is various, as it can result in degraded navigation accuracy or in a complete loss of signal tracking. All communication systems transmitting at carrier frequencies close to the frequency band of the GNSS receiver can be a potential source of interference [1].

The interference can be of intentional (e.g. jamming and spoofing) and unintentional (e.g. spurious emissions of other radio systems) nature. The focus of the area classification process lies on the unintentional interference which is typically of relatively low power and therefore of local nature. In contrast to jamming and spoofing which rather appear at a single place sporadically, the unintentional interferences are expected to be observed on regular basis.

III. INTERFERENCE DETECTION TECHNIQUES

In general, interference detection techniques are classified in precorrelation and postcorrelation techniques. Precorrelation techniques are applied to the spread spectrum received signal before any despreading operation while postcorrelation techniques require, as pre-condition, that the signal acquisition and tracking have been met. Therefore, the distinction between different techniques is related to the different stage of the receiver chain in which they work [1].

The next sub-section describes the following approaches:

- SQM Techniques
- Automatic Gain Control monitoring
- ADC bin histogram
- PSD monitor

A. SQM Techniques

At the correlation level, the presence of interference causes the deformation of the cross-correlation function (CCF) of the spreading code used by the navigation signal. Some GNSS receivers allow collecting several correlation results for different spacing value with respect to the prompt correlator, e.g. by using multi-correlator structures. The sampling of CCF enables to use Signal Quality Monitoring (SQM) techniques for the RFI detection [2], [3], [4].

B. Automatic Gain Control

Many papers investigated the use of Automatic Gain Control (AGC) level monitoring as an interference detection technique and demonstrated the AGC is a valuable hardware indicator to assess the presence of interfering signals. The AGC is a hardware component of most receiver front-ends aiming at adapting the receiver input gain to keep quantization losses as minimum as possible. As depicted in Fig. 1, it is normally located between the analog portion of the front-end and the Analog-to-Digital Converter (ADC) to adjust the gain of the front-end to that of ADC input range [6]. Quantization losses can occur during signal sampling and quantization and they depend on the ratio between the ADC's maximum quantization threshold, L, the number of bits utilized, and the incoming signal standard deviation, σ [7]. The AGC optimizes the L/σ ratio adapting the power of the incoming signal to minimize the digitalization losses. This functionality is implemented in any GNSS receiver that uses multibit quantization [1], [8].

The AGC level monitoring is a precorrelation technique aiming at the detection of additional signals in the receiver frequency band that are normally not present. The assumption is that interfering signals are more powerful than the authentic ones; therefore the monitoring of receiver power measurements via the observation of the AGC level variation can provide an evidence of the presence of RFI [9].

In a GNSS receiver, assuming no interference, the AGC level exclusively depends on the ambient noise environment rather than the signal power as the received signal power level is below of the thermal noise floor [8]. In case of an unlikely presence of interference, the AGC level drops sharply in response to increased power in the GNSS band. In this sense, the variation of the AGC level can be used to indicate the presence of interference [10].

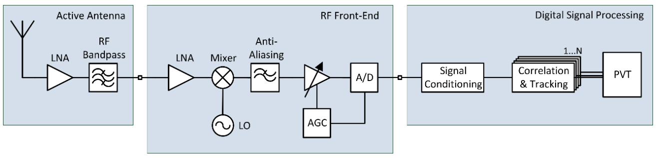

Fig. 1. Typical signal processing chain of a GNSS receiver

C. ADC bin histogram

Some GNSS receivers deliver measurements of the ADC bins histogram, which can be also used for the purposes of RFI detection [16]. The ADC bin histogram can be seen as a discretized representation of the Probability Density Function (PDF) of the amplitude of the signal at the ADC input. In an interference-free case the ADC input is dominated by the thermal noise and the amplitudes of the signal should follow the Gaussian distribution. In the case of interference, the form of the ADC bin histogram starts to deviate from the Gaussian one and a corresponding test metric can be formed to detect this deviation.

D. PSD monitor

The spectral monitoring is an interference detection technique at precorrelation level. It works in the frequency-domain via wave analysis methods applied on the GNSS SIS received at the GNSS receiver antenna.

