4000130453/20/NL/MP/mk

GNSS Signal Quality Monitoring Solution for New Integrity Applications (MONINT)

Final Presentation

March 03, 2022

INNOVATING SOLUTIONS

Agenda

- ❑ Introduction
- ❑ Project background and Objectives
- ❑ Signal Quality Monitoring (SQM) Definition and Characterization
- ❑ Platform Design
- ❑ Test Campaign Results
- ❑ Conclusions and Recommendations

Introduction to GMV

A global high technology group

Multinational technology group

6th European Space Industrial Group

Private capital

2,500+ employees

Roots tied to Space

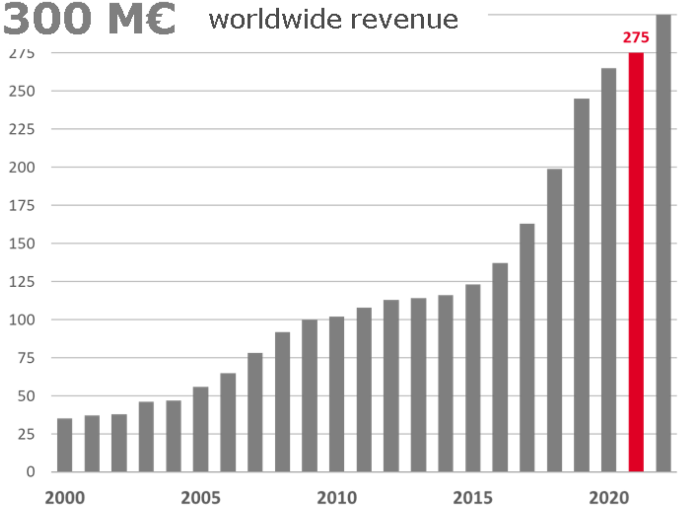
CMMI level 5

CMMIDEV/5

Founded in **1984**

Companies in 12 countries

300 M€ worldwide revenue



Space, Aeronautics, Defense & Security, Intelligent Transportation, Banking & Finances, ICT Industries

Space	Defense	IT	Transport
57%	10%	17%	16%

International technology leadership

#1 Worldwide Satellite Control Center provider to commercial telecom operators (+300 Satellite missions worldwide)

First ever **worldwide** intraoperative radiotherapy planning system

Responsible of safety critical systems of European GNSS systems (EGNOS and Galileo)

Leader of Intelligent Transportation Systems for the **public transport sector** (+100 cities in Europe, Asia and America)

GMV's ***checker ATM security*** is the worldwide leader as multivendor cyber security protection for ATMs

Navigation

- Leading GCS (Segment Prime) and main subsystems development: sKMF, SCCF, FDF
- Leading G2G G/S
- Development of critical GMS subsystems: Orbit Synchr. Processing (OSPF), Security Monitoring (GSMC), PRS Point-of-Contact Platform (POC-P)
- Operations support to GSOp
- PRS receiver development (PRESENCE), Spanish CPA

- Development of EGNOS central processing facility – processing set (CPF-PS)
- Development EGNOS application specific qualification facility (ASQF)
- Development of EGNOS Data Access System (EDAS)
- Development of EURONOTAM

- Development and operation of Galileo's Time & Geodesy Validation Facility (TGVF)
- Development and operation of the Galileo Reference Center (GRC)
- Development of Galileo Service Center (GSC) infrastructure
- Return-Link Service Provider of the Search and Rescue Service (RLSP-SAR)
- GSMC infrastructure on GSMC-S and POCP-S
- Galileo High Accuracy Data Generator (HADG)

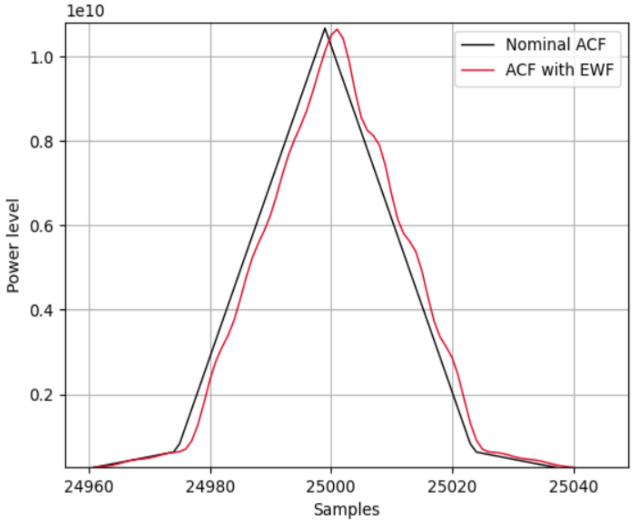
International market & products:
- Performance monitoring and SBAS contracts with Roscosmos
- SBAS related contracts for OACI, SANSA, ISRO and the Korean ADD
- New generation SBAS prototype system for Geoscience Australia

Timing and PPP services
- DOWR White Rabbit GNSS Receiver
- TOWR UTC generation and distribution is presented
- magicGNSS SBAS and PPP User Terminal

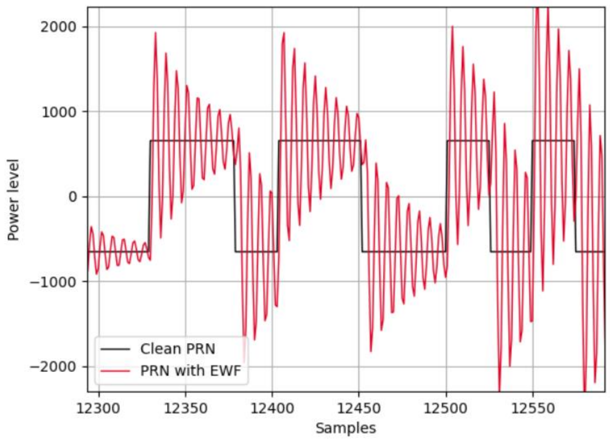
Project Background and Objectives

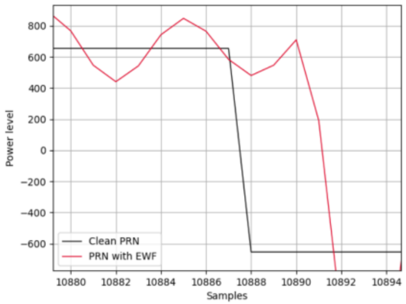
What is an Evil Waveform (EWF)?

