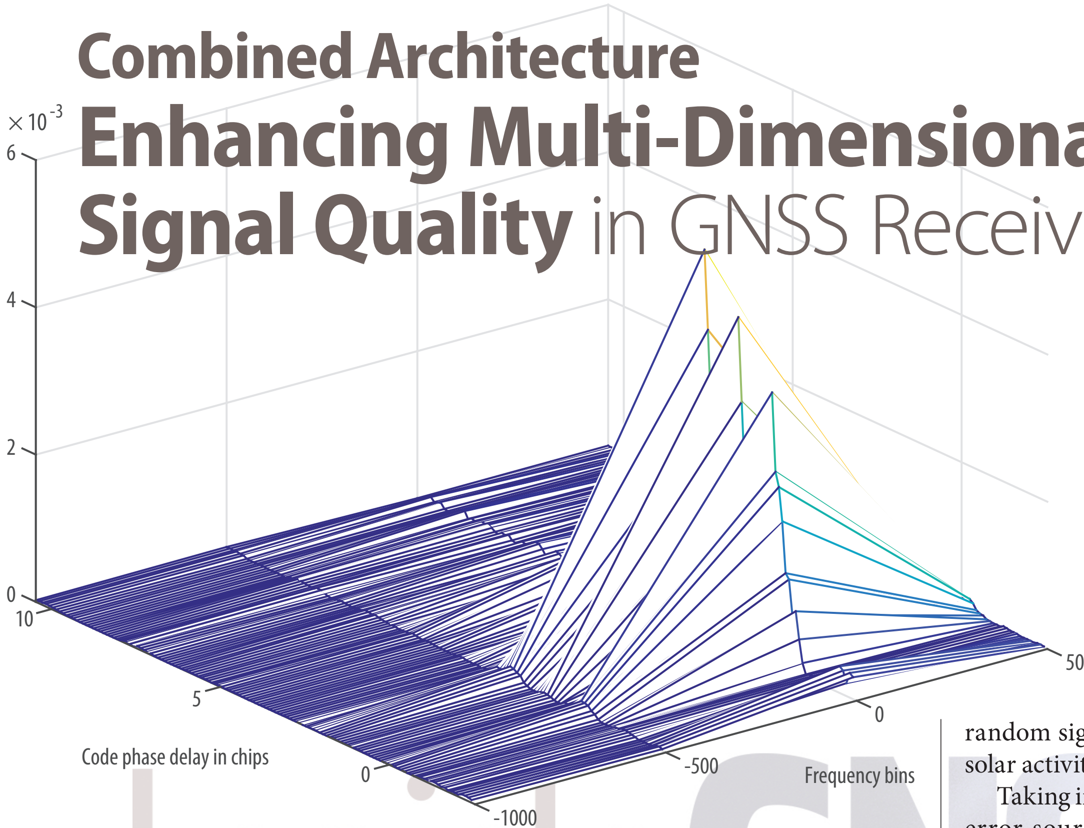
Combined Architecture Enhancing Multi-Dimensional Signal Quality in GNSS Receivers



Multipath effects: time acquisition mesh generated at 45 dB-Hz for GPS signal for a fading channel with 4 paths; the fading channel model has a power decay profile (PDP) with a coefficient of 0.5;

Multipath, interference, and ionospheric effects represent some of the leading sources of error affecting GNSS signals. This article proposes a combined architecture for future GNSS receivers that addresses all three.

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The success of GNSS caused the technology to become a standard and essential tool for navigation in several markets, such as transportation, civil engineering, precise agriculture, and time reference. However, GNSS systems are vulnerable to a range of threats related to the transmitter or receiver systems, the propagation channel, and external interferences.

Multipath, interference, and ionospheric distortions are three main error sources in satellite-based positioning. Global navigation satellite systems were designed to operate in perfect line-of-sight conditions. However, the GNSS observables are highly influenced by signals reaching the receiver along multiple propagation paths (multipath) in locations with increased possibility of reflection or refraction of the signal, such as urban scenarios. Furthermore, due to their very low power at the Earth surface, GNSS signals are vulnerable to radio frequency interference (RFI), which can severely degrade the receiver performance. Finally, ionosphere is another important error source in single frequency positioning, as it introduces random signal delays according to the solar activity.