In nominal condition, the power level of the GNSS SIS, captured at the antenna level, is below the thermal noise that it is assumed to be white over the whole digitization bandwidth. In free-interference condition, the spectral estimate of the signal, just after the receiver front-end, is given by the equivalent transfer function of the front-end, multiplied by the variance of the noise that passed through the analog front-end [1]. Therefore, an interfering signal characterized by a power level bigger than the noise power level could be detected using properly the spectral estimate of the signal in output of the receiver frond-end. In particular, this spectral estimate is compared with a spectral mask defined in nominal free-interference condition.

The spectral estimate is the computation of the Power Spectral Density (PSD) of the GNSS received signal. At this aim, several methods can be used such as normalized Fast Fourier Transform (FFT) or periodogram methods. The result of the power spectral monitoring is affected by the antialiasing filter built in receiver front end and used to attenuate the frequency components greater than the half of the sampling frequency at a level below the dynamic range of the Analog-to-Digital Converter (ADC). Otherwise, these last would appear as a signal at frequency lower than the half sampling frequency.

In particular, the parameters of the antialiasing filter of interest for the spectral estimate are the Amplitude/Gain flatness and the Flatness frequency. The Gain Flatness is the maximum variation of the filter gain in the passband. In a real filter, unlike what happens for ideal filter, the gain in the passband is not constant but it fluctuates with respect to the nominal gain up to a maximum value (Fig. 2)

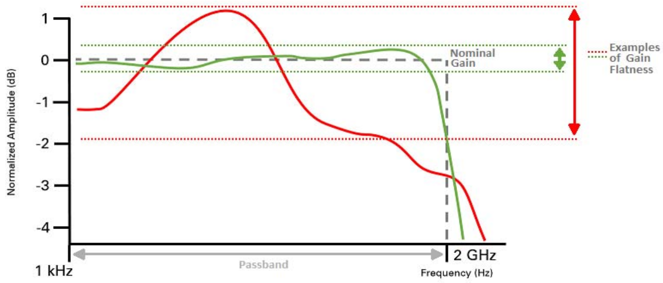

Fig. 2. Amplitude/Gain Flatness example

This parameter is important since the filter changes the frequency components amplitude of the signal in input. Therefore, the spectrum of the GNSS SIS received at the antenna level and incoming into the filter is different from the outgoing signal that it is also the estimated spectrum through Welch's method. In general, the amplitude flatness has to be as small as possible in order to have a power spectral density estimation as close as possible to the true one.

The cutoff frequency is the boundary between the passband and the transition band and the attenuation is -3dB (or half-power bandwidth) respect with the maximum nominal gain in passband.

As depicted in Fig. 3, the power drops sharply in the range between the $f_{flatness}$ and the cutoff frequency, where $f_{flatness}$ is the frequency in which the gain is below the gain flatness.

Considering the above, the flatness frequency has an important role in the identification of true measurement bandwidth for the power spectral density computation.

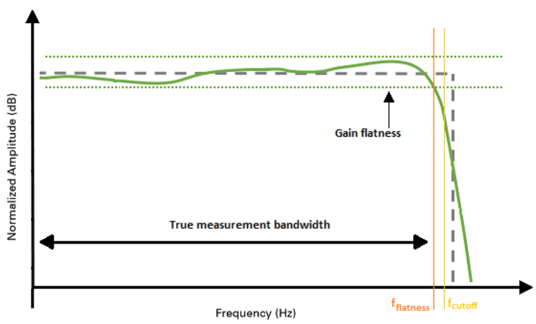

Fig. 3. True measurement bandwidth example

IV. MULTIPATH AND NLOS DETECTION TECHNIQUES

In general, the detection techniques presented in the literature have as ultimate goal the exclusion or mitigation of the multipath and NLOS in order to make the receiver more robust. In our case, we are interested in detection techniques as sensitive as possible so that we can classify and therefore protect against areas with possible risk of these threats. Nevertheless, the detection techniques found in the literature can be also used for the track area classification, just with some additional considerations that we will mentioned in Section V and VI. Furthermore, as the classification process do not necessary requires real time processing, some more techniques are available and can be studied. This section reviews some potential techniques for the detection of multipath and NLOS for the classification process.