The first occurrence of Evil Waveform occurred in 1993 on SVN19, with a differentially corrected vertical error up to 8m



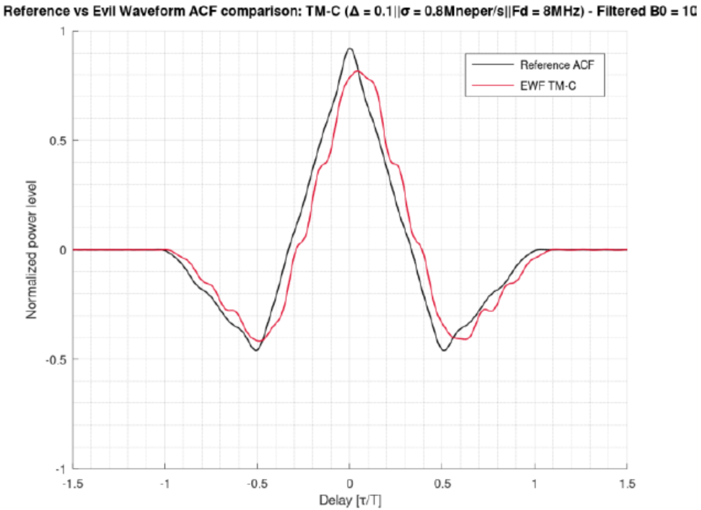
BPSK(1) ACF



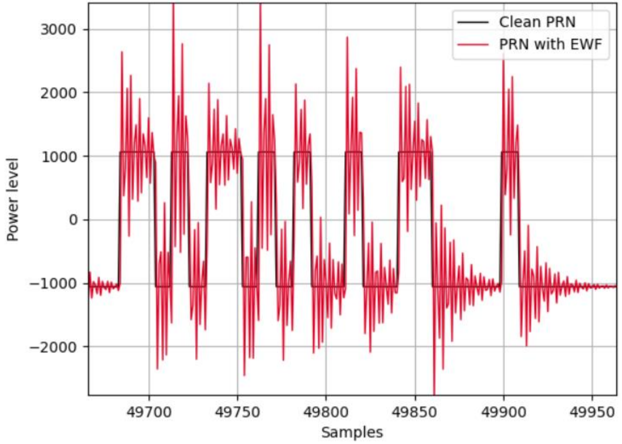


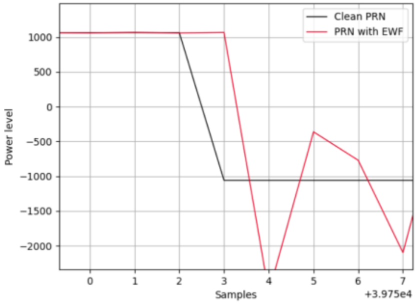
What is an Evil Waveform (EWF)?

Evil Waveform is a deformation at the signal generation unit which leads to positioning error in the user receivers



CBOC(6,1,1/11) ACF





Target Market

- Need for GNSS Evil Waveform Monitoring
  - In 1990 a HW chain failure in GPS Block II satellite caused the satellite to transmit an anomalous waveform
  - In 1993 an error of 3-8 meters was measured during aeronautical exercises

- Integrity applications need to monitor signal quality and in particular evil waveforms

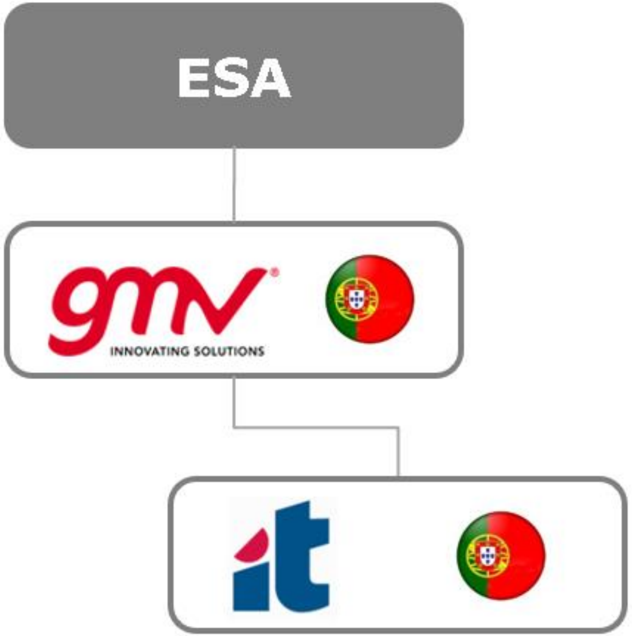
- Emergent Commercial Market requires
  - Target Integrity Risks ~10-7
  - Redundancy, availability, reliability…
  - Stringent Service Level Agreements (SLA)
  - Multiple site deployment

- Target markets include Aeronautical, Automotive (autonomous driving), Maritime, Others

MONINT Objectives

GNSS Signal Quality Monitoring Solution for New Integrity Applications

- Understand and quantify the impact of EWF
- Define EWF detection techniques
- Development of signal generation capability to create signals impaired with EWF at SA and BB IQ.
- Design and development of a platform capable of being representative of a receiver
- Testing of the detector and its adequacy to the use case.



SQM Definition and Characterization

TM and SQM Definition and Characterization

Threat Models (TM) definition

TM-A1 (digital distortion after modulation by the code signal)
TM-A2 (digital distortion in the sub-carriers)
TM-B (analog distortion, modeled with a second order system)
TM-C1 (TM-A1 plus TM-B)
TM-C2 (TM-A2 plus TM-B)

Evil waveforms detection

Uses tests based on ratio metrics:
- Simple ratio
- Difference ratio
- Sum ratio
- Combination of all types of tests

Threat Models (TM)

Modulations

- BPSK(m)
- BOCs(m,m)
- CBOCp (CBOC(6,1,1/11) pilot with BOCs(1,1) receiver)

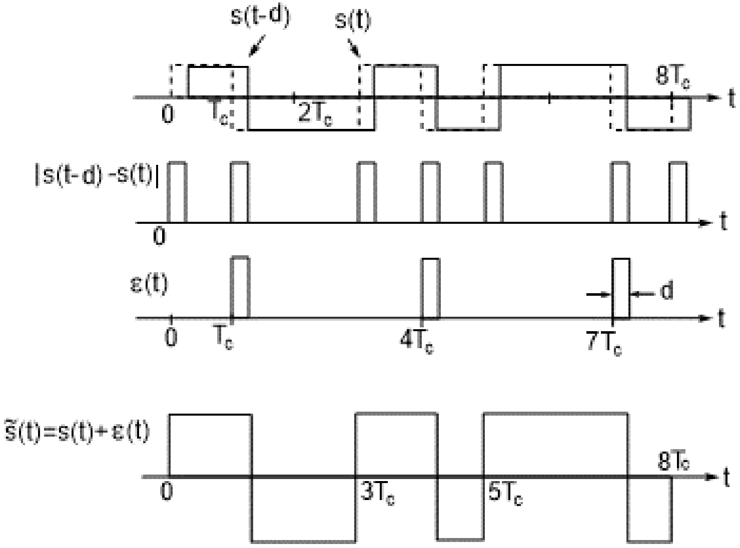
We obtained analytic expressions for cross-correlation with distorted signals, assuming

- Semi-analytic (SA) approach
- Infinite length (ideal) codes
- Ideal lowpass and Butterworth filters

In particular, for ideal filtering we obtained expressions based on the sine integral function which lead to very fast computation-> useful in extensive Monte Carlo simulations

Example of EWF-A1 signal generation

BPSK(m) signal:



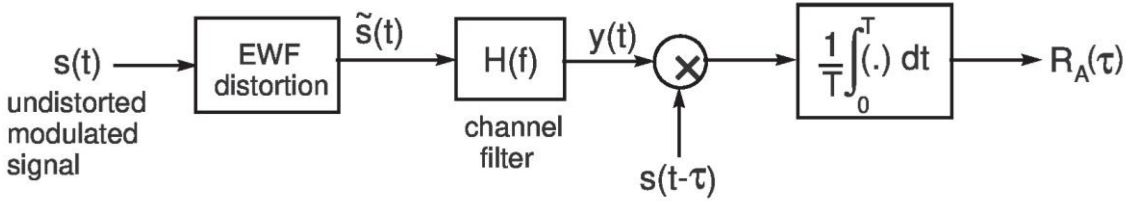
$s(t)$– undistorted signal

$\varepsilon(t)$ – error signal

$\tilde{s}(t) = s(t) + \varepsilon(t)$ – distorted signal

TM-A1 BPSK(m)

Block diagram of the cross-correlation generation:

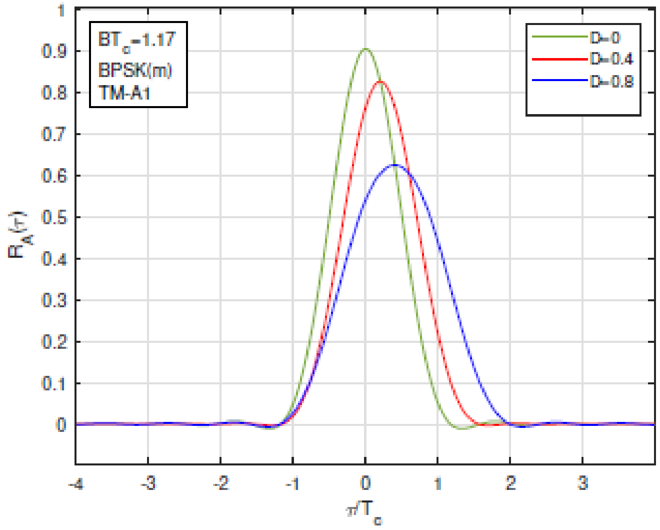


For ideal filter with bandwidth BT_c

$$R_A(\tau) = \frac{1}{2} I_{s2c}(1{,}2\pi(\tau/T_c), BT_c)$$
$$+\frac{1}{2} I_{s2c}(1{,}2\pi(\tau/T_c - D), BT_c)$$

$I_{s2c}(a, b, c)$ can be expressed using the Si(.) function

$D = d/T_c$



2B=24 MHz for m=10

Evil waveform detection

- Bank of N pairs of early-late correlators and prompt correlator (2N+1 correlators)
- Uniform spacing, Δ
- Carrier to noise ratio, C/N0
- Correlation interval, T

Metrics and tests

Simple ratio metric

$$\mu_1 = \frac{Z_L}{Z_P}$$

Difference ratio metric

$$\mu_2 = \frac{Z_E - Z_L}{Z_P}$$

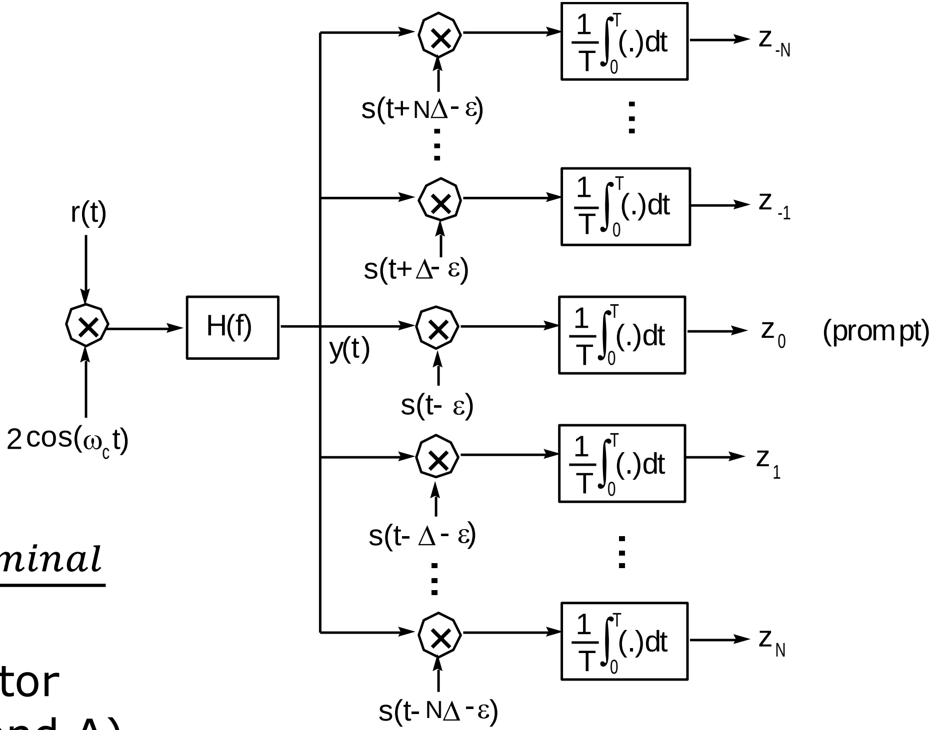
Sum ratio metric

$$\mu_3 = \frac{Z_E + Z_L}{Z_P}$$

Test

$$T_i = \frac{\mu_{measured} - \mu_{nominal}}{\lambda}$$

$\lambda =$ normalization factor (depends on $(C/N_0)T$ and Δ)



- Three different types of tests: T1, T2 and T3

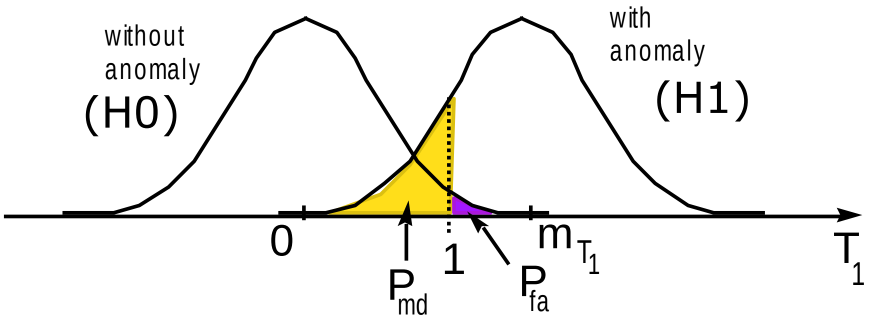
Probabilities of false alarm and missing detection

$$\mathrm{P_{fa}} = \mathrm{Prob}\{T_i > 1 | H_0\}, \qquad T_i \sim N(0, \sigma_0^2)$$

$$\mathrm{P_{md}} = \mathrm{Prob}\{T_i < 1 | H_1\}, \qquad T_i \sim N(m, \sigma_1^2), \quad m > 0$$

Decision criterion:

$$\begin{cases} T_i < 1 \ \rightarrow \text{anomaly absent } (H_0) \\ T_i \geq 1 \ \rightarrow \text{anomaly present } (H_1) \end{cases}$$

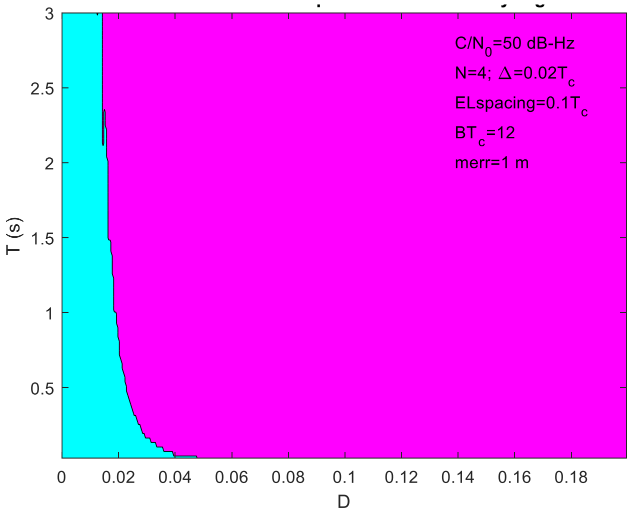


To increase the reliability of the SQM algorithms the decisions are based on:

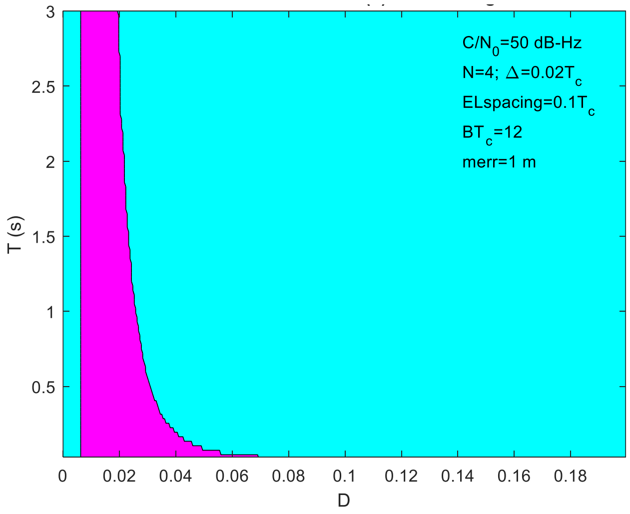
- more than one pair of correlators
- combination of the three types of tests

TM-A Detectability and hazard regions

Detectability



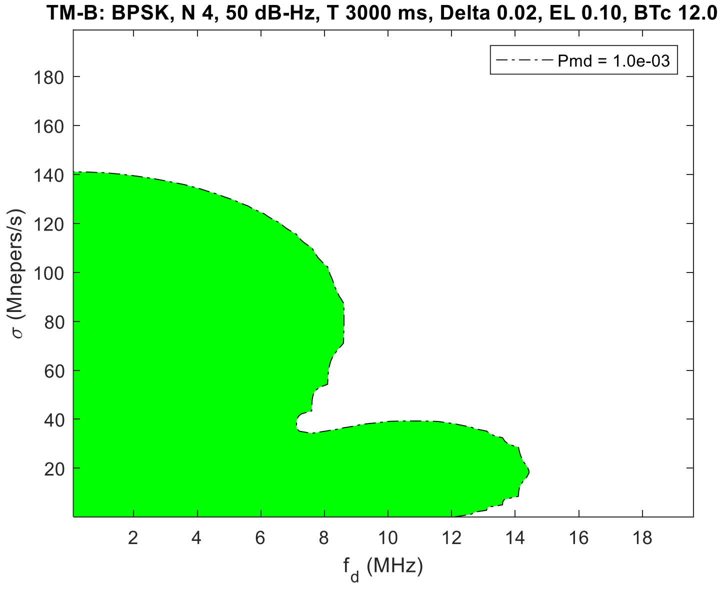
Hazard



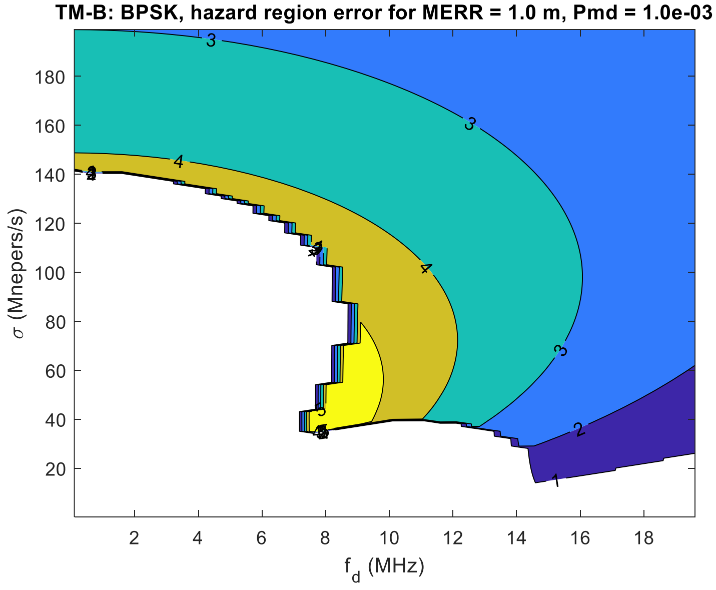
BPSK(1), N=4, BTc=12, MERR = 1m

TM-B Detectability and hazard regions

Detectability



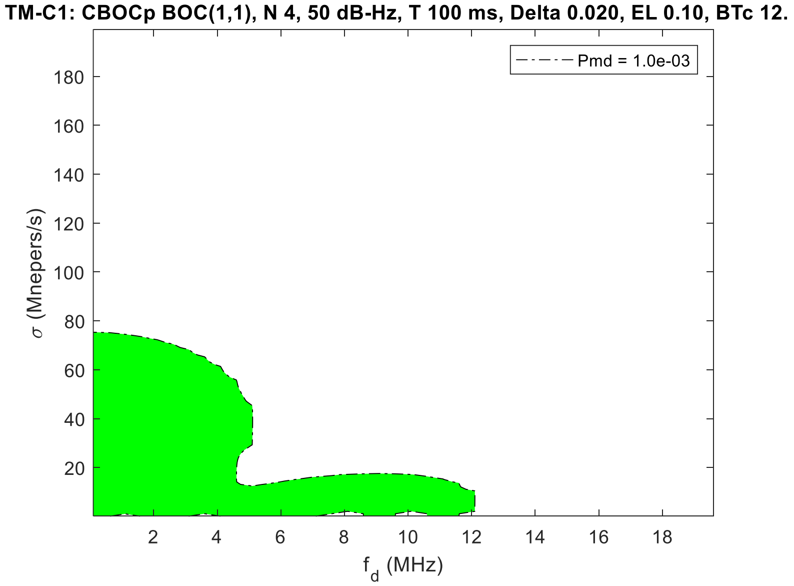
Hazard



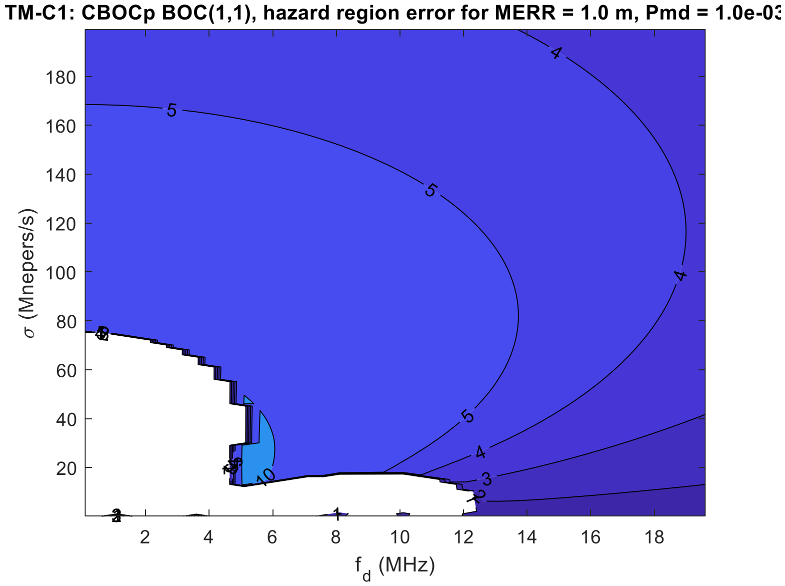
BPSK(1), N=4, BTc=12, T=3 s, D=0.01, MERR = 1m

TM-C1 Detectability and hazard regions

Detectability



Hazard



CBOCp, N=4, BTc=12, T=100 ms, D=0.01, MERR = 1m

Remarks from the simulations

1. The EWF detection performance improves with the number N of pairs of correlators but for N>4 the improvements tend to be residual.

2. The regions of detectability increase with the coherent integration interval T but the important parameter to be considered in the performance analysis is the product $(C/N_0)T$. Large values of T imply significant delays (latency) in the anomaly detection, which may not be tolerable in quickly moving receivers.

3. Simulations were carried in benign conditions: perfectly known (C/N_0), ideal operation of the DLL (tracking undisturbed by thermal noise or dynamic stress). So, the results are upper bounds on the expected performance in a real receiver.

4. Previous simulation results were obtained using a MERR of 1 meter. Changing this value usually has a significant impact in the determination of the hazard regions.

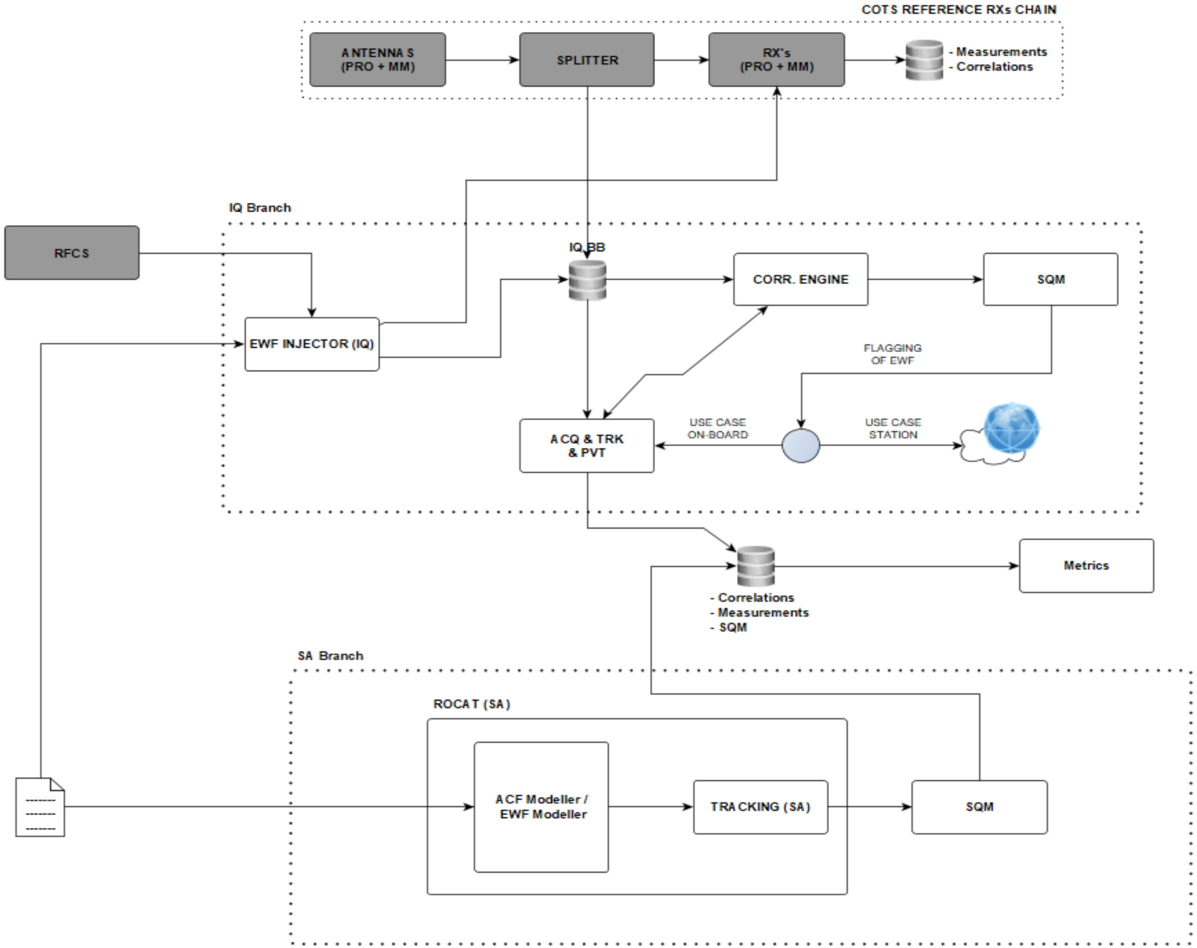
5. The usefulness of the EWF detection algorithms may be deteriorated in the presence of multipath, which limits their applicability in mobile scenarios. However, they are still useful in fixed stations where multipath effect is well controlled.

Platform Design

Full Platform

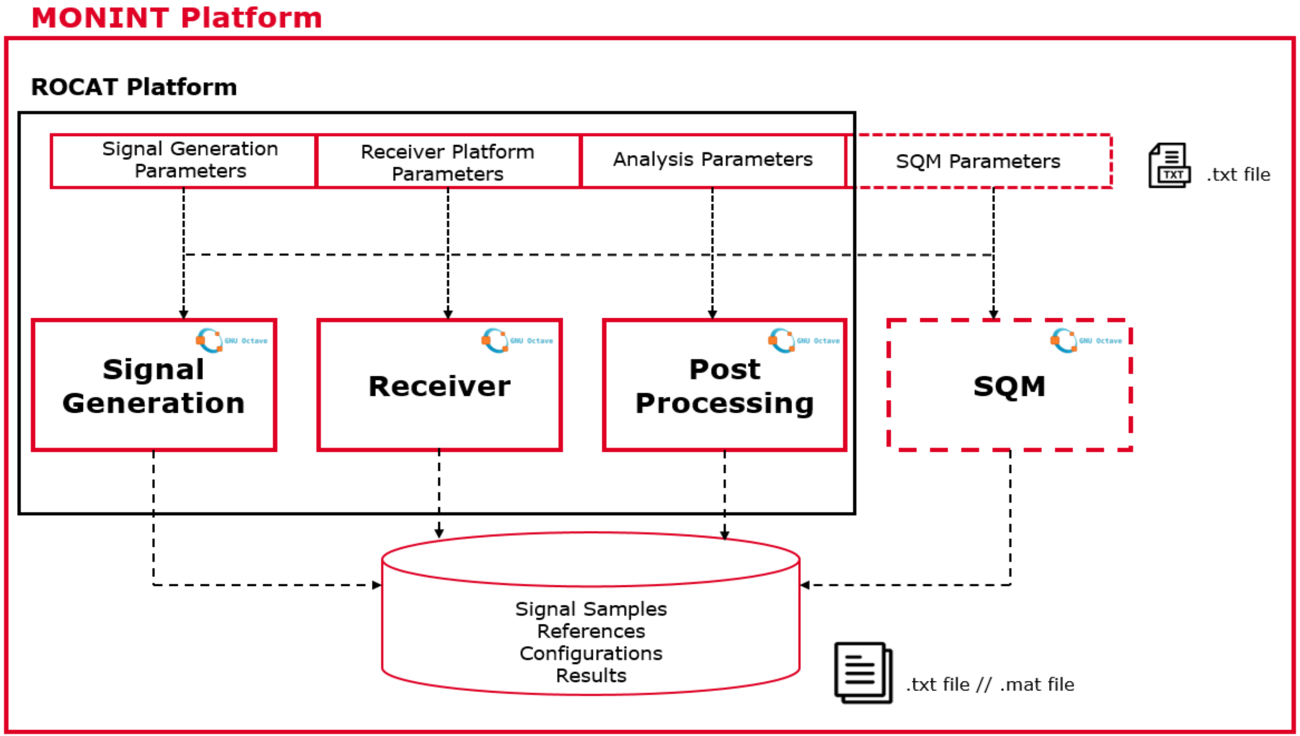
Three branches:

- Semi-Analytical (SA) branch
- IQ branch
- COTS Rx branch



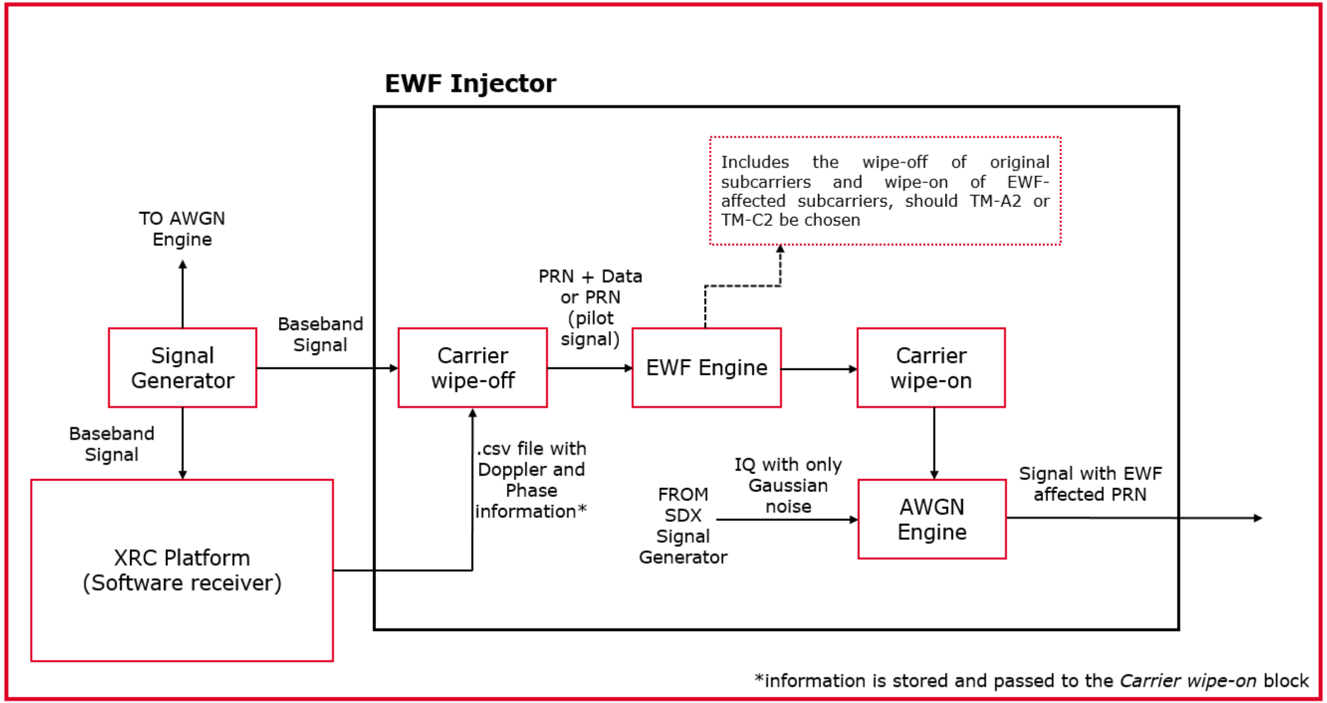
Platform Design – Semi-Analytical branch

- Based on the pre-existing ROCAT platform to which EWF capabilities were added
- The SQM block implements the metrics and tests to perform EWF detection, based on correlator outputs.



Platform Design – IQ branch

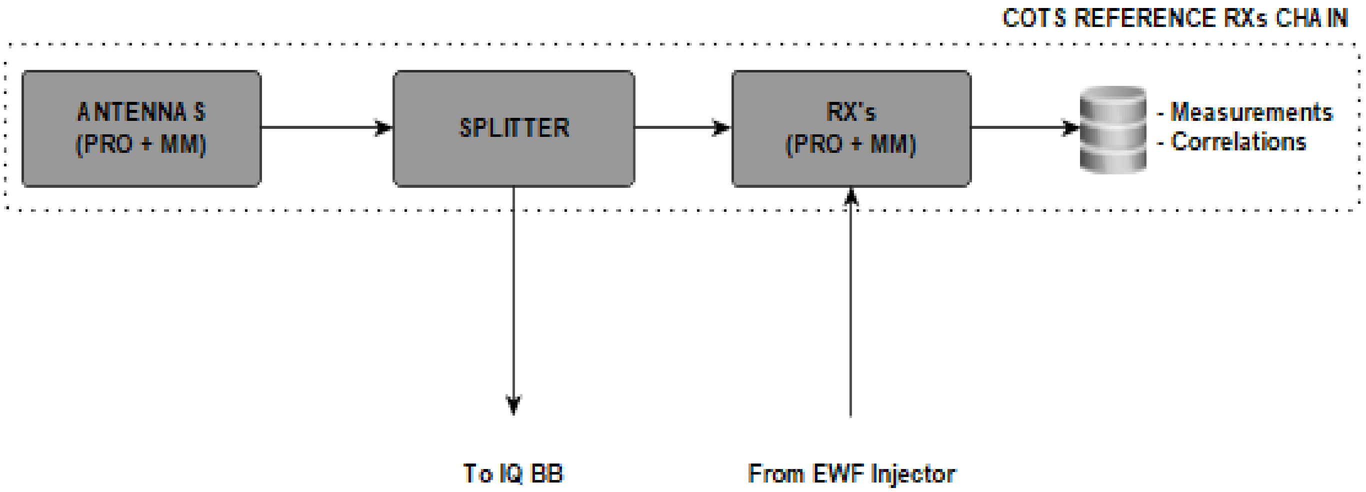
- A nominal IQ signal file injects is used as a baseline
- The injection of EWF is performed by manipulating the IQ samples



Platform Design – COTS Rx Branch

- Live signals are processed to analyze the detector performance in clean environment

- Injection of IQ files distorted by EWF can be replayed in RF and fed to a COTS receiver for processing, allowing measuring the impact.



Test Campaign Results

Performance Results – Preliminary SA Testing
Test Plan

To characterize and evaluate the SQM detection mechanism, extensive simulations were run for this purpose, having the theoretical analysis of the detection region plots as a baseline.

The SA branch of the MONINT platform was chosen for running the aforementioned simulation campaign, as it allows for greater flexibility in receiver/SQM architecture, as well as for greater ease in the EWF generation process.

The targets to meet were: $P_{MD} = 1 \cdot 10^{-3}$ and $P_{FA} = 1.5 \cdot 10^{-7}$. Clear and Borderline detection cases considered.

Modulations	Threat Model	Dynamics	Simulation Time (s)	CN0 values (dB-Hz)	Integration time (ms)	Number of Monte Carlos
BPSK(1) **BOCs(1,1)** **CBOC(6,1,1/11) pilot processed as BOCs(1,1)** **BPSK(10)**	TM-A1, TM-B, TM-C1, TM-A2, TM-C2	Static, Vehicular	4	35; 50	100	1000

Performance Results – Preliminary SA Testing

Main Results and Conclusions

- The scenario where the best performance was obtained was the "Clear Detection" static, with $C/N_0 = 50$dB-Hz and $T = 100$ms with $P_{md} = 0$ obtained for all modulations and EWF TMs.

- There is noticeable degradation in EWF detection performance when considering the "Borderline Detection" cases, agreeing with the detectability/hazard regions theoretical plots.

- Dynamics were found to hinder EWF detection performance, making it unable to achieve $P_{md} = 1 \cdot 10^{-3}$ especially during periods of change in Dynamics (acceleration, deceleration,…)

- As expected, lower values for C/N_0 leads to worse performance in terms of missed detections.

- The Semi-Analytical simulations have validated the theoretical analysis, in terms of P_{md} for Clear Detection and Borderline Detection cases with the transition between both cases being abrupt rather than a smooth increase of the P_{md} value

- Future iterations of the EWF detector will consider a M of N detection scheme, where several detections of EWF over a pre-determined period of time are needed to flag its presence

Performance Results – SA Test Campaign
Test Plan

- With the information from the preliminary SA testing, a more focused SA campaign was designed.
- The target value of $1.5 \cdot 10^{-7}$ now refers to a probability of false detection P_{FD}. The P_{FA} now refers to issuing alarms after 5 consecutive positive decisons regarding EWF.

Modulations	Dynamics	Scenario Conditions (Expected)	Integration Time	Signal	EWF Effects	Simulated Time	Number of Mt Carlo runs
E1 – CBOC(6,1,1/11)pilot L1 – BPSK(1)	Static	Open Sky Scenario with 50 dB-Hz	100ms	SA platform	No EWF and EWF effects TM-A1, TM-B, TM-C1, TM-A2, TM-C2	10 seconds	Until 100 errors are registered (minimum 100 Mt Carlo runs)

Performance Results – SA Test Campaign

Main Results and Conclusions

- The Semi-Analytical simulations have validated the theoretical analysis, in terms of P_{MD} for Clear Detection and Borderline Detection cases.

- It was also shown with the SA simulations that the registered probability of false detection P_{fd} was very far from the theoretical value of $P_{fd} = 1.5 \cdot 10^{-7}$ used for the design of the EWF detection tests.

- Because the issuing of an alarm regarding the presence of EWF would only be done in the case of registering 5 consecutive detections a $P_{FA} = 0$ was registered.

Performance Results – Synthetic/Real Signals IQ Test Campaign

Test Plan

- With the conclusions and results gathered form the SA platform, the techniques are more tuned and now ready for the synthetic signals simulations in order to attest the performance of the EWF detector under real conditions.

Test Cases	Receiver	Dynamics	Scenario Conditions (Expected)	Integration Time	Signal	EWF Effects	Number of satellites	Simulated Time
TC-IQ-001		Static		100ms	Signal Generator	EWF applicable to 1 satellite in an On/Off manner		
TC-IQ-002	XRC Software Receiver	Vehicular	Open Sky Scenario with satellites at [45;40]dB-Hz	20ms	Signal Generator		Approximately 11 (5 GPS and 6 Galileo)	240 s
TC-IQ-003		Static		100ms	Real Signals	No EWF Effects		

Performance Results – Synthetic/Real Signals IQ Test Campaign

Test Plan

The considered scenarios aim at:

- **TC-IQ-001** – Evaluate the impact of several EWF effects on the code estimations (XRC Software Receiver) comparing with a reference without EWF;
- **TC-IQ-002** – Same as TC-001, but with user dynamics; The dynamics considered are a square trajectory.
- **TC-IQ-003** – Evaluate the EWF Detector's probability of false-alarm for real signals.

Modulations	Threat Model
BPSK(1) **CBOC(6,1,1/11)** **BPSK(10)**	TM-A1, TM-B, TM-C1, TM-A2, TM-C2

Performance Results – Synthetic/Real Signals IQ Test Campaign

Main Results and Conclusions

- **TC-IQ-01**

  45dB-Hz Clear Detection cases were always detected, with probability of missed alarm (not issuing an alert when EWF is present) $PMA=0$ and TTA values of 0.5 seconds.

  For the Borderline Detection cases, $PMA=0$ was also verified but with increased missed detections (5 consecutive detections are needed to issue an alarm), with TTA of 1 to 2 seconds.

  As expected, when considering 40dB-Hz, the results worsened across the three modulations, with the detector only maintaining good performance in terms of PMA for the Clear Detection cases.

Performance Results – Synthetic/Real Signals IQ Test Campaign

Main Results and Conclusions

- **TC-IQ-02**

For GPS signals TM-A1 Clear detection case presented $P_{MA} = 0.75$. For all other TMs and cases, the detector was not able to detect the presence of EWF.

For the CBOC modulation, the detector presented values of $P_{MA} = 0$ for the Clear Detection cases, with the value of P_{MD} for TM-A2 improving.

For the Borderline Detection tests, the registered values of P_{MA} were of 1, with the detector failing to produce any alarm.

As expected, a generalized loss of detector performance was observed across the three modulations and respective TMs for TC-IQ-002, when lowering the C/N_0.

Performance Results – Synthetic/Real Signals IQ Test Campaign

Main Results and Conclusions

- **TC-IQ-03**

  For TC-IQ-003, no alarm regarding the presence of EWF was issued, showing that the detector, with its policy of only issuing an alarm if 5 consecutive detections are made, performed very well, not issuing a single false alarm.

Performance Results – Joint Analysis of SA, IQ and Real Signals Results

SA *vs* IQ	**SA *vs* Real Signals**
TC-SA-001 *vs* TC-IQ-001	TC-SA-001 *vs* TC-IQ-003
For Clear detection P_{MD} results, there is a considerable similarity between SA and IQ results	Match in the observed P_{FA} values
For Borderline detection cases, IQ simulations show that the increase in value of P_{MD} is more subtle than what the SA results demonstrated.	Implementation for real signals required more robustness in defining the thresholds for detection, lowering the observed P_{FD} to values of 0.
In terms of TTA results translate relatively well from SA to IQ simulations for Clear Detection	Near perfect match between SA and IQ simulations in terms of TTA, strengthening the confidence in both SA and real signal results.

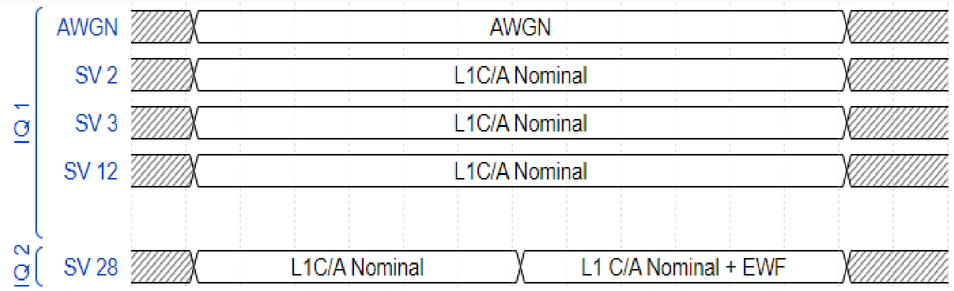
Performance Results – PVT Results

Test Plan

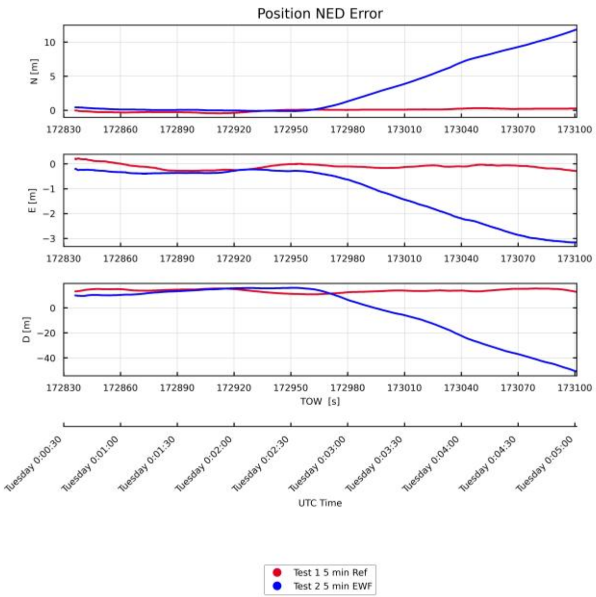
Two test cases were considered:

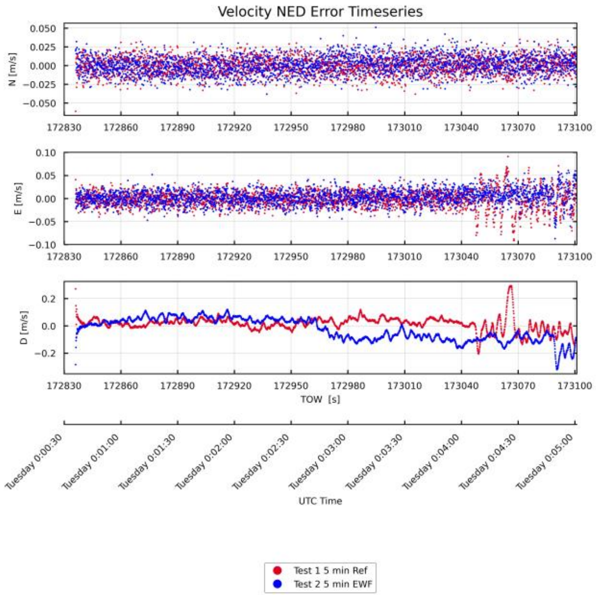
- **Test 1**: the four satellites are considered to have nominal signals during the whole test duration (5 minutes), unaffected by EWF. This test will serve as the baseline of performance, against which the test with signals with EWF will be compared.
- **Test 2**: the four satellites are considered to have nominal signals for the first half of the simulation (2.5 minutes) and for the second half, SV28 is affected by EWF TM-C1 while the rest SVs remain unaffected. The purpose of this test is to observe the impact of having one of the satellites used for producing the positioning solution affected by EWF and how that translates in terms of PVT loss of performance.

SVID	Modulation	Dynamics	EWF TM	Duration
SV02	GPS L1 C/A	Static	TM-C1 Clear Detection (Δ = 0.01023 || σ = 8.8 || Fd = 2MHz)	5 minutes
SV03				
SV12				
SV28				



Performance Results – PVT Results
Main Results and Conclusions

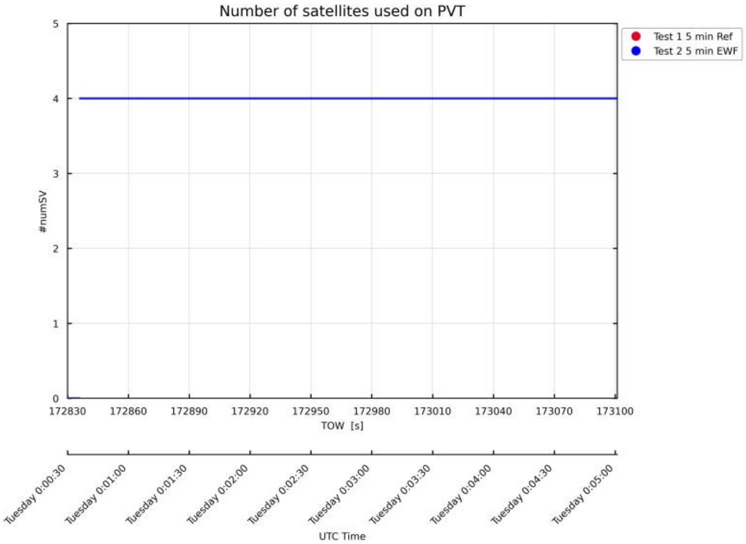


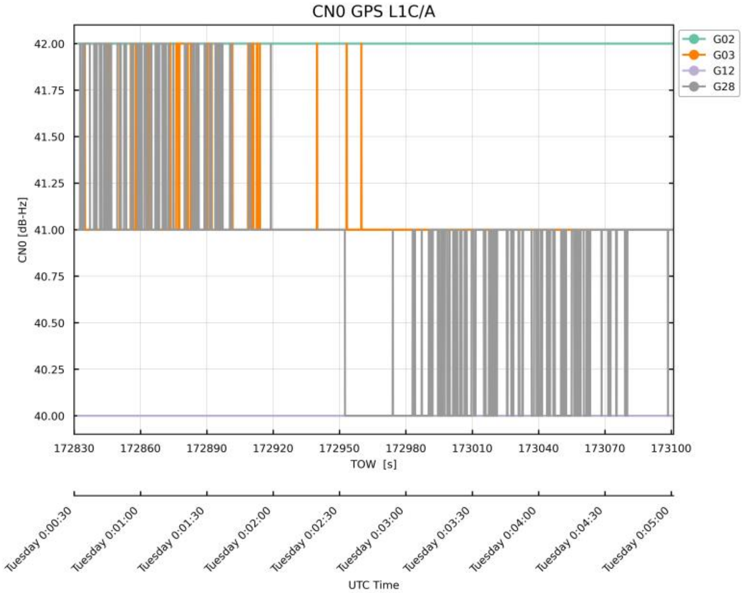


- Position errors quickly increase in the presence of EWF (blue lines). Increase in velocity error is much more subtle

Performance Results – PVT Results

Main Results and Conclusions



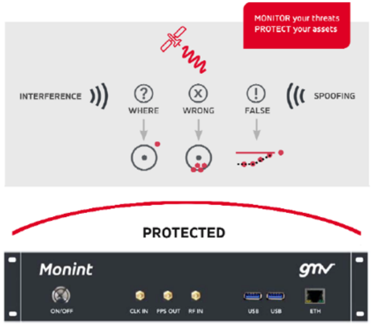


- All satellites remain available with EWF despite a slight drop in C/N0 of the affected signal

Conclusions and Recommendations

Conclusions

- Performance quickly drops when EWF is present.
- C/N0 of the affected satellite also drops by 1dB-Hz, which does not represent a significant impact in this metric, even if clearly noticeable.
- Affected satellite is never subject to a loss of lock, continuing to contribute to the positioning solution.
- **It is shown that an EWF detection mechanism is paramount to guarantee the integrity of the positioning system.**



SIGNAL QUALITY MONITORING
INTEGRITY MONITORING

> Multi-constellation
> Multi-frequency
> Classified signals monitoring
> Evil Wave Form Detection

Recommendations

- **Future Outlook**
    1) Support to additional constellations;
    2) Monitoring of Other Signal impairments;
    3) Sky Monitoring with Dissemination of Impairment Flags.

Thank you

MONINT Team

Further questions: space.portugal@gmv.com

INNOVATING SOLUTIONS