Characterization of GNSS Multipath in Nominal Open-Sky Scenario for Safe Railway Localization

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Abstract: *Railway transportation systems have high accuracy and high integrity demands for safe localisation. There has been an increased interest in using GNSS (Global Navigation Satellite Systems), but its position determination in urban environment can be highly degraded because of the presence of reflected signals (i.e. multipath). This paper tackles the characterisation of multipath in code measurements caused exclusively by the vehicle and the antenna installation. First, Code-Minus-Carrier (CMC) method for autonomously isolating multipath is presented. Second, an error model of the isolated multipath based on Gaussian overbounding is derived. The presented methodology is supported by real measurements collected in an open-sky Railway scenario with a commercial and an experimental train.*

1. Introduction

Railway transportation systems like train signalling or automatic train control require accurate and robust localization solutions for safe operations. For these, Global Navigation Satellite Systems (GNSS) are envisioned to play a major role to achieve the high accuracy, high integrity localization demands and to reduce costs in infrastructure implementation and maintenance by relying mainly on onboard equipment. However, GNSS positioning can be challenging in railway environments because the GNSS signals can be highly affected by multiple reflections (i.e. multipath) and other GNSS threats like non-line-of-sight (NLOS) signals or the presence of interferences. In particular, multipath is considered to be one of the largest sources of ranging errors in urban environments because it is highly environmental dependent, which makes it difficult to predict and to characterize.

Previous work mitigating, detecting or estimating multipath can be classified depending on the GNSS receiver processing stage in which the techniques or algorithms are proposed.
At the antenna and front-end levels, choke-ring antennas are widely used at ground stations to mitigate multipath [1]. Dual polarization antennas are also proposed to estimate and remove multipath signals components [2], [3]. At the correlator signal processing level, several techniques can be very powerful to estimate and mitigate multipath [4]. For example, multicorrelator structures used in signal quality monitoring [5] have shown great potential to reduce or reject the impact of multipath [6]. Finally, at the post-correlation domain, most techniques are mainly focus on code multipath modelling (e.g., for aviation applications [7]), detection [8] or their adjustment at position estimator level [9].The main advantage of dealing with multipath at this stage is that algorithms can be implemented with cost-of-the-shelf antennas and receivers, and they do not rely on complex techniques. This make them cost efficient solutions that may be interesting for certain applications.
However, the detection or estimation of multipath at post-correlation level typically relies on some statistical knowledge or assumption about the nominal or faulty model of the error [10].

Due to the complex and varying environment in land-based applications, it is not possible in general to derive a multipath model suitable for any situation that can be used for safety-related applications as it is typically proposed in aviation [7]. However, the impact of antenna installation, vehicle antenna surroundings and receiver configuration are expected to have some level of consistent impact on multipath independently of the dynamic environment [11].

In this paper, we propose to separate the total contribution of multipath on code measurement error between the expected permanent effects (such as antenna, installation and receiver configuration) and the additional varying multipath contribution due to buildings, trees, or the presence of other objects along a vehicle trajectory. We assume that to either detect code measurements with large multipath error or adapt their model in dynamic scenarios, the statistical information about the permanent static multipath is essential. This paper focus on the development of a methodology to derive a reference model for the permanent multipath by means of data collection in a controlled, static and open-sky scenario.

In order to do that, we first introduce the Code-Minus-Carrier method for isolating multipath errors from other GNSS system and atmospheric errors. Then, Gaussian overbounding is used to derive conservative error models on data collected with a train in an open-sky scenario. The implications and use cases of the derived models and methodology are finally commented.

2. Methodology

2.1. Approach to handle multipath for urban environments

GNSS user equipment can receive reflected signals in addition to or instead of the direct path signals from a given satellite. According to [12], most signal reflections for land applications are caused by the surrounding environment. Those reflections are mostly caused by the ground, surrounding buildings and structures, other vehicles and trees. Contrary to that, the most commonly occurring reflections in air, sea and space applications are caused by the vehicle structure and the antenna installation. Even though it is not the main cause of multipath error, the multipath error caused by the vehicle structure and the antenna installation are also present in land applications. In this work, we differentiate between the multipath error in code measurements when the vehicle is moving and experiencing a changing environment and the multipath caused by the vehicle and the antenna installation which is expected to have similar stochastic properties for a given satellite elevation and azimuth with respect to the user. Consequently, and in order to create a nomenclature distinction, the multipath caused by the vehicle structure and antenna structure are, in this paper, referred to as permanent multipath.