A. SQM Techniques

Similar to the detection of radio frequency interference, the observation of the form of the PRN code correlation function can be also beneficial for detecting the effect of multipath propagation. In order to detect the presence of strong multipath echoes the signal quality monitoring approach makes use of multiple correlators placed at different early-late spacing values. The SQM test metrics are formed then from the correlator outputs in order to assess the symmetry of the correlation function as well as the difference in the steepness of the early and late slope of the function [2][3][4].

B. Pseudorange Monitors

Pseudoranges are the primary measurement that is used for the computation of position. Therefore, the presence of a multipath or NLOS signal component will corrupt already the pseudorange measurement. Local detection techniques can be therefore already designed to analyze the presence of these threats at the pseudorange level. Most common techniques include:

- Pseudorange vs smoothed pseudorange
- Code-minus-Carrier (CmC)
- CmC difference (CmCD)

A smoothed pseudorange targets to remove the low-pass components of the pseudorange measurements. That is mainly the noise and multipath. By comparing a smoothed pseudorange with the raw pseudorange, we could isolate the sudden presence of a NLOS signal or a sudden multipath component that drives the correlators away from the LOS signal. Some limitation of this technique is the fact that in order to perform some smoothing, we need the availability of several epochs continuously, which may be difficult to obtain in railway scenarios.

The difference between pseudorange and carrier-phase measurements can be used as an observable (commonly referred as code-minus-carrier (CmC)) for the multipath error, thermal noise error plus ionospheric error. This is due to the fact that the range, satellite and receiver clock biases and tropospheric delay are common to both measurements [12]. The ionospheric error cannot be directly removed since it affects with different sign each of the measurements. If the goal is to isolate the multipath error, the ionospheric error can be removed by using SBAS, by estimating the ionospheric error in post-processing with a curve fitting or by using dual-frequency measurements. This technique of pseudorange multipath isolation also relies on the fact that the thermal noise and multipath error manifestation in carrier phase measurements is negligible with respect to code phase measurements. The main limitation of this technique is the difficulty to isolate completely the multipath or NLOS signal component from the ionospheric and the carrier phase integer ambiguity that is still present in the observable.

Due to the limitations of performing most of the analysis in post-processing and the difficulty to model correctly the effect of the subtraction of the mean to the data to get rid of the integer ambiguity, another technique based on the time difference of the CmC can be also used as decision metric:

$$dz_n = \frac{|\rho_n - \phi_n| - |\rho_{n-1} - \phi_{n-1}|}{t_n - t_{n-1}}, \tag{3}$$

where the subscript n refers to the time epoch. By taking the time difference of the CmC, and assuming that no cycle slip has occurred, we eliminate the integer ambiguity term. So that:

$$dz_n = 2\dot{I} + \dot{m}_\rho + \dot{\varepsilon}_\rho, \tag{4}$$

where $\dot{I}$ is the ionospheric divergence rate, $\dot{m}_\rho$ is the multipath rate and $\dot{\varepsilon}_\rho$ is the difference of the receiver noise at the two epochs. Due to the nature of multipath and its short temporal and spatial correlation with respect to the ionospheric divergence rate, the presence of an area with high multipath will produce fast changes in the dz_n estimator. Notice that a smooth version of this difference is normally used as Code/Carrier Divergence (CCD) monitor in GBAS. In GBAS, smoothing is applied because the purpose of the monitor is to detect ionospheric fronts which are low frequency effects and therefore the interest relies on low pass filtering the measurements to reduce the noise level. In our scenario however, we are interested in the medium/high frequency of the multipath, and therefore we won't consider initially any smoothing of the differentiated CmC.

Both presented test (i.e. CmC and CmC difference) follow a Gaussian distribution and therefore suitable thresholds can be easily defined taking into account the expected variance of the distribution in the nominal case and given a certain probability of false alarm.

C. CN0 Monitors

The Carrier-to-Noise (CN0) ratio is a value that is available in commercial receivers and can therefore be used as an observable for the presence of an interferer [10]. Furthermore, relying on the principle that multipath may affect constructively or destructively in different frequencies, the comparison of CN0 ratios on multiple frequencies can be also used for multipath detection [11]. The CN0 in nominal open sky scenarios is highly dependent on the receiver configuration and the satellite signal power at the reception. This latter has been traditionally identified and modelled with respect to the elevation angle of the transmitting satellite [12]. These effects and parameters must therefore be taken into account in order to set parametrically an appropriate threshold which indicates the case where the nominal error model for a specific GNSS local threat is applicable or not, and therefore if the threat impact is bounded or not.