Taking into account these three main error sources and some of the most promising detection and mitigation methods for coping with them, we propose a combined architecture for future GNSS receivers, including advanced multipath detection for integrity assessment, jamming interference detection, and a data-driven (DD) framework for long-term, near–real time ionospheric modeling. This article also overviews the state-of-the-art techniques relating to these challenges.

Introduction

The first section of this article will address the three major error sources in GNSS navigation. The next section provides an overview of the state-of-the-art solutions relating to multipath detection, interference detection, and ionospheric delay mitigation. The third section introduces three new algorithms to address each of these challenges and presents timely results from each. We also discuss the motivation for choosing each of these algorithms with respect to the existing ones. We then introduce our proposed architecture using the three proposed approaches before wrapping up the article with a discussion about the conclusions and future work.

Challenges to GNSS

Let's take a closer look at these three factors afflicting GNSS operations.

Multipath Propagation. The phenomenon of multipath is a particular concern for urban and road applications. Service integrity, defined as providing valid and timely alerts when the system should not be used for the intended operation, is an important factor for users in these sectors.

Two alternative solutions — multipath mitigation and multipath detection — are employed to tackle the multipath problem in GNSS. The former case has been studied extensively, leading to a large number of proposed solutions. See, for example, the articles by G. Seco-Granados *et alia,* M. B. H. Bhuiyan *et alia,* and E. S. Lohan *et alia* listed in the Additional Resources section near the end of this article. However, for lower complexity alternatives and with the advent of four independent GNSSs with many satellites in view, multipath detection schemes might provide enough information to enable advanced integrity methods (e.g., using only the satellites that do not suffer from multipath).

Multipath detection has been addressed to a lesser extent so far. As mentioned earlier, we can benefit just by knowing about the presence of multipath in the processed signal. This benefit comes from applying different processing scenarios according to whether multipath is present or absent. In some cases, the mitigation and elimination of multipath is not as relevant as the information about the presence of this effect.

A primary focus of this article is multipath detection in the presence of multipath and non–line-of-sight (NLOS) signals, which can be considered the major threats to integrity for urban users. We continue the work presented by D. Egea-Roca *et alia,* building on the domain of satellite geometry assessment for ensuring signal-level integrity based on the application of the quickest detection theory to multipath detection. This innovative algorithm can be further applied to the development of the proposed architecture of the GNSS receiver.

The article by D. Egea-Roca *et alia* described the adoption of cumulative sum (CUSUM)-based metrics as the quickest detection of multipath. In this approach, the correlator output samples were analyzed with metrics of different approaches, namely: carrier-to-noise power density ratio (C/N_0), code discriminator output, and the correlation curve. These correlator outputs were prompting integrity flags in the navigation solution.

In continuing this line of work, here we undertake an analysis of satellite geometry with respect to satellite pseudorange errors and integrity flags generated with the metrics mentioned earlier. These experiments allow for the improvement of the multipath detection algorithm and enable the designer to understand the relationships among the quickest detection and integrity parameters.

Integrity. RFI is a major threat because GNSS signals are received at the Earth surface with very low power. Undesired interferers that may appear in the GNSS bands can affect the receiver performance, leading to a degraded accuracy in the navigation solution or even to a complete denial of service. We can classify RFI as either narrowband or wideband, depending on whether its bandwidth is small or large with respect to the bandwidth of the desired GNSS signal.

Another distinction can be made between unintentional and intentional interference. Jamming is an example of the latter type of RFI and has become a big concern in the GNSS field due to the increasing availability of low-cost jammers able to broadcast powerful signals into the GNSS bands. Although illegal, these devices can quite easily be purchased over the Internet for prices that range from a few tens to several hundreds of dollars.

Several studies have analyzed the properties of the signals emitted by GNSS jammers, and their impact on GNSS receivers has been widely investigated. (See, for example, the articles by R. Bauernfeind *et alia* and S. Savasta *et alia* listed in Additional Resources.). Depending on the internal architecture and algorithms, various receivers react differently to the interference, but the common jamming effect is an increase in the noise component and therefore a reduction in the C/N_0 estimated by the receiver.

In order to guarantee the integrity of the navigation solution, the receiver should be able to identify an interference occurrence and mitigate its effects. The need to detect the presence of jamming becomes even more crucial in critical applications, such as precision aircraft landing, harbor approach, and emergency response operation.

Later in this article we will propose a new and reliable jamming detection algorithm to be used in future GNSS receiver architecture.