An approach to isolating and overbounding multipath errors of data collected during static measurements was presented in [13]. However, in [13], the authors overbound the errors only as a baseline for further analysis. In addition, when the measurements are collected the antenna is not installed on a vehicle, for that reason the multipath caused by the vehicle and the antenna installation cannot be assessed.
Characterizing the permanent multipath independently can allow to better understand in a second step the impact the surroundings has on the pseudorange error independently of the antenna installation. Furthermore, it is possible to derive thresholds based on the permanent multipath models to build a fault detection and exclusion algorithm for pseudoranges with large multipath error in dynamic situations. Derivation of FDE techniques for multipath in code measurements

has already been developed and implemented for example in [14]. In addition, an error model of permanent multipath can be used as a reference model for similar application, similar vehicles or similar antenna installations.

2.2.Multipath Isolation

In order to isolate multipath from other GNSS systems and atmospheric error sources, different techniques exist [15]. In this paper, we select the Code-Minus-Carrier (CMC) method [16] because it can be implemented with cost-off-the-shelf antennas and because its overall maturity in other applications like Ground-based Augmentation Systems (GBAS) [17].

The code (pseudorange) measurements and the carrier phase measurements for a single receiver, satellite *s* and frequency *j* at a certain time epoch *k* can be expressed with the following expressions:

$$\rho_k^{s,j} = \left||x_k^s - x_k|\right| + b_k - b_k^s + T_k^s + I_k^{s,j} + K_k^j - K_k^{s,j} + MP_k^{s,j} + \varepsilon_k^{s,j}, \quad (1)$$

$$\Phi_k^{s,j} = \left||x_k^s - x_k|\right| + b_k - b_k^s + T_k^s - I_k^{s,j} + K_k^j - K_k^{s,j} + N_{j,k}^s\lambda_j + mp_k^{s,j} + \xi_k^{s,j}. \quad (2)$$

Where $\left||x_k^s - x_k|\right|$ is the true geometric distance between the satellite s (x_k^s) and the receiver (x_k), b_k, b_k^s are receiver clock bias and satellite s clock bias from GNSS time scale, T_k^s is the tropospheric error, $I_k^{s,j}$ is the ionospheric error all given in meters. K_k^j is the receiver instrumental (hardware) delay, $K_k^{s,j}$ is the satellite instrumental (hardware) delay, $N_{j,k}^s$ is the carrier phase integer ambiguity given in cycles, λ_j is the corresponding wavelength of the frequency j. Lastly, $MP_k^{s,j}$ is the multipath error of code measurements and $mp_k^{s,j}$ is the multipath error of carrier phase measurements, both in meters. While $\varepsilon_k^{s,j}$ and $\xi_k^{s,j}$ represent the residual noise errors in meters for code measurements and carrier phase measurements respectively.

The CMC is computed by calculating the difference between pseudorange measurements and the corresponding carrier phase measurements. The CMC observable is:

$$CMC_k^s = \rho_k^s - \Phi_k^s = MP_{\rho,k}^s + (2I_k^s - \lambda N_k^s) + (\varepsilon_k^s - mp_{\Phi,k}^s - \xi_k^s). \quad (3)$$

The CMC combination removes the clock errors, tropospheric delays and ephemeris errors. However, what remains is the code multipath error, carrier-phase multipath error, code and carrier-phase noise, carrier-phase ambiguities and twice the ionospheric delay. Since the carrier-phase multipath and the carrier-phase noise are of several orders of magnitude smaller than the code multipath and noise, it is commonly assumed carrier-phase multipath and noise are negligible when compared to code multipath and noise.

In order to isolate the code multipath twice the ionospheric error and the integer ambiguity term have to be removed. The ionospheric error can be removed by using two carrier-phase measurements following the approach in [7]. The created linear combination of the carrier-phase ambiguities can be removed using the fact that the integer ambiguities remain constant during a continuously tracked and cycle slip free period [10], this bias can be estimated by averaging and removed.

The main advantage of the Code-Minus-Carrier method is that the method does not need any augmentation system information and it is not computationally heavy. Notice that with this method it is not possible to differentiate between noise and multipath and therefore the isolation of multipath with CMC includes the noise error term.