CN0 can be used as a criterion for NLOS/LOS detection. This requires the choice of a threshold that can be elevation-dependent. Typical CN0 values in an L1 C/A code receiver are between 37 to 45dB-Hz. The threshold will have to be chosen either theoretically or after a learning step in order to take into account the equipment used. One can found in the literature some examples of CN0 modelling of distribution that could be used as examples for multipath or NLOS detection based on CN0.

Classical models are used to model SNR distributions under LOS and NLOS hypotheses respectively with Rician and log-normal distributions as in Fig. 4 [15] (cf. - Here the SNR is represented instead CN0 but both indicate the signal strength of the different satellites they are tracking). The distribution can also be refined as a function of the satellite elevation [16].

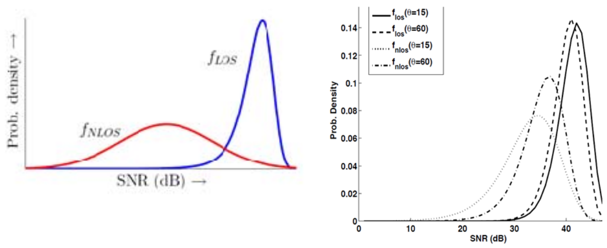

Fig. 4. The LOS/NLOS satellite channels were modelled according to Rician/log-Normal distributions (a. source: [15], b. source: [16])

D. Residual-based test

The analysis of the residuals generated after the computation of the position and time solution in GNSS has been extensively used as a fault detection method in many different transportation systems [22]. This test is part of the analysis performed in Receiver Autonomous Integrity Monitoring in civil aviation in order to assess the level of trust (i.e. integrity) of the system in a determined situation. In our situation, we will just use this fault detection mechanism as an additional test that can potentially detect the presence of NLOS pseudorange measurements.

As previously introduced, this test is based on the construction of the residual vector as main observable. The positioning problem can be expressed by the following measurement equation:

$$\mathbf{z} = \mathbf{H}\mathbf{x} + \boldsymbol{\varepsilon}, \tag{5}$$

where $\mathbf{z}$ is the normalized pseudorange measurement vector, $\mathbf{x}$ is the 3D position and time, $\mathbf{H}$ is the geometric matrix that projects the position and time to the measurement domain, and $\boldsymbol{\varepsilon}$ is the normalized noise associated to the measurements.

A least-square estimator of $\mathbf{x}$ is found by:

$$\hat{\mathbf{x}} = \underbrace{\left(\mathbf{H}^{\mathbf{T}}\mathbf{H}\right)^{-1}\mathbf{H}^{\mathbf{T}}}_{\mathbf{S}}\,\mathbf{z}. \tag{6}$$

And the residual vector $\mathbf{r}$ can be extracted as:

$$\mathbf{r} = (\mathbf{I} - \mathbf{HS})\mathbf{z}. \tag{7}$$

A test statistic can be derived with the square of the residuals:

$$\mathrm{q} = \mathbf{r}^{\mathbf{T}}\mathbf{r}. \tag{8}$$

In a fault-free situation, the test $\mathbf{q}$ follows a central chi-square distribution with n-m degrees of freedom, where n is the number of measurements and m is the number of estimated parameters (i.e., in this case 4). In case of the presence of some type of faults in the pseudorange measurements, the test will follow a non-central chi-square distribution. In order to perform the test, a threshold can be computed from the inverse cumulative density distribution given the degrees of freedom and a given probability of false alarm.

Note that this test does not give any particular information about the mode or the source of the fault. Since in the railway environment the fault modes could have in principle any profile (i.e., single and multiple/simultaneous faulty measurements with different magnitudes), it is not possible to isolate the faulty measurements without making very strong and possibly unrealistic assumptions. Therefore, this detection method should be used in this context as an additional source of information about the environment and its results should be always contrasted with other techniques.

