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► **To cite this version:**

Syed Ali Kazim, Nourdine Ait Tmazirte, Juliette Marais, Avag Tsaturyan. On the impact of jamming on Horizontal Protection Level and Integrity Assessment for Terrestrial Localization. ION ITM 2022 - International Technical Meeting of Institute of Navigation, Jan 2022, Long Beach, CA, United States. 15p. hal-03545790

**HAL Id: hal-03545790**

**<https://hal.science/hal-03545790>**

Submitted on 27 Jan 2022

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# On the impact of jamming on Horizontal Protection Level and Integrity Assessment for Terrestrial Localization

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## BIOGRAPHIES

Syed Ali Kazim has done a master's degree in Electronic Engineering. He received a specialization degree in Navigation and Related Applications from Politecnico di Torino (Italy) in 2017. He is currently a Ph.D. student at University Gustave Eiffel. His research activities are mainly devoted to GNSS signal characterization, error modelling and localization systems.

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Avag Tsaturyan works for M3Systems as a systems engineer focused on GNSS test and measurement activities since 2018. He received a master degree in automation and control systems from the National Polytechnic University of Armenia in 2016.

## ABSTRACT

Localization function for an advanced intelligent transport system, such as an autonomous vehicle, must ensure various operational requirements such as safety, accuracy, availability and continuity of service, anytime, anywhere, at a reasonable cost. Global Navigation Satellite System (GNSS) have many advantages insofar as they present the most accessible technology to the user to determine its position with a certain accuracy without prior knowledge. However, in an environment where signal reception may not be optimal especially due to phenomena such as satellite blockage, multipath, intentional or unintentional interferences and spoofing, it becomes very challenging to meet all these requirements, especially those related to operational safety. The latter is measured by evaluating the integrity of the localization function. It can be evaluated through a Protection Level, which is calculated by the receiver to self-monitor its integrity, also called RAIM (Receiver Autonomous Integrity Monitoring).

In the literature, integrity in presence of multipath and NLOS has been extensively investigated [1] as well interference detection and mitigation solutions [2]. However, the impact of interference presence and mitigation on integrity monitoring is not deeply addressed yet.

In this study, we evaluate some key performance indicators (KPI's) for GNSS users. These indicators will be evaluated for three different cases; 1) when no interference is applied and clean GNSS signals are processed. 2) In the presence of interference but without any mitigation technique. 3) After applying a mitigation technique at the pre-correlation level to filter the interference signal.

The mitigation technique relies on state-of-the-art Notch filters provided by a Septentrio receiver. The interference signals are generated in the laboratory to produce disturbances in the GNSS band.

Thus, and thanks to the a priori knowledge of the true position, it is possible to establish the Stanford diagrams for these cases. A deep analysis of performance in the presence and absence of interferences and in the presence and absence of a mitigation technique allows the first conclusions to be drawn on the evolution of accuracy, availability and operational safety indicators. The preliminary results reveal the importance of considering, from the design phase of the localization function, the possibility of dealing with this phenomenon, in particular in the measurement weighting model to use for enhanced performance.

## **INTRODUCTION**

The future of land transportation is revolutionizing toward providing more intelligent, connected, sustainable, autonomous and shared mobility. Nevertheless, there are associated many challenges with these future technologies and services. Among them will be the development of a robust localization system. The localization function complemented with the perception and the control can ensure safe navigation. Similar to other functions, the localization function has to meet some requirements during the design phase that must be guaranteed prior to the deployment.

The future trend of land transportation has highlighted the importance of Global Navigation Satellite System (GNSS) among other positioning technology. The main benefit of satellite positioning is that it can provide absolute position anywhere on the earth without any prior knowledge. GNSS relies on very weak signals therefore the signals are very much susceptible to many threats that could come from the nearby environment where the receiver is operating. Some of the very common threats include multipath, Non-line of sight (NLOS) signal, signal blockage and intentional/ unintentional interferences. These threats challenge the performance of the localization system. The performance indicator of the localization system varies depending on the application. Generally, the performance of the localization is evaluated from accuracy, availability and integrity.

In literature, the phenomenon of multipath and NLOS effects are extensively investigated, especially dealing with the detection and mitigation by either compensation (weighting) strategy and (or) by the exclusion of the faulty measurements [3][4]. The detection of such events brings integrity whereas mitigation improves the availability of the system. A proper weighting scheme with a multi-parametric model can simultaneously improve the integrity while reducing the cases of unavailability [5].

The importance of these three levers of action: the correct weighting of measurements, the detection of errors and their mitigation is therefore essential to achieve objectives that may seem paradoxical (Integrity / Safety versus availability). These studies presented the performance of the proposed solution in dealing with NLOS and multipath. The presence of NLOS and multipath affects one or very few measurements depending on the density of the obstacles around the acquisition but interference whether intentional or non-intentional effects all the measurements in a similar manner.