2.3. Conservative Multipath Error Modelling

This section provides a methodology for deriving an error model of the permanent multipath caused by the vehicle structure and antenna installation based on a two-step Gaussian of the previously isolated carrier-phase multipath and noise errors.
In general, as presented in [18], the overbounding methodology can be divided into two steps. First step being determining the probable distribution of errors which is done by collecting a sample distribution. However, the collected sample should be such that the error distribution of the sample data is representative of the error distribution of the desired environmental situation that is being modelled. Second step is to prove that the collected empirical set of errors can be replaced by a simpler distribution. According to [19] that simpler distribution is most commonly the normal distribution since it is the only finite variance distribution that remains stable through convolution. Therefore, the residual multipath error distribution can be bounded using a Gaussian distribution.

Overbounding can be done by utilizing the Cumulative Density Function (CDF) as presented in [19]. According to this approach the left-hand side of the CDF and the right-hand side are separately calculated. The idea of [19] is that of combining the two methods. Where first an intermediate symmetrical unimodal distribution that overbounds the actual distribution in the sense of paired overbounding is introduced. Second, Gaussian overbound of the intermediate distribution is determinate. In this way the prerequisite of having a symmetric and unimodal distribution is bypassed.

3. Experimental setup

Data collected with two different antenna installations on two different trains was used for the derivation of errors in this paper. First data set was collected during a measurement campaign in Cagliari, Italy. In an open-sky and static conditions during a course of 32 hours. The location of the train during the data recording is depicted in Fig. 1. The setup consisted of a commercial train ALn668-3136 from Trenitalia. The GNSS antenna installed on the train was Antcom G5 (Fig. 2) antenna and it was internally connected with a Javad Delta-3N receiver. The receiver was collecting raw measurements with a sampling rate of 10 Hz.

Figure 1. Location of the train during data acquisition, Italy.

Figure 2. Antenna installation, Italy.

The second data set was collected during a measurement campaign in Almorchon, Spain, in an open-sky and static environment Fig. 3 and over 8 hours. The setup consisted of a train from ADIF and an Antcom G8 antenna (Fig. 4) which was internally connected to a Javad Delta-3 receiver. The raw measurements were collected with a same sampling rate as in the Italian setup of 10 Hz.

Figure 3. Location of the train during data acquisition, Spain.

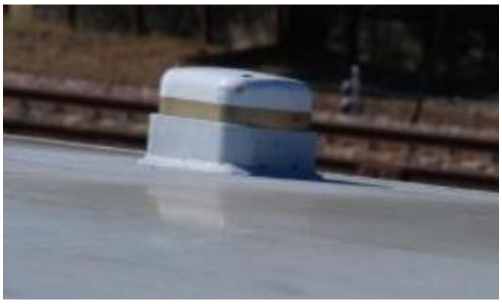

Figure 4. Antenna installation, Spain.

4. Result

Permanent multipath was isolated and the conservative error models were derived for both the Italian and Spanish measurement locations.

4.1.Permanent Multipath Isolation

Since the measurements were conducted in an open-sky and static conditions (Fig. 1 and Fig. 3) without any surrounding buildings and objects in imminent vicinity, it is presumed that the isolated multipath and noise is caused by the vehicle structure and the antenna installation. The estimated multipath error caused by the vehicle structure and the antenna installation as well as its distribution with respect to the satellite elevation for both Italian and Spanish location of the GPS L1 is showed in Fig. 5 and Fig. 6.

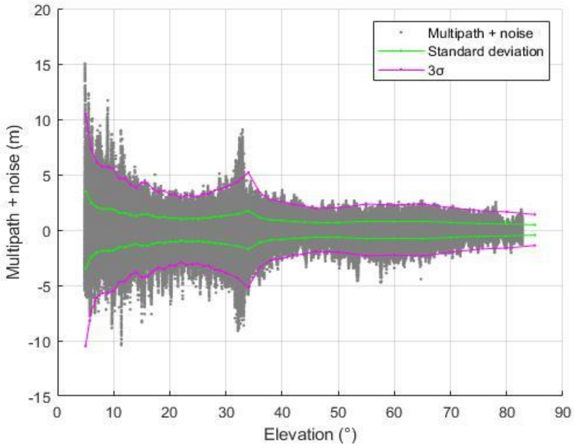

Figure 5. Multipath, noise and standard deviation for GPS L1, Italy.