E. Inertial sensor Monitor

An inertial measurement unit (IMU) provides with information about the dynamics of the vehicle (i.e., specific forces and angular rates) that can be integrated in order to obtain velocity and position solutions given an initial point. Since the IMU measurements are independent from GNSS, the inertial solution can be "compared" with the GNSS one to detect problems in the GNSS solution. A more typically way of coupling GNSS with inertial is with a Kalman filter. In there it is possible to couple the inertial sensor directly with the pseudorange measurements. In a similar way of the previous residual-based test, the Kalman filter can produce a residual observable (commonly known as innovation) from the difference between the inertial predicted position and the current pseudorange measurements. A test can be derived based on the innovation sequence, providing a higher sensitivity to GNSS multipath and NLOS signals due to the short term accuracy that the inertial sensor can provide [23].

F. Camera Monitor

As propagation of GNSS signal reception can be described based on the Optical geometry laws, satellite visibility in its optical sense gives good information on line-of-sight signals. Indeed, a signal received directly is received when the path between the satellite and the receiver is performed over the direct visibility line; it means that nothing interrupts the reception between us and that the propagation time of the signal will allow the optimal estimation of the distance performed. The limit between obstacle and direct visibility area corresponds to the optical horizon line.

Thus, NLOS detection can be performed based on information collected on the surroundings of the antenna with the use of an embedded camera pointing the sky, in order to identify the surrounding obstacles. With such a solution, the images are acquired with a camera placed along a vertical axis on the top of the train, close to the receiver antenna. Contrary to the use of 3D models where the user position has to be defined in the model, the acquisition point is close to the antenna and requires no additional operation. As the train path are predetermined, constrained by the tracks one single run is required for image acquisition. With images, at each instant t, and when images and GNSS data are recorded with synchronization solutions, positions of the satellites received can directly be compared to masking elevation angles detected by image processing in order to determine whether they are received directly.

This process has been used previously in the projects LOCOPROL, CAPLOC [14] and more recently, in the RHINOS project as a long term investigation area, cameras are also used for environment modelling [15].

V. CONSIDERATIONS FOR DETECTION METHOD SELECTION

The detection techniques proposed in this paper result of discussions between GNSS requirements and railway operation constraints. The classification process must be cost effective and based on techniques with a certain level of maturity that do not introduce a high level of complexity. In the same sense, the measurement equipment must be non-intrusive with respect to the vehicle. Because of these requirements, the primary equipment under consideration shall then be composed of a GNSS receiver offering multi-frequency raw data and a spectrum analyzer. In Table I, it is reported the summary of the different techniques currently under consideration in terms of different aspects like complexity and sensitivity to different local GNSS threats.

A several step approach has been chosen in order to evaluate the benefits of detection based on GNSS raw data. In a further step, data coming from other sources such as inertial sensors and a camera will be used to complement the detection techniques.

VI. DISCUSSIONS AND NEXT STEPS IN ERSAT GGC WP4

In this paper, we have presented different techniques for local GNSS threat detection that can be found in the literature and have some level of technology maturity so that they can be considered for a future railway standard process. However, the context of the threat detection techniques is normally slightly different from the purpose presented in this paper. Whereas these techniques are normally used in the final GNSS receiver in order to guarantee as much as possible the integrity of the position solution and therefore it is used as a countermeasure, within the context of ERSAT GGC project, the main goal is the classification of track areas as suitable or not suitable for placing virtual balises. In this sense, there are several remaining challenges that prevent these detection techniques from being completely suitable for the survey process.

The detection techniques should satisfy therefore that the final Virtual Balise Transmission System must not experience a GNSS measurement behavior due to local threats worse than the receiver and techniques used for the classification if used in the same conditions. This is especially critical since there is not available currently a definition or specification of a railway receiver MOPS. The detection techniques and the parameters used in order to extract the observables shall be designed in such a way that the results bound in a worst case sense the performance of any receiver with other parameters.

Next steps of work in this objective is the development and assessment of the here mentioned techniques on known and representative datasets. Apart from the local threats, the VBs shouldn't be placed in locations where we can expect a limited number of visible satellites. Therefore, the classification process will also take into account the detection of areas with degraded GNSS performance.