Ionospheric Effects. The ionosphere can be the source of large errors in single-frequency GNSS positioning, causing differences of tens to hundreds of meters in the measured distance from the receiver to the satellite. This difference is proportional to the total electron content (TEC) encountered by the signal in the path from the satellite to the receiver, as described in Equation (1):

$$I = \frac{40.3}{f^2} F * VTEC \qquad (1)$$

where *F* is a geometry factor describing the inclination of the signal according to the satellite elevation, *f* is the signal frequency, and *VTEC* is the vertical total electron content at the ionospheric pierce point (IPP), which is the point where the signal crosses the ionosphere.

The TEC varies with time of year, the solar and geomagnetic activity, and also depends on the coordinates of the IPP. This combination of variables generates complex dynamics, whose modeling has been approached from both physics and empirical perspectives. (Note the articles by J. A. Klobuchar and M. Hernández-Pajares *et alia* in Additional Resources.) A physical model must either consider many variables or make a lot of assumptions, while empirical models tend to be more adapted to real situations.

There is a continuous increment in GNSS data, thus providing new opportunities to approach existing problems. Very few tools allow for processing large datasets and tuning the models in a reasonable amount of time (T. Hey).

Alternatives based on data-driven (DD) techniques are possible and offer a novel and rapidly expanding research domain in GNSS. In particular, studies applying DD methods to ionospheric modeling have shown promising results (e.g., Z. Huang *et alia*).

A reliable ionospheric model should be able to incorporate incoming data in real time, in an efficient way, with low-cost equipment. In this article we also introduce a new workflow for the generation of DD ionospheric models that can be used by single frequency receivers.

Detection and Mitigation Solutions

Various techniques exist for tackling the effects of various GNSS error sources. This section describes the state of the art for multipath detection, interference detection, and ionospheric error mitigation, as they are related to the core content of our research.

Multipath Detection. Multipath is an important limiting factor in precise GNSS measurements. Receiving reflected signals along multiple propagation paths causes a bias in the time-delay estimation of the receiver's delay lock loop (DLL). This is caused by a coherent multipath, typically from specular reflections with the time-delay difference on the order or smaller than the inverse of signal bandwidth and a Doppler difference smaller than the difference of coherent correlation level. As a result, the correlation peak becomes distorted, causing deteriorated positioning accuracy. Multipath affects all GNSS observables; however, in this article, we focus mainly on the pseudorange.

As mentioned earlier, the two alternatives for dealing with multipath are multipath mitigation techniques and multipath detection techniques, which are the focus here. Indeed, multipath detection techniques offer a low-complexity alternative to multipath mitigation.

Regardless of whether the user needs multipath mitigation (in some cases simply knowing that multipath is present in the signal is sufficient), detection techniques are applied in receivers. In recent years, different approaches to this topic were presented, mainly using external information about the sources of multipath. Such external information can contain databases with information about the buildings in surroundings (map-matching), external sensors such as inertial measurement units, or application of fisheye cameras for excluding NLOS signals.

However, the complexity of such solutions does not allow for implementation in mass-market receivers, and, what is more, the detection of the occurrence of multipath is not provided instantaneously with the processed signal samples. This latter factor means that these techniques would not fulfill the requirements of liability- or safety-of-life-critical applications.

Herein lies the motivation for applying the methods of the quickest detection theory. D. Egea-Roca *et alia* provided the theoretical description of this application in multipath in GNSS signals. Our work here extends the previous effort and provides a fast way of selecting the integrity parameters.

Interference Detection. Various GNSS observables, available at different stages of the receiver processing chain, are affected by the jamming signal and therefore can be used as decision statistics. Interference detection techniques can be mainly classified into three categories: pre-correlation strategies, which perform signal processing on IF samples, post-processing techniques, which utilize receiver observables from the satellite acquisition and tracking process, and automatic gain control–based methods, which use the AGC values to assess the operating environment of the GNSS receiver.

The pre-correlation approach is performed at the receiving end before the correlation stage. Several techniques are proposed in literature. One of the simplest methods is the energy detector, which measures the received signal energy during a finite time interval and compares it to a predefined threshold. Hence, the decision statistic of the energy detector is as described in Equation (2):

$$r(y) = \frac{1}{N}\sum_{n=1}^{N}|y[n]|^2 \qquad (2)$$

where $y[n]$ are the received signal samples, and N is the number of samples. This method can be used to detect any type of interference and does not require any knowledge of the interfering signal to be detected. However, it requires an interference-free signal sequence for extracting statistical signal properties necessary to set the threshold.

