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GNSS Interference Monitoring and Detection (GIMAD) System †

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Abstract: In the last few years, gradually more systems have relied on the Global Navigation Satellite System (GNSS) for their correct functioning. These systems include safety-critical applications such as airports or emergency services. Given the wide number of GNSS applications and the current availability of affordable and easily configurable Software-Defined Radio (SDR) devices, GNSS has become the target of numerous Radio Frequency Interference (RFI) attacks. Thus, RFI has become a real threat for GNSS and, hence, for those systems relying on it. With the purpose of detecting, characterizing, and localizing RFI not only in GNSS frequency bands but also in other daily-used frequency bands, a GNSS Interference Monitoring and Detection (GIMAD) prototype has been developed, with special emphasis on its deployment in safety-critical environments such as airports. GIMAD contemplates European Geostationary Navigation Overlay Service (EGNOS) V3 and International Civil Aviation Organization (ICAO) Ground Based Augmentation System (GBAS) RFI masks covering both in-band and out-band RFIs. In addition, GIMAD was tested in a real-field scenario.

Keywords: GNSS; GPS; Galileo; RFI; Jamming; RFI detection; RFI characterization; AoA; ICAO; EGNOS; GBAS

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1. Introduction

Radio Frequency Interference (RFI) jeopardizes satellite-based navigation applications. This is especially relevant in safety-critical activities where aspects such as availability, integrity, and/or continuity are of outmost importance. In order to mitigate and face an RFI in critical infrastructures/areas, the design of GNSS Interference Monitoring and Detection (GIMAD) was already presented in [1]. Now, this design has been implemented into a prototype.

The use case from which the system requirements are derived is presented in Section 2. Considering the above-mentioned requirements, a GIMAD prototype description is presented in Section 3, including the different parts of the architecture. Algorithms implemented in the design stage have been verified, and the key verification results are shown in Section 4. Finally, Section 5 contains the main conclusions.

2. Use Case and System Requirements

Airports are critical infrastructures where satellite-based navigation applications are needed to be particularly protected. RFI detection and monitoring campaigns have already been conducted around several airports around the world. For example, at Newark's airport in the USA, the Ground Based Augmentation System (GBAS) was affected due to the presence of jammers onboard vehicles passing through the highway near the airport [2]. The jammer device made the GBAS reference receiver lose track of GPS satellites, thus impacting GBAS operations. As a result, the Spanish Air Navigation Service Provider (ENAIRE) has brought out the risks that such interferences may cause and the real need for a monitoring system for early detection of RFIs.

In order to protect GNSS availability and thus airport operations, International Civil Aviation Organization (ICAO) RFI masks have been devised in order to provide the maximum recommended interference levels [3]. For a similar purpose, there are also European Geostationary Navigation Overlay Service (EGNOS) v3 masks. However, RFI monitoring campaigns have demonstrated that these masks are not always fulfilled. For example, infractions of such RFI masks have been observed at Frankfurt airport in Germany [4] including violations of the ICAO SARPs CW interference thresholds.

For that reason, both ICAO and EGNOS RFI masks have been adopted in the design of the GIMAD system, covering the frequency range from 800 to 1900 MHz.

Considering the outcomes of RFI detection campaigns at international airports, an operational use case has been devised by the Spanish ANSP (ENAIRE), as illustrated in Figure 1 shows that when a jammer is detected by any of the monitoring stations in the monitoring network, the station shall send an alarm message to the central processor. In the case in which the power of the transmitter is high enough to be detected by more than one monitoring station, the central processor shall provide the accurate position of the interference source. In parallel, the central processor shall also trigger an alarm inside the ATC HMI (Air Traffic Control Human Machine Interface) warning about the presence of an undesired interference. In some cases, the Air Traffic Control Officers (ATCOs) can send warnings to the pilots reporting the unreliability of GNSS signals. As a consequence of alarms, the ANSP as well as national authorities are informed of the events with the objective of localizing and dismantling the interference source.

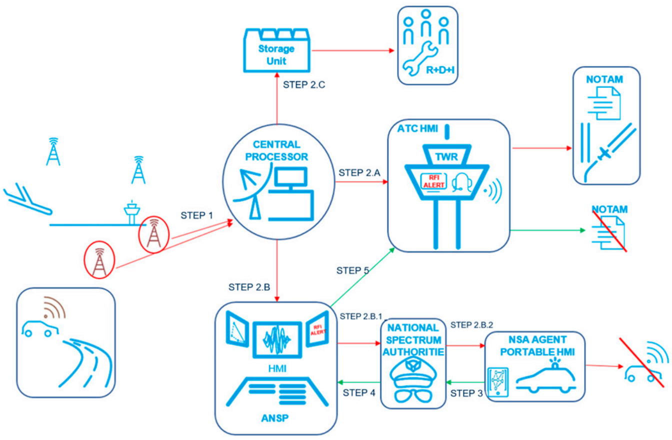

Figure 1. Operation use case (ENAIRE).

3. GIMAD Prototype Description

Following the GIMAD design introduced in [1], a GIMAD prototype has been implemented and tested.

The main components of the architecture are represented in Figure 2 and consist of the following.

1. **Antenna set**, integrating three different antenna types for different purposes:
    (a) Two GNSS antennas receiving in-band GNSS signals. One antenna for RFI detection purposes and another one for GNSS clock steering with a narrow-band pass filter.
    (b) Wide-band Fixed Reception Pattern Antenna (FRPA), whose main mission is detecting out-of-band interferences.

(c) Two Controlled Reception Pattern Antennas (CRPAs), used to determine the Angle of Arrival (AoA) of the RFI. One antenna set is used for in-band and the other for out-band RFI direction of arrival (DoA) determination. Each CRPA is made up of four individual receiving elements, allowing the possibility of determining the direction of up to three interferences.

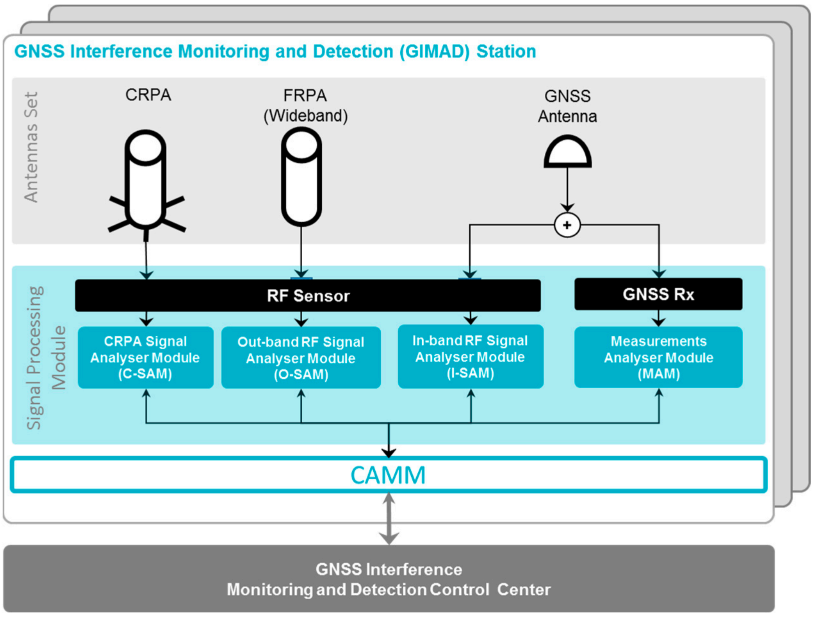

Figure 2. GIMAD Station architecture.

The GIMAD antenna set has been deployed at INDRA's Barcelona 22@ roof headquarters, as shown in Figure 3.

Figure 3. GIMAD antenna set installed at the INDRA's Barcelona 22@ building.

2. **Signal Processing Module** (SPM), with specific techniques for identification, characterization, and localization of RFI. It is composed of:
   (a) Measurement Analyzer Module (MAM). Post-correlator block that analyzes the observables of the GNSS receiver. It provides extra information about constellations/bands/satellite status.

   (b) In-band RF Signal Analyzer Module (I-SAM). The RF output of the GNSS antenna is redirected to this module, which digitalizes the received signal and applies pre-correlation algorithms for RFI detection, characterization, and localization to the baseband IQ samples.
   (c) Out-band RF Signal Analyzer Module (O-SAM). It is analogous to I-SAM but focuses on out-band processing.
   (d) CRPA Signal Analyzer Module (C-SAM). It provides a preliminary determination of the AoA RFI source.
3. **Control, Alert, and Monitoring Module (CAMM)**, which consolidates the SPM outputs, saves data for further analysis, generates alerts, and performs monitoring and control of the stations interfacing with the control center.
4. **GIMAD Control Center (GIMAD CC)**, which aims to monitor the status of the different GIMAD stations, manage the network, and provide a more accurate localization of the RFI source. An example of the GUI interface of the GIMAD CC is shown in Figure 4.

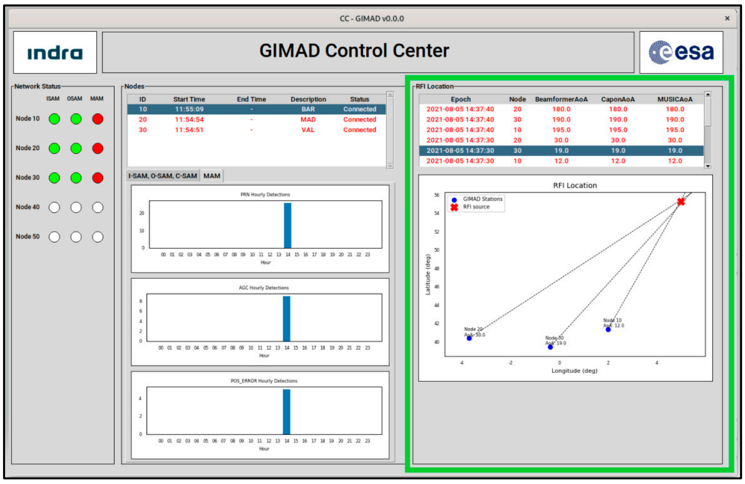

Figure 4. GIMAD CC example.

3.1. Signal Processing Module (SPM)

Three main operational blocks run under the SPM, which are named after the three main functionalities that they pursue: Detection, Characterization and Localization. Figure 5 summarizes the SPM modules in a block diagram.

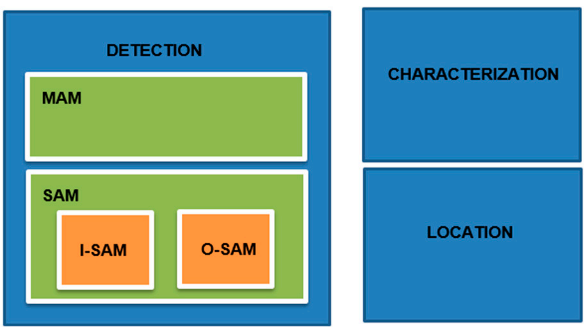

Figure 5. SPM modules.

The selected algorithms running behind them are described next.

3.1.1. Detection Modules/Algorithms

I-SAM and O-SAM modules from the Detection block in Figure 5 will assess the presence or not of RFI signals, performing a time-frequency characterization when a detection is confirmed.

The selected algorithms for interference detection in I-SAM/O-SAM are:

- Excess Kurtosis;
- Normalized sixth cumulant;
- Power level;
- Excess Kurtosis Fast Fourier Transform (FFT);
- Sixth cumulant FFT;
- Power Spectral Density (PSD) Peak Power.

If an interference alert is provided by any of the previous algorithms, the time-frequency characterization of the collected signal is performed.

Further details on algorithms and decision keys for selection can be found in [1].

Complementary to previous detection modules, the MAM module will be in charge of monitoring the GNSS receiver post-correlation observables for both detecting the presence of interference in the GNSS band and assessing the impact of the interference signals in the GNSS receiver. This is done by constantly comparing the current time evolution of each monitoring sudden changes in the measured observables.

The selected parameters for RFI detection and impact assessment in MAM are:

- Automatic Gain Control (AGC) level variations;
- Carrier-to-Noise Ratio (C/N0) variations;
- Pseudorange deviations;
- Carrier phase deviations;
- Position accuracy.

3.1.2. Characterization Modules/Algorithms

The characterization of the time–frequency of the monitored signal can be undertaken by means of (i) a spectrogram, (ii) the Wigner–Ville distribution, and (iii) a cyclostationary spectrum.

Further details on algorithms and decision keys for selection can be found in [1].

3.1.3. Localization Modules/Algorithms

C-SAM will assess the RFI AoA by performing a statistical analysis of the incoming signal at the CRPA antenna. The C-SAM concept is based on antenna array processing; thus, it combines the phase offsets of the received signal for each CRPA radiating element in order to estimate the AoA.

In order to accurately measure these phase differences and consequently enhance the AoA accuracy, the CRPA needs to be properly calibrated.

The selected algorithms for performing AoA estimations are (i) Spatial Filtering (Beamformer), (ii) MUltiple SIgnal Classification (MUSIC), and (iii) CAPON beamformer.

MUSIC is the default algorithm, while Beamformer and CAPON are kept as secondary methods, mainly because of the typically higher angle resolution of MUSIC with respect to the other two algorithms, although MUSIC is more computationally demanding.

4. Results

The GIMAD system was tested by capturing real GNSS signals and combining them with a generated RFI with an HP Agile signal generator. Testing included both injected (I-SAM, O-SAM, and MAM) and radiated (C-SAM only) RFI for a GIMAD station. The full capabilities of the system will be available after deploying more stations. In the following subsections, the key results for I-SAM, O-SAM, MAM, and C-SAM modules are presented hereafter.

4.1. I-SAM Test Results

A real GNSS signal was combined with an RFI signal generated by a signal generator. Then, this signal was injected into a National Instruments USRP-2945 where the signal was digitalized. IQ samples were sent to the SPM, where detection algorithms run. As expected, the probability of detecting RFI is higher when the Interference-to-Noise Ratio (INR) is higher. The GIMAD system is capable of detecting a pulsed interference RFI of −75 dBm with a duty cycle of 14%, a pulse duration of 1 ms, and a pulse repetition of 7 ms, as shown in Figure 6.

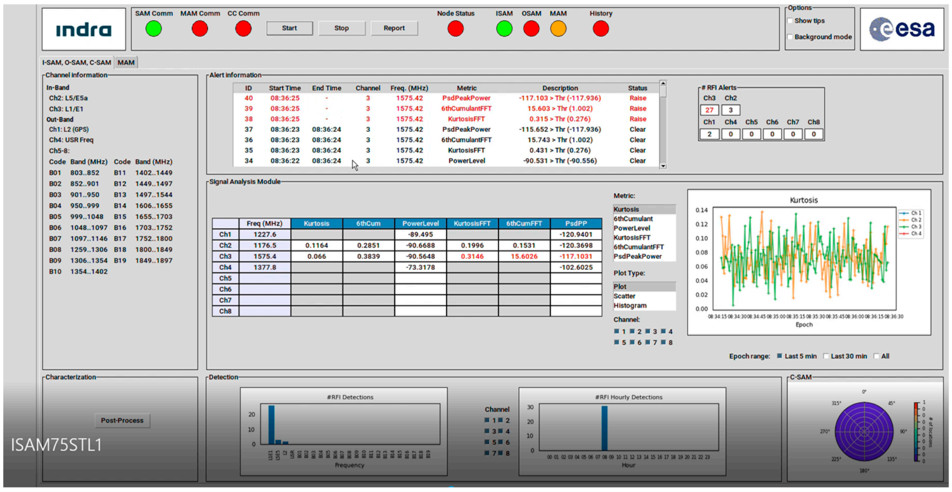

Figure 6. GIMAD CAMM (ISAM) detecting a pulsed RFI on L1.

Figure 6 shows the techniques Excess Kurtosis FFT, 6th Cumulant FFT, and PSD Peak Power in red, which trigger an alarm. Other techniques (such as Power Level) cannot detect the RFI. This result is in line with the Receiver Operating Characteristic (ROC) curve analysis previously simulated, where algorithms working with signals in the frequency domain achieve a higher probability of detection (pd) at the same pfa (probability of a false alarm).

4.2. MAM Test Results

A real GNSS signal was combined with an RFI signal generated by a signal generator. Then, the combined signal was injected into a GNSS receiver. GNSS observables extracted from the receiver were sent to the SPM, where algorithms based on detecting RFI from GNSS observables were applied. The GIMAD system can detect single-tone interference centered at L1 (1575.42 MHz) with a −40 dBm.

The GNSS data received from a satellite varies depending on its trajectory. Taking this into account, the MAM algorithm is conceived as an adaptive algorithm in the sense that it adapts to the evolutionary changes of the C/N_0, phase, and pseudorange of the satellites. Figure 7 below shows the RFI detection through the abnormal deviations of the AGC and the phase. Similar results for L5 have been obtained.

4.3. O-SAM Test Results

A competitive result in O-SAM where a challenging pulsed interference signal with a 1% duty cycle and pulse duration of 125 μs detected by GIMAD is shown in Figure 8 below.

Again, the pulsed RFI combined with the received real signal from the wide-band antenna in the B02 band (covering 50 MHz, from 850 to 900 MHz) has been injected using a combiner into the USRP NI-2945.

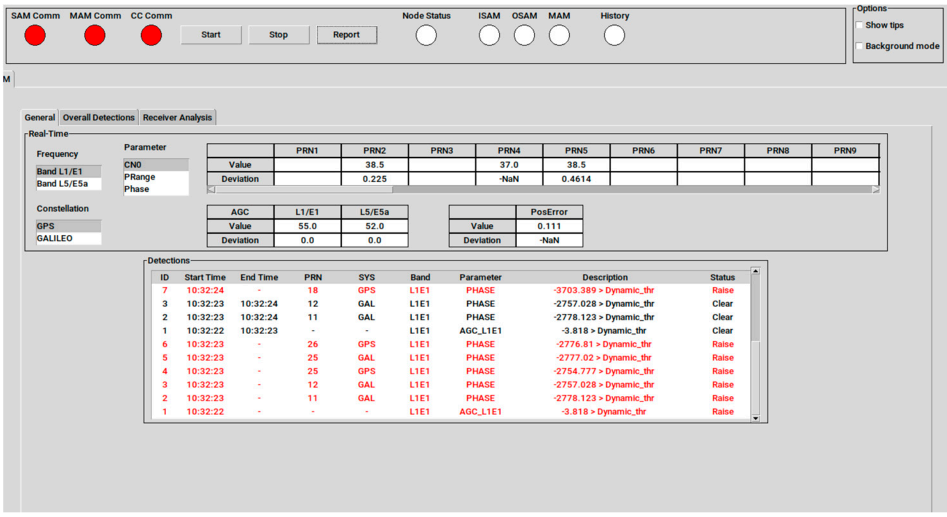

Figure 7. GIMAD CAMM (MAM) real-time detection on L1.

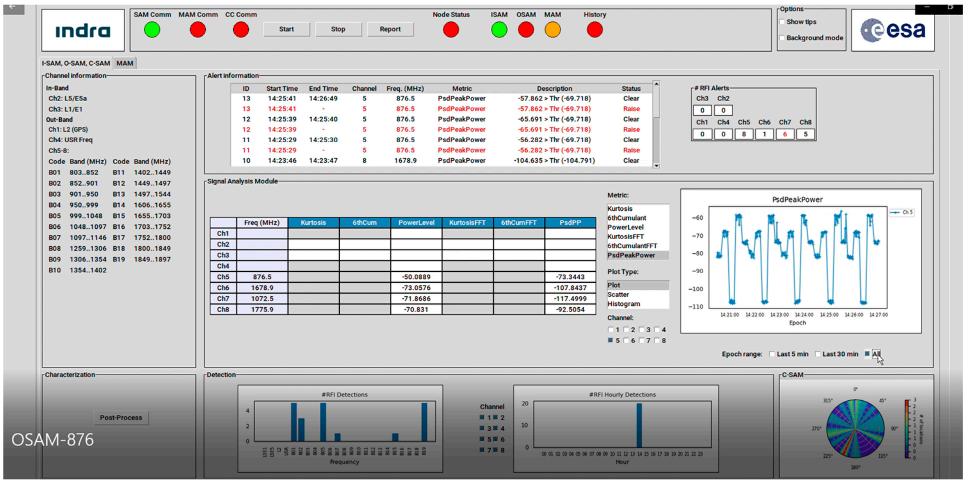

Figure 8. GIMAD CAMM (O-SAM) real-time detection at 876 MHz.

4.4. C-SAM Test Results

The out-band CRPA and the in-band CRPA of the GIMAD antenna set underwent calibration in an anechoic chamber, as is illustrated in Figure 9. During this calibration process, angular calibration parameters (relative amplitude and relative phase) were obtained for each carrier frequency and certain array orientations. The obtained calibration corrections had to be applied for the estimation of the AoA at the carrier frequency under analysis.

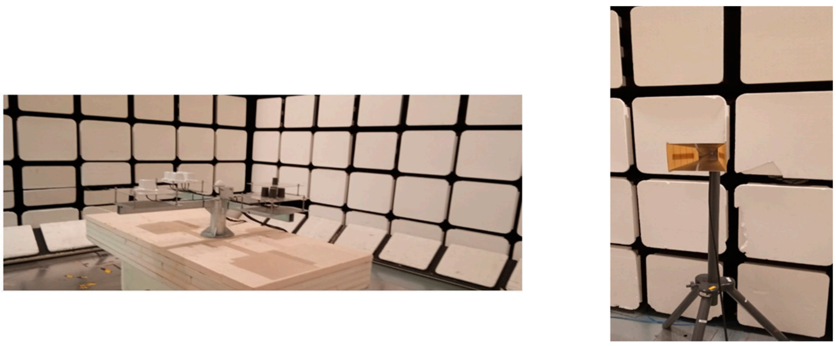

Figure 9. AOA calibration in an anechoic chamber.

In order to obtain the calibration parameters, the CRPAs were rotated with a moving platform rather than a fixed transmitting antenna.

In a second round, once the calibration parameters were already computed, the CSAM algorithms were tested first in the anechoic chamber.

Two cases are presented: the Out-of-Band (OOB) RFI AoA estimation and the In-Band RFI AoA estimation.

In order to address the OOB AoA estimation, an RFI of 827.5 MHz is broadcast inside the anechoic chamber. This OOB RFI is active from snapshot 200 to 700, as shown in Figure 10. The estimated AoA error is given for the different AoA techniques. Beamformer is depicted in blue, Capon in orange, and MUSIC in yellow. We observe in Figure 11 that the maximum AoA error is for Beamformer, which is about 10°. For Capon and MUSIC, the AoA error is below 4°.

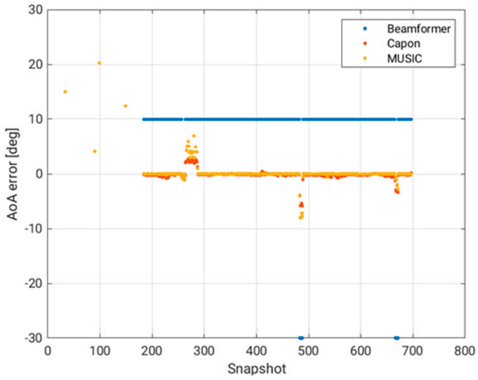

Figure 10. AoA estimation for 827.5 MHz RFI in the anechoic chamber.

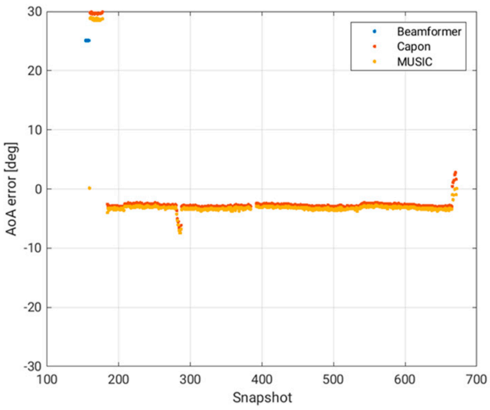

Figure 11. AoA estimation for 1575.42 MHz RFI in the anechoic chamber.

The technique that provides better AoA estimation without filtering and is considered the primary localization technique is MUSIC. In order to address the in-band AoA estimation, an RFI of 1575.42 MHz (L1) is broadcast inside the anechoic chamber. It shows an accurate estimation of the angle of arrival of the L1 RFI using MUSIC and Capon techniques.

5. Conclusions

GIMAD has been developed and verified. The verification results have shown that GIMAD is capable of detecting, characterizing, and localizing RFI both in-band and out-band. The GIMAD prototype uses algorithms based not only on GNSS observables but also on IQ samples. The combination of the selected algorithms maximizes the detection probability, as they emphasize different metrics. The capability of detecting very short interference signals (125 µs) has been verified, in line with EGNOS v3/ICAO GBAS RFI masks. Thus, it targets not only the aeronautical segment but also safety-critical environments.

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Conflicts of Interest: Authors Enric Obiols-Bernaus, Lorena Tortajada-Ropero, Àngel Creus-Blanch, and Antonio González-Novell was employed by INDRA Sistemas. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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