VII. CONCLUSIONS

In the last years, GSA, ERA, ESA S2R and some railway IMs have setup innovation activities with the main objective to define and implement a common R&D framework where the evolution of the ERTMS/ETCS specification roadmap can be implemented. The introduction of the GNSS Positioning technology has been recognized as one of the main key contributors for the future signaling system/concept.

In this context, the definition of the Virtual Balise Transmission System (VBTS) as one functional block of the new possible ERTMS/ETCS functional architecture has been started. Therefore, new ERTMS/ETCS specifications shall include the minimum performance, safety and operational requirements (MOPS) required for guaranteeing the interoperability among ERTMS constituents of different suppliers.

Consequently, any On-Board subsystem will run safely on any Trackside subsystem, provided that they are both compliant with the new expected ERTMS specifications, and that the trackside has been designed and developed to enable the On-Board subsystem to manage GNSS system and local hazard causes and to protect the train. These protections work safely and properly only if the VBTS error models and the GNSS monitoring techniques, implemented in the VBTS to bound the virtual balise position errors, are valid along all the track areas where the train can run.

ERSAT-GGC is the first project that addresses the aspects of the classification of the track areas, where VBs can be (logically) placed, to a priori prevent the risk of these unbounded position errors due to area environmental permanent properties with respect to sky visibility, multipath, NLOS, and in-band and near out-of-band interference. We think that the ERSAT-GGC project can be considered as the pioneer R&D project on this critical and important R&D topic.

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References

[1] F. Dovis, GNSS Interference Threats and Countermeasures, Artech House, 2015.

[2] M. Irsigler, "Multipath Propagation, Mitigation and Monitoring in the Light of Galileo and the Modernized GPS", Ph.D. Thesis, Bundeswehr University, Munich, Germany, 2008.

[3] A. Pirsiavash, A. Broumandan, G. Lachapelle, "Characterization of Signal Quality Monitoring Techniques for Multipath Detection in GNSS Applications", *Sensors*, vol. 17(7), 1579, 2017.

[4] A. Gostishchev, F. Fohlmeister, A. Konovaltsev, "Robust Multipath Detection by Intra- and Inter-Domain Fusion with Real-Time Capability," Proceedings of IEEE/ION PLANS 2018, Monterey, CA, April 2018, pp. 605-614.

[5] The Royal Academy of Engineering, "Global Navigation Space System: Reliance and Vulnerabilities," 2011. [Online]. Available: https://www.raeng.org.uk/publications/reports/global-navigation-space-systems.

[6] D. Akos, "Who's Afraid of the Spoofer? GPS/GNSS Spoofing Detection via Automatic Gain Control (AGC)," Journal of Navigation, vol. 59, no. 4, pp. 281-290, 2012.

[7] H. Borowski, O. Isoz, F. M. Eklöf, S. Lo and D. Akos., "Detecting False Signals with Automatic Gain Control," GPS World, 29 February 2016. [Online]. Available: http://gpsworld.com/detecting-false-signals-automatic-gain-control-1280.

[8] F. Bastide, D. Akos, C. Macabiau and B. Roturier, "Automatic Gain Control (AGC) as an Interference Assessment Tool," in ION GPS, Portland, 2003.

[9] E. G. Manfredini, D. M. Akos, Y.-H. Chen, S. Lo, T. Walter and P. Enge, "Effective GPS Spoofing Detection Utilizing Metrics from Commercial Receivers," in Proceedings of the 2018 International Technical Meeting of The Institute of Navigation, Reston, VA, 2018.

[10] M. Z. H. Bhuiyan, H. Kuusniemi, S. Söderholm and E. Airos, "The Impact of Interference on GNSS Receiver Observables – A Running Digital Sum Based Simple Jammer Detector," September 2014, Radioengineering 23(3):898-906.

[11] Marais, J., Flancquart, A., & Lefebvre, S. (2006). Satellite availability in a railway mountainous environment: Can we use satellite positioning for safety applications? In World Congress on Railway Research (WCRR), Montréal.

[12] Marais, J., Meunier, B., & Berbineau, M. (2000). Evaluation of GPS availability for train positioning along a railway line. In Vehicular Technology Conference, 2000. IEEE-VTS Fall VTC 2000. 52nd (Vol. 5, pp. 2060-2067).