Variations of the standard energy detector can be performed in the time domain as well as in the frequency domain.

A frequency domain algorithm for detection of continuous wave (CW) interference was proposed by A. T. Balaei (Additional Resources). The idea is to detect the interference by investigating the power spectral density fluctuation in the frequency bins under investigation using a two-sample T-test: the first population is from a part of the GPS signal fast Fourier transform (FFT) that is known to be interference-free (assessment window), and the second population is taken from the period in which the test is done (evaluation window). The same procedure can also be adopted in the time domain.

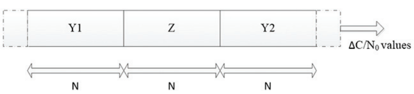
Interference detection post-processing techniques are based on receiver measurements from the acquisition and tracking stages. Possible decision statistics include the correlator output power, the correlator output power variance, and the carrier phase vacillation. The performance of these parameters under varying levels and types of interference is demonstrated in the work by A. Ndili and P. Enge listed in the Additional Resources section.

Another valuable post-correlation metric that can be used for GNSS interference detection is C/N_0. In GNSS baseband processing, the C/N_0 value is used to assess the signal quality of the tracked satellite. In the absence of interference, it can be defined as:

$$C/N_0 = 10\log_{10}(SNR \cdot BW) \qquad (3)$$

where C is the power of the GNSS signals, N_0 is the receiver noise power in one hertz, and BW is the receiver's three-decibel–equivalent bandwidth.

In the presence of in-band jamming, the receiver perceives an increase in the noise component, resulting in a degraded C/N_0. Therefore, we can use this parameter as an observation metric to identify the occurrence of jamming. The fact that a GPS satellite appears in the same place in the sky each sidereal day with similar C/N_0 values except in the presence of interference can be exploited as shown, for example, in the work by R. J. R. Thompson *et alia,* where the interference detection is based on day-to-day C/N_0 differences ($\Delta C/N_0$). The mean of $\Delta C/N_0$ in a window is compared to a threshold determined by estimating the noise in the surrounding windows of $\Delta C/N_0$ values.



The decision is based on the following comparison:

$$|\text{mean}(Z)| > |\text{mean}(Y)| + 2 \cdot \sigma(Y)$$

where $|\text{mean}(Z)|$ is the absolute value of the mean of $\Delta C/N_0$ values in the window under test Z, $|\text{mean}(Y)|$ is the absolute value of the largest mean value in the surrounding windows Y1 and Y2, and $\sigma(Y)$ is the largest sigma value in the surrounding windows. As a drop in $\Delta C/N_0$ occurs, the mean in Z will increase. If no change occurs in mean and standard deviation in the surrounding windows, we can reasonably assume that the drop is caused by an interferer.

The paper by Y. Ying *et alia* presents another C/N_0-based detection strategy where, at each epoch, the C/N_0 value of each tracked satellite is compared with a predetermined threshold based on the elevation angle of the satellite. If the value is below the threshold, a failure is declared for the satellite. Multiple failures of more than a certain number of satellites within the same epoch lead to a conclusion that interference has occurred.

Yet another valuable tool to assess the operating environment of the receiver and to detect an interference occurrence is the AGC value, as discussed in the articles by F. Bastide *et alia* and J. H. Yang *et alia* (Additional Resources). AGC is a fundamental component in a GNSS receiver. Any time multibit quantization is implemented, AGC is necessary.

The AGC can be seen as a variable gain amplifier whose main role is to adjust the input signal power in order to minimize the quantization losses. The signal-to-noise ratio degradation at the correlator output of the receiver due to the quantization process is, in fact, a function of the ratio between the maximum quantization threshold and the input noise level. As explained in the paper by F. Bastide *et alia,* this ratio has an optimal value that minimizes the quantization losses, and the role of the AGC is therefore to ensure that the optimal ratio is used by adjusting the input signal power.

In a GNSS receiver, where the signal is much weaker than the noise, the AGC is driven by the ambient noise rather than by the GNSS signal. However, in the presence of jamming, the AGC level decreases in response to an increased power in the GNSS band.

In this article, four jamming detection schemes based on AGC and C/N_0 are tested. On the basis of the obtained results, we propose the best performing method for the combined receiver architecture.