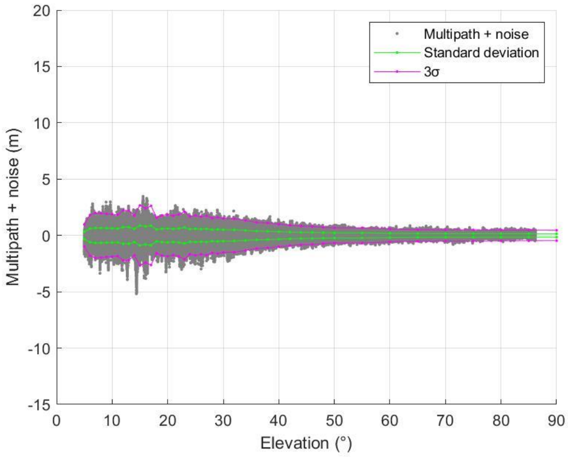

Figure 6. Multipath, noise and standard deviation for GPS L1, Spain.

Additionally, the empirical standard deviation and empirical 3-sigma (99.7 %) is also included. The axes of both plots have been adjusted for easier comparison.

As we can see, the magnitude of the isolated permanent multipath error in Italy at certain satellite elevations reaches an absolute error of almost 10 meters. The significant magnitude of the permanent multipath and noise observed prompted us to characterizing multipath and permanent multipath separately. Characterizing them separately will allow for a better understanding of the impact the surrounding has on the pseudorange error independently of the vehicle structure and antenna installation.

4.2. Overbounded Multipath Error Model

After we isolated the multipath caused by the vehicle structure and the antenna installation from other ranging errors, we proceeded with deriving the overbounding models of the isolated error. The overbounded model used is a zero-mean Gaussian distribution. Multipath errors were separated in 5° bins based on the elevation angles of the satellites. The distribution of samples per elevation bins is such that less samples are contained in low elevation bins (0°-5° and 5°-10°) and high elevation bins (80°-85° and 85°-90°). With all other elevation bins exceeding 50 000 samples.

The Gaussian overbound is computed separately for the left- and right-hand side. Fig. 7 and Fig. 8 show the largest sigma between the left and the right-sided values of the Gaussian overbound.

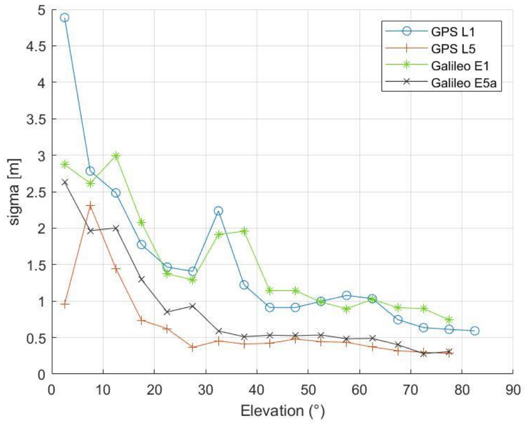

Figure 7. 1 sigma of overbounding Gaussian model for different elevations, constellations and frequencies, Italy.

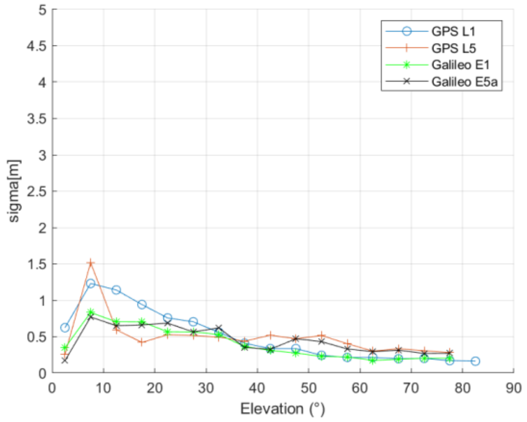

Figure 8. 1 sigma of overbounding Gaussian model for different elevations, constellations and frequencies, Spain.

Fig. 9, Fig. 10, Fig. 11 and Fig. 12 present the cumulative density function of the obtained permanent multipath estimation for different satellite elevations. Multipath and noise is given in meters and the satellite elevation in degrees.