[13] R. Calcagno, S. Fazio, S. Savasta and F. Dovis, "An interference detection algorithm for COTS GNSS receivers," in *5th ESA Workshop on Satellite Navigation Technologies and European Workshop on GNSS Signals and Signal Processing (NAVITEC)*, Noordwijk, 2010.

[14] P. R. R. Strode and P. D. Groves, "GNSS multipath detection using three-frequency signal-to-noise measurements," *GPS Solutions,* vol. 20, pp. 399-412, 01 7 2016.

[15] J.-H. Wang and Y. Tao, "High-Sensitivity GPS data classification based on signal degradation conditions," *IEEE Transaction on Vehicular Technology,* vol. 56, no. 2, 2007.

[16] J. Marais, C. C. Meurie, D. Attia, Y. Ruichek and A. Flancquart, "Toward accurate localization in guided transport: combining GNSS data and imaging information," Transportation Research Part C: Emerging Technologies, vol. 43, pp. 188-197, 2014.

[17] S. Tay and J. Marais, "Weighting models for GPS pseudorange observations for land transportation in urban canyons," in 6th European Workshop on GNSS Signals and Signal Processing, Munich, 2013.

[18] S. Roberts, "Railway environment modelling," in RHINOS project workshop, Stanford, CA, USA, 2016.

[19] T. Suzuki and N. Kubo, "N-LOS GNSS signal detection using fish-eye camera for vehicle navigation in urban environments," in *In Institute of Navigation, the 27th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2014)*, 2014.

[20] A. T. Irish, J. T. Isaacs, F. Quitin, J. P. Hespanha and U. Madhow, "Belief propagation based localization and mapping using sparsely sampled GNSS SNR measurements," in IEEE International Conference on Robotics and Automation (ICRA), Hong Kong, China.

[21] J. T. Isaacs, A. T. Irish, F. Quitin, U. Madhow and J. P. Hespanha, "Bayesian localization and mapping using GNSS SNR measurements," in IEEE/ION Position, Location and Navigation Symposium (PLANS), Monterey, California, 2014.

[22] A. Grosch, O. García Crespillo, I. Martini and C. Günther, "Snapshot residual and Kalman Filter based fault detection and exclusion schemes for robust railway navigation," 2017 European Navigation Conference (ENC), Lausanne, 2017, pp. 36-47.

[23] O. García Crespillo, A. Grosch, J. Skaloud, M. Meurer, "Innovation vs Residual KF Based GNSS/INS Autonomous Integrity Monitoring in Single Fault Scenario," Proceedings of the 30th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2017), Portland, Oregon, September 2017, pp. 2126-2136.

GNSS Techniques comparison				
Detection Technique	***Input Data***	***Targeted Local GNSS threat***	***Receiver parameters to be considered***	***Pros and Cons***
AGC monitor	AGC value	Radio frequency interference	Receiver noise figure	Low complexity; AGC values are not a part of standardreceiver messages, but often available as a part of the receiver status information
PSD monitor	I/Q samples or spectral information	Narrowband or partial-band radio frequency interference	Noise figure of recording system	High complexity; Big amount of data to be stored and processed
Test of PVT Residuals (RAIM like)	Code- and Carrier Pseudoranges, Doppler	NLOS, strong multipath	tracking loops bandwidth and integration time: these affect the nominal ranging error	Moderate complexity; Cost-effective
Raw pseudorange minus Carrier-smoothed pseudorange	Code pseudorange and carrier phases	Receiver Noise and Multipath	As above. Also, the smoothing time of the hatch filter.	Low complexity
Code-Minus-Carrier Divergence (CMCD)	Code- and Carrier Pseudoranges	Multipath	tracking loops bandwidth, correlator spacing and integration time: these affect the nominal ranging error	Low complexity; It can be performed in principle with any receiver.
Observation of Carrier to Noise ratio (CN0)	CN0 measured values	Radio frequency interference, Multipath	Receiver noise figure	C/N0 values are available from almost any type of data formats, e.g. NMEA, RINEX, proprietary binary formats
Variation of CN0 at different carriers	CN0 measurements at multiple carriers (e.g. E1 & E5a)	Multipath, Radio frequency interference	Receiver noise figure	Low Complexity

Table 1 Summary of different techniques