Ionospheric Error Mitigation. Because the severity of ionospheric effects on GNSS signal propagation depends on the signal frequency, the effect can be reduced to first order by a dual-frequency receiver. The ionospheric delay can be calculated as:

$$I = \frac{f_2^2}{f_1^2 - f_2^2}\,(P_2 - P_1) \qquad (4)$$

where I is the delay, $f_{1,2}$ are the frequencies of the signals, and $P_{1,2}$ are the corresponding measurements on the two GPS-frequencies.

For single-frequency users, ionospheric error can be calculated at the receiver in real time or in the post-processing phase. In either case, single-frequency users may adopt a variety of approaches. Among the most common are:

- Klobuchar Model —Employed by GPS users, this model is based on an empirical approach and includes a vertical delay based on a constant value at nighttime and a half-cosine function in daytime. This approach reduces the RMS ionospheric range error by an estimated 50 percent.
- NeQuick Ionospheric Model — NeQuick is a tridimensional and time-dependent ionospheric electron density model that calculates electron density in the ionosphere as a function of the position and time. This model is proposed for use in Galileo single-frequency receivers and is based on the original profiler proposed in the article by G. Di Giovanni and S. M. Radicella.
- International Reference Ionosphere (IRI) — This is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). These organizations produce an empirical standard model of the ionosphere based on all available data sources. For given location, time, and date, IRI provides monthly averages of the electron density, electron temperature, ion temperature, and ion composition in the ionospheric altitude range (described in the work by D. Bilitza). Further research, however, determined that IRI presents poor performance in years of high solar activity (see the article by S. Kumar *et alia* in Additional Resources).
- IGS Global Ionospheric Maps — The International GNSS Service (IGS) is an international collaboration with more than 200 participating organizations in more than 80 countries. The IGS generates precision products suitable for GNSS applications, including ionospheric maps, from information recorded in their network of receivers around the world. The maps provide TEC content in a grid of 5 degrees (longitude) by 2.5 degrees (latitude). IGS map performance depends on the density of receivers used, which means that in some locations the results obtained are derived from interpolation between distant points, instead of real local data.

In general, these methods provide a wide coverage, but lack detail of ionospheric behavior. For this reason, various methods that use local data to generate models are currently being studied, including:

- Artificial Neural Networks (ANN) — Approximations have been made to model ionosphere through ANNs for Brazil, China, India, Japan, and South Africa (see D. V. Ratnam *et alia;* W. C. Machado *et alia*). Results have shown better performance than IRI maps and agreement with IGS maps.
- Multivariate Adaptive Regression Splines (MARS) — MARS are used to estimate the VTEC approximation models. The estimated VTEC model applied to GPS single-frequency precise point positioning has better positioning accuracy in comparison to the IGS global ionosphere map, according to results presented in the article by S.-P. Kao *et alia*).

In general, the results obtained with DD methods provide a local improvement over the global models; however, unexplored regions, datasets, and DD methods remain to be evaluated and incorporated in GNSS applications.

Innovative Algorithms

Considering the need to deal with the previously mentioned GNSS impairments, we propose three promising new solutions: multipath and jamming detection schemes, and data-driven models to mitigate ionospheric effects. Implementing these options in future GNSS receivers with combined architecture can enable multi-dimensional signal quality enhancements.

Multipath Detection. D. Egea-Roca *et alia* presented the quickest detection framework for multipath detection for single-antenna GNSS receivers with the goal of providing signal-level integrity. The multipath detection was to be performed with CUSUM algorithms adapted for three different metrics, based on different post-correlation parameters, such as C/N_0, code discriminator output, and the correlation curve. The metrics were then used for the analysis of real data, collected within the European Commission–funded Integrity for GNSS Receivers (IGNSSRX) project, as described in the paper by E. Dominguez *et alia* (Additional Resources).

From the three metrics' outputs, a signal-integrity navigation flag was generated, with two strategies: restrictive and permissive. The former strategy declares a fault whenever any metric declared one, leading to a very high probability of false alarm (PFA) and resulting in too many discarded measurements. The restrictive strategy also does not improve with respect to nominal results. The permissive strategy declares a fault when at least two metrics declare so and outperforms nominal results even with the high PFA and performs better than the restrictive strategy. The permissive flags were then improved with respect to the high false alarm rate and missed detection, producing flags that allow the navigation solution to provide less than 10 meters of horizontal position error (HPE) for 95% of epochs.