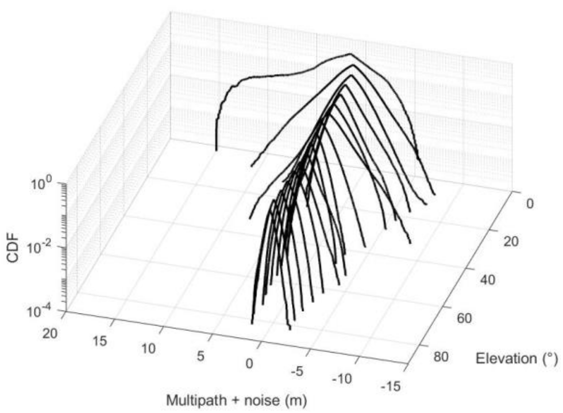

Figure 9. Folded CDF, multipath and noise per elevation bins, GPS L1, Italy.

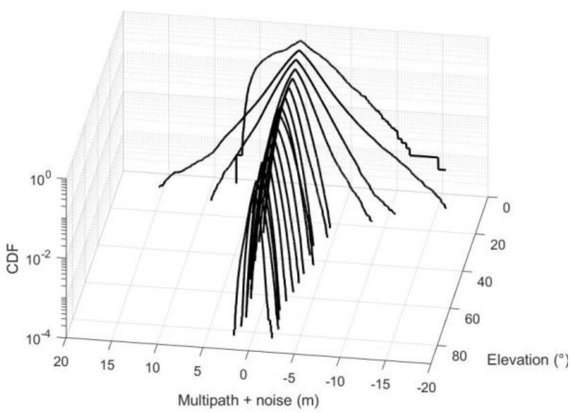

Figure 10. Folded CDF, multipath and noise per elevation bins, GPS L2, Italy.

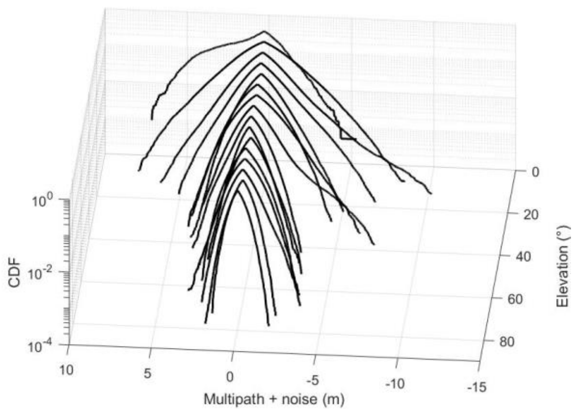

Figure 11. Folded CDF, multipath and noise per elevation bins, Galileo E1, Italy.

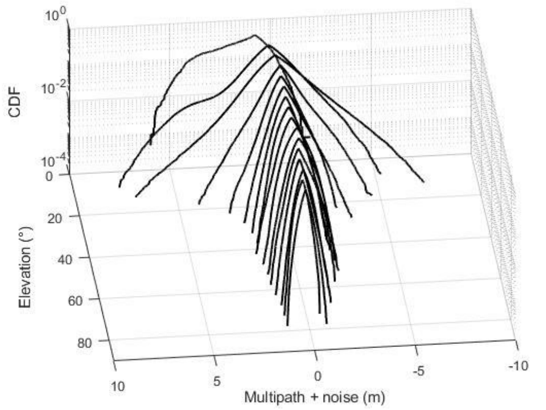

Figure 12. Folded CDF, multipath and noise per elevation bins, Galileo E5a, Italy.

5. Conclusion

In this work, we showed with an example that the permanently present multipath caused by the antenna installation and the vehicle structure can cause significant pseudorange errors. We show the magnitude of the permanent multipath by comparing two different antenna installations. In the first installation the GPS L1 may be more subjected to reflections in the vicinity of the antenna, which can be observed by the increase of the isolated multipath error around 30-40 degrees. By showing that, we propose separate characterization of the multipath caused by the surroundings and the multipath caused by the antenna installation when high accuracy and high integrity solutions are needed. However, this methodology can only be implemented if a long static, open-sky measurement is collected, which allows for successful isolation of the permanent multipath.

This paper develops a methodology to derive a reference model for the permanent multipath, and future work will tackle the use of these models for detection or adaptation of multipath in the dynamic scenarios and adaptation of antenna installations. The proposed modelling of multipath in open-sky and static scenario provides a reference model that can be used to detect significant high multipath caused by the surroundings or other objects. For example, it can be used as a reference model for a fault detector. The model can also be used as a reference model to normalize the measurements for further processing.

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References

[1] S. Hilla and M. Cline, "Evaluating Pseudorange Multipath Effects at Stations in the National CORS Network," *GPS Solutions,* no. 7, p. 253–267, 2004.

[2] D. Manandhar, R. Shibasaki and P.-L. Normark, "GPS Signal Analysis Using LHCP / RHCP Antenna and Software GPS Receiver," in *ION GNSS*, 2004.

[3] Z. Jiang and P. Groves, "NLOS GPS Signal Detection Using a Dual-Polarisation Antenna," *GPS Solut,* vol. 18, pp. 15-26, 2014.

[4] N. Blanco-Delgado and F. Nunes, "Multipath Estimation in Multicorrelator GNSS Receivers Using the Maximum Likelihood Principle," in *ION GNSS*, 2012.

[5] A. Iliopoulos, C. Enneking, O. Garcia Crespillo, T. Jost, S. Thoelert and F. Antreich, "Multicorrelator Signal Tracking and Signal Quality Monitoring for GNSS with Extended Kalman Filter," in *IEEE Aerospace Conference*, 2017.

[6] C. Siebert, A. Konovaltsev and M. Meurer, "Multipath Rejection Using Multi-Frequency Multi-Correlator Based GNSS Receiver With an Extended Kalman Filter," in *2022 International Technical Meeting of The Institute of Navigation*, 2022.

[7] M. -S. Circiu, Integrity Aspects for Dual-frequency Dual-Constellation Ground Based Augmentation System (GBAS), Dissertation, RWTH Aachen, 2020.

[8] A. Grosch, O. Garcia Crespillo, I. Martini and C. Günther, "Snapshot Residual and Kalman Filter Based Fault Detection and Exclusion Schemes for Robust Railway Navigation," in *2017 European Navigation Conference (ENC)*, 2017.

[9] O. Garcia Crespillo, A. Grosch, P. A. Adjroloh, C. Zhu, R. Capua, F. Frittella and O. Kutik, "Multisensor Localization Architecture for High-Accuracy and High-Integrity Land-based Applications," in *ION GNSS*, 2022.

[10] M. Caamano, O. Garcia Crespillo, D. Gerberth and A. Grosch, "Detection of GNSS Multipath with Time-Differenced Code-Minus-Carrier for Land-Based Applications," in *2020 European Navigation Conference (ENC)*, Dresden, 2020.

[11] S. Caizzone, M. -S. Circiu, W. Elmarissi, C. Enneking, M. Rippl and M. Sgammini, "On the Role of the Antenna on GNSS Pseudorange and Multipath Errors and its Impact on DFMC Multipath Models for Avionics," *Navigation, Journal of the Institute of Navigation,* vol. 69, no. 3, 2022.

[12] P. Groves, Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems, Second Edition, Boston, London: Artech house, 2013.

[13] S. Khanafseh, B. Kujur, M. Joerger, T. Walter, S. Pullen, J. Blanch, K. Doherty, L. Norman, L. de Groot and B. Pervan, "GNSS Multipath Error Modeling for Automative Application," in *ION GNSS*, 2018.

[14] S. Rogothaman, M. Maaref and Z. M. Kassas, "Multipath-Optimal UAV Trajectory Planning for Urban UAV Navigation with Cellular Signals," in *IEEE 90th Vehicular Technology Conference*, 2019.

[15] A. Pirsiavash, A. Broumandan, G. Lachapelle and K. O'Keefe, "GNSS Code Multipath Mitigation by Cascading Measurement Monitornig Techniques," *Sensors,* vol. 18, no. 6, 2008.

[16] M. S. Braasch, "Isolation of GPS Multipath and Receiver Tracking Errors," *Navigation,* vol. 41, no. 4, pp. 415-435, 1994.

[17] RTCA/SC-159, "RTCA/DO-253D: Minimum Operational Performance Standards for GPS Local Area Augmentation System Airborne Equipment," RTCA, 2017.

[18] J. Blanch, T. Walter and P. Enge, "Gaussian Bounds of Sample Distributions for Integrity Analysis," *IEEE,* vol. 55, no. 4, pp. 1806-1815, 2018.

[19] J. Blanch, T. Walter and P. Enge, "A Method to Determine Strict Gaussian Bounds of a Sample Distribution," in *ION GNSS* , 2017.