In literature, several approaches are investigated to detect and counter the effects of the interference signal. These techniques are implemented at various signal-processing stages of the receiver chain. These techniques are typically implemented at the Front-end level, pre-correlation level, post-correlation level, and navigation level. Signal processing techniques are well investigated to counter the interference signal [6]-[17]. Spatial filtering [18][19] uses multiple antennas to control digitally the gain pattern of the antenna towards the GNSS satellites while suppressing the signal coming from the direction of the interferer. In vector tracking [20][21] each channel is jointly tracked through the feedback of a receiver state from the navigation module thus allow increased robustness of the receiver in the presence of interferer, and lastly, Inertial Aiding [22] uses other sensors such as accelerometer, gyroscope, and cameras as a countermeasure to the interference. [23] presented the effect of interference mitigation measures on the estimated position, in other words on the requirement of accuracy. This study attempts to assess the impact on the KPIs for a particular interference scenario before and after mitigation is applied. For this reason, three scenarios will be presented where GNSS signal is acquired 1) in the absence of interference 2) in the presence of interference but without interference mitigation 3) interference in the presence of active mitigation technique.

The paper is divided into several sections. Section 1 is devoted to the interference. We will discuss sources of interference, different characteristics of interference signal and a classical interference mitigation technique. Section 2 is dedicated to the positioning function mainly discussing the weighted least square (WLS) solution, some common and well know weighting schemes and a classical manner to estimate the protection level. Section 3 will be focusing of the acquisition system used to collect GNSS measurements, the interference scenario similar to discontinuous frequency hopping, lastly the analysis of the results and the future work.

## **I. INTERFERENCE: A MATTER OF CONCERN FOR GNSS?**

In this section, we present some potential interference sources, their characteristics and some classical techniques to mitigate or suppress the effects of an interfering signal.

The GNSS receiver relies on satellite signals that are already very weak as they arrive at the antenna placed on the ground. Due to this reason, the receiver operation can be easily disrupted in presence of an interfering signal. Consequently, it can degrade the performance of the receiver. In the worst case, it also can overpower completed satellite signals and deprive receiver from acquiring and tracking the satellite signals.

### **A. Interference sources and signal characteristics**

Radio Frequency Interference (RFI) can be divided into two categories: intentional and unintentional interference. Personal Privacy devices (PPDs) also known as jammers are the most common source of intentional interference. In the case of jamming, the interferer deliberately transmits signals inside the GNSS band with such devices to prevent the receiver from acquiring the satellite signals. Although it is illegal to use such devices but several reported incidents pointed out jammer as the source of interference causing GNSS service outages in a large area. These devices are very cheap and can be easily purchased from online stores.

The other form is the unintentional form of interference that could be an in-band or out-band interference. Since GNSS is also sharing some of its frequency resources with other wireless systems that are transmitting the signals within the same frequency band. It includes aeronautical systems (DME/TACAN) and amateur radio services. These systems are also the potential interference sources that can severely affect the tracking capabilities of the receiver. There are many communication systems described in [24] that can be possible sources of interference

These wide ranges of interference sources will affect differently the GNSS receiver. The distortion on the GNSS signals induced by the interference sources largely depends on the characteristics of the interfering signal. It could include frequency, modulation, duration, power, bandwidth and the rate of frequency change for the time-varying interference signal. Figure 1 illustrates the spectral characteristics

of some common interference signals; 1) Single tone Amplitude Modulation (AM), 2) Frequency Hopping, 3) Dual-tone chirp and 4) DME-like signal.