Improving the multipath detection algorithm required a careful determination of the relation between the generated flags and the satellite geometry and pseudorange errors as well as their influence on the navigation solution. To examine this, two cases were analyzed based on the single-frequency GPS and GLONASS data collected in the IGNSSRX project in the densely urbanized city of London on April 24, 2014:

1. In the first case the epoch navigation flag was set to invalid, but the HPE was below CEP80 (CEP80 = 1.28 · horizontal dilution of precision (HDOP) · user equivalent range error (UERE) = 9.14 meters, covering 80–81 percent of the probability range for horizontal error),
2. In the second one, the epoch navigation flag was set to valid, but the HPE was above the threshold of CEP80.

Both these cases are important in evaluating the appropriateness of the navigation solution. In order to characterize the relation between the geometry of tracked satellites and the observation error, **Tables 1** and **2** provide the values of the position dilution of precision (PDOP) bins, together with the mean values from the epoch of the median pseudorange errors. The pseudorange errors as well as HPE were calculated as true errors in post-processing using the data from the IGNSSRX project.

In the first case (Table 1), before applying the flags and for most of the epochs, the value of PDOP is below 3, showing good observation conditions. After applying the flags, the situation changes significantly — most of the observations now have poor observation conditions, but still show lower mean values of median pseudorange. The satellites with good geometry and larger values of pseudorange error are rejected, resulting in poorer observation conditions.

In the second case (Table 2), before applying the flags, all the observations have PDOP values below 3. After the application of flags, the situation again changes significantly: the PDOP values are distributed among all the bins, with the lowest number for the PDOP above 6. What is more, the mean values of median pseudorange error are smallest for the PDOP values above 6, indicating that even though the error is not big, it can strongly influence the navigation solution because of the large PDOP value.

PDOP bin	Number of observations		Mean pseudorange median error (m)	
<1;3>	56	4	6.76	6.90
(3:6>	6	16	12.92	8.44
(6;∞)	3	45	20.14	9.65

Table 1 Flag invalid, HPE < CEP80, before (red) and after (blue) applying the flags

PDOP bin	Number of observations		Mean pseudorange median error (m)	
<1;3>	70	24	8.47	6.17
(3:6>	0	30	-	8.57
(6;∞)	0	16	-	3.71

Table 2 Flag valid, HPE > CEP80, before (red) and after (blue) applying the flags

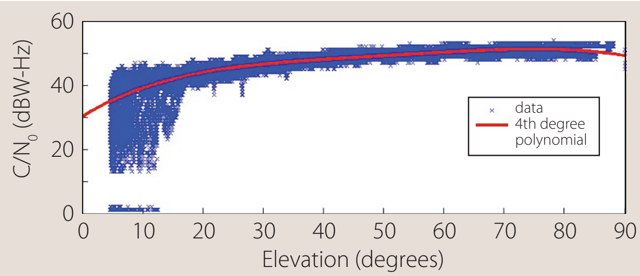


FIGURE 1 Polynomial fit of C/N_0 versus elevation

	AGC-based only	C/N_0-based only	AGC or C/N_0	AGC and C/N_0
DS1	100%	90.54%	100%	90.54%
DS2	100%	85.53%	100%	85.53%
DS3	100%	99.83%	100%	99.92%

Table 3 Percentage of time jamming is detected

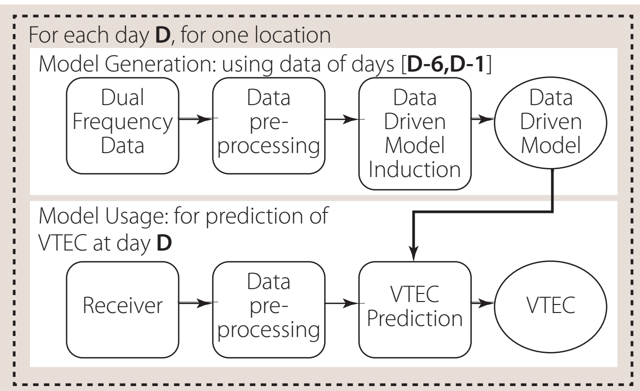


FIGURE 2 Workflow for generation and usage of data-driven ionospheric models

However, the number of identified epochs in both cases is low and may be not fully representative, and one can see that the geometry of the solution is influenced significantly. Therefore, improvements on the availability of the satellites may be beneficial for epochs with large HPE, so *weighing the satellite measurements instead of rejecting them could improve the solution*. Also, analyzing a greater number of different scenarios could help in better understanding the relations between the multipath detection and the navigation solution, allowing for full implementation of the integrity parameters calculation, such as time to alert, integrity risk, and protection level, in order to relate these values to the multipath detection method.

Jamming Detection Scheme. After selecting AGC and C/N_0 values as decision statistics, four jamming detection algorithms were evaluated by using a single-frequency, 32-channel, GPS/Galileo/GLONASS receiver.

The first jamming detection algorithm is AGC-based only. At each epoch where measurements are received, the AGC value is compared with a threshold value, chosen according to the behavior of this parameter in the absence of interference. If the AGC value is below the threshold, jamming is considered to be present.

The second approach is, instead, only based on C/N_0 values. Each tracked satellite is tested and, according to its elevation angle, the corresponding C/N_0 reference value is calculated. For a number of days, C/N_0 values were recorded and, because these change with the elevation angle, the observed values were processed versus elevation.

The reference curve against satellite elevation was obtained through a fourth-degree polynomial fitting, as shown in **Figure 1**. Because the receiver internal C/N_0 estimation algorithm was unknown, this *a posteriori* approach was the only one possible.

If the difference between the C/N_0 reference value of the tested satellite and the actual C/N_0 is larger than a specified threshold, the satellite is declared "not good." If the number of satellites declared "not good" within the same epoch is greater than half of the satellites tracked in that epoch, jamming is considered to be present.

In addition, two combinations of these schemes were tested: the logical AND operation between their outputs (jamming is declared only when both schemes declare so) and the logical OR operation (jamming is declared when at least one scheme declares it so).

Three datasets were used for testing the four algorithms, with various interference powers and different interference interval durations. In each case, we calculated the number of times the detector output (jamming "present" or "not present") was correct. We observed that the *AGC-based detection method has the best performance*, always being able to detect the jamming occurrence. The comparison between the tested detection schemes for the different datasets (DS1, DS2, and DS3) is shown in **Table 3**.

Data Driven Models for Ionospheric Mitigation. We propose the generation of DD local ionospheric models using data from dual-frequency receivers, which is also suitable for being used by single-frequency receivers, as seen in **Figure 2**.

The workflow has as input six days of data from dual-frequency receivers, which is pre-processed to obtain ionospheric delays as described in Equation (4). The data is then transformed to VTEC according to Equation (1). Once the VTEC has been calculated, a DD model is generated. For this work, we used Random Forest Regression. The resulting model can be used for a single-frequency receiver at Day 7.

The models were generated and tested with historical data from the IGS data network. We used the IGS raw data from receivers to generate models and IGS ionospheric maps for the evaluation phase.

The selected IGS stations were:

- bogt (Bogotá, Colombia), glps (Puerto Ayora, Ecuador) — located in low latitude
- leij (Leipzig, Germany), warn (Warnemünde, Germany) — located in mid latitude

The dates selected were:

- Jan 1–31, 2009 — a period of low solar activity
- May 1–31 2014 — high solar activity

The combination of the stations and dates allowed the evaluation of the algorithm in different scenarios, as indicated in **Table 4**.

	Mid Latitude	Low Latitude
Low solar activity	Scenario A	Scenario B
High solar activity	Scenario C	Scenario D

Table 4 Scenario definitions for VTEC prediction and evaluation

We evaluated the performance of the models by comparing the VTEC predicted by the Klobuchar model, the IGS maps, and the DD model against the VTEC obtained from a dual-frequency receiver. **Figure 3** presents the error in VTEC for the models and shows that the proposed algorithm produces a better VTEC prediction in all scenarios.

Figure 4 presents the error in the user position domain. The comparison is made between the residual error in final user position when ionospheric error is corrected with VTEC obtained from the dual-frequency combination and the different models studied. It can be seen that the *Data Driven models yield position errors below one meter.*

Proposed Architecture

Taking into account the three GNSS channel impairments discussed earlier (i.e., multipath, jamming, and ionosphere), we propose a combined architecture for future GNSS receivers (**Figure 5**) implementing some of the most promising solutions to deal with these error sources. The blocks in blue represent the main contributions of this article. The proposed architecture includes a jamming detection module based on AGC levels; a multipath detection block based on C/N_0, DLL, and correlation curve, which behaves as an integrity indicator when used in the navigation filter; and a data-driven method for near–real-time ionosphere modeling used to correct the ionospheric delay error.

Conclusions

The main objective of this article has been to address three of the main error sources in GNSS and to propose promising solutions to be adopted in a combined architecture for future receivers.

We propose an AGC-based jamming detection. With respect to post-correlation techniques, the receiver does not require tracking of the GNSS signal and, therefore, is adequate for characterization of intentional interference whose power is stronger than the receiver's tracking threshold.

In addition, we have offered a quick method of multipath detection, avoiding the complexity of multipath mitigation techniques. Consequently, this approach is less complex and easier to implement for real-time solutions. Finally, data-driven models can be used for ionospheric error mitigation in the vicinity of a dual-frequency receiver, providing better performance when compared to the Klobuchar model and IGS ionospheric maps.

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The authors also acknowledge the

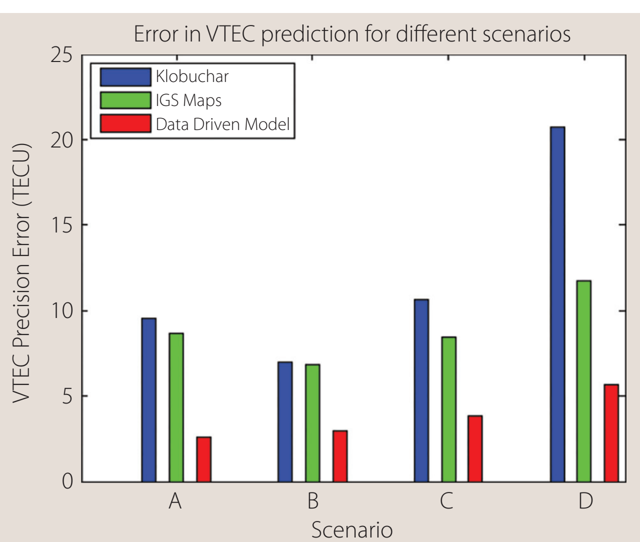

FIGURE 3 Error in VTEC predicted by different models with respect to VTEC obtained from dual-frequency combination

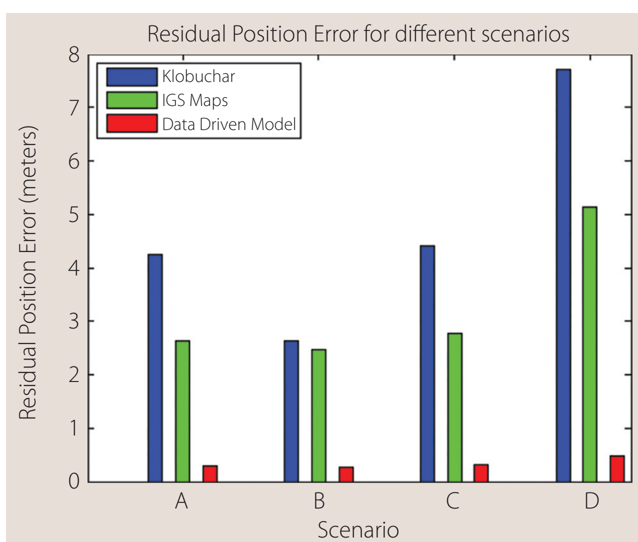

FIGURE 4 Residual error in position when ionospheric error is corrected with VTEC predicted by different models with respect to ionospheric error mitigation (VTEC obtained from dual-frequency combination)

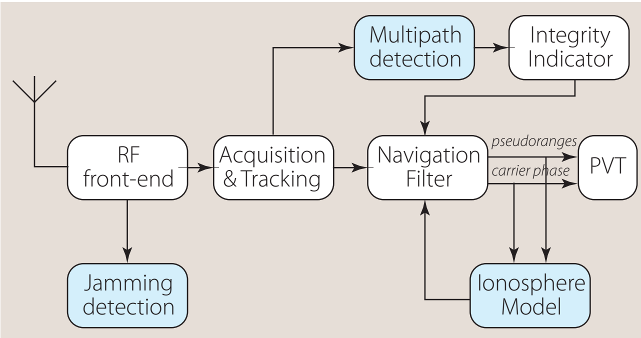

FIGURE 5 Block diagram of the combined receiver architecture

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Manufacturers

The GPS/Galileo/GLONASS receiver used in the analysis of the jamming detection algorithms was the NV08C-CSM from **NVS Technologies AG**, Montlingen, Switzerland.

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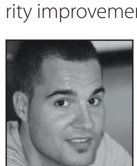

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