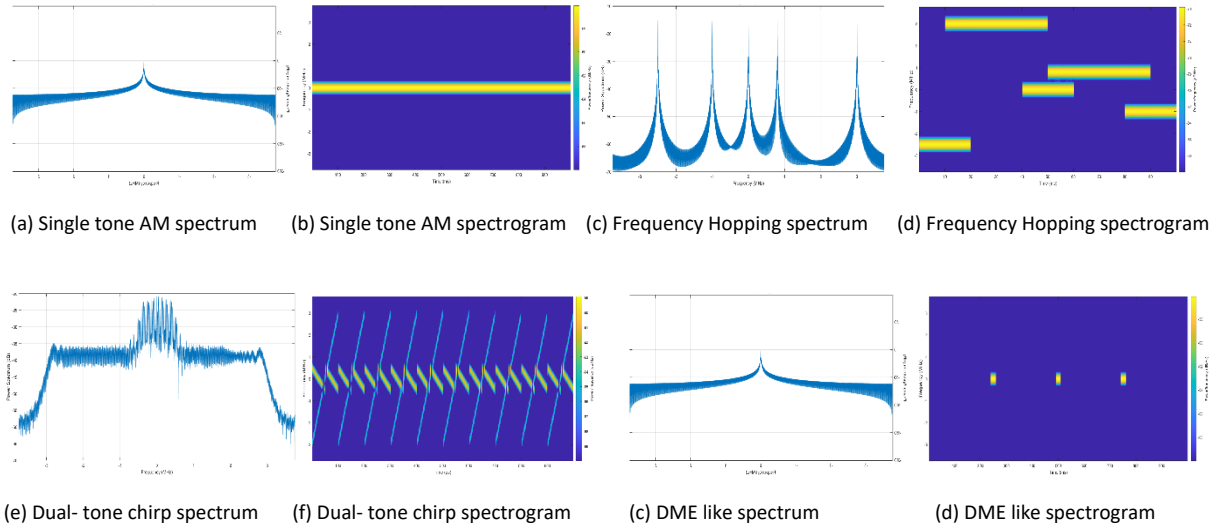


Figure 1. The spectral characteristic of some typical interference signals in the baseband.

## B. Interference mitigation technique at signal processing stage

In literature, several approaches have been investigated to detect and counter the effects of the jamming signal. The preferable manner is to suppress the unwanted signal in the initial stages perhaps before signal spreading (i.e. correlation with the local code). It is because post-correlation methods require a normal signal acquisition and tracking as a precondition.

The techniques at the pre-correlation level are well investigated in the literature. In [5]-[7] the pulse blanking method is considered for the suppression of interference from DME/TACAN system. In some of the pulse banking architecture behavior of AGC is monitored to activate the blanking system. [9]-[12] different architectures of Adaptive Notch Filter are investigated to cancel the effect of the time-varying CWI interference. [13] investigated the uses of Wigner-Ville Distribution (WVD) to estimate the instantaneous frequency of the signal and notch filter for suppressing interference signal. [14]-[17] assess the use of wavelet techniques for suppressing the CW and pulse interference.

## C. Mitigation technique: Adaptive Notch Filter (ANF)

The Adaptive Notch Filter (ANF) is the extension of the Notch Filter (NF) or Band Reject Filter that has a flat response for a maximum portion of the frequencies while it rejects a very small portion of the frequency spectrum.

In ANF architecture, the NF block is supported by an adaptation block that continuously updates the coefficients of the notch filter. A proper selection of adaptation parameters will allow the filter to effectively track and suppress the interfering signal. This will allow the receiver to operate even in the presence of an interfering signal.

The transfer function of the single-pole Infinite Impulse Response (IIR) notch filter is given as:

$$H(z) = \frac{1 - z_0 z^{-1}}{1 - k_\alpha z_0 z^{-1}} \quad (1)$$

where  $k_\alpha \in [0,1)$  is the pole contraction that regulates the bandwidth of the notch.  $z_0$  is the zero of the filter which determines the notch center frequency which corresponds to the estimated jamming frequency.

The relation between  $z_0$  and the notch frequency  $f_0$  is expressed as

$$f_0 = \frac{f_s}{2\pi} \angle z_0 \quad (2)$$

Where  $f_s$  is the sampling frequency. An ideal notch filter would have a narrow notch bandwidth to suppress the jamming signal while preserving mostly the GNSS signal. The 3dB bandwidth of the filter can be estimated as

$$B_{3dB} \approx (1 - k_\alpha) f_s \pi / 10 \quad (3)$$

This indicates that as  $k_\alpha$  approaches to 1 the bandwidth of the notch gets narrower.

The ANF has an adaptation block that continuously moves the  $z_0$  in the complex plane and converges to the interference central frequency using a gradient descent algorithm. At each step, it iteratively minimizes the energy of the cost function and updates the value of  $z_0$ .

$$z_0[n] = z_0[n-1] - \mu[n] g(J[n]) \quad (4)$$

Where  $\mu[n]$  is the algorithm step,  $g(J[n])$  is the stochastic gradient of the cost function  $J[n]$ . The cost function can be set either to minimize the expectation of the output energy of the autoregressive block or the output energy of the notch filter [23].

## II. INTEGRATION ALGORITHM, WEIGHTING SCHEMES AND PROTECTION LEVEL COMPUTATION

### A. The Weighted Least Square (WLS)

The behavior of the localization function is very much linked to the positioning estimation filter. It can be a snapshot method such as Ordinary Least Square (OLS) or the Weighting Least Square (WLS), or the recursive method such as Kalman Filter. In our work, we have chosen the snapshot method, particularly the WLS algorithm. This allows us to capture the impact of interference and also avoid the smoothing effect due to recursivity in the position estimation.

The linearized pseudorange observation can be written as

$$\delta\rho = H \times \delta X + \epsilon \quad (5)$$

Where  $\delta\rho$  is the difference between the measured pseudorange and the predicted pseudorange that is estimated from the linearization point.  $H$  is the linearized observation matrix.  $\delta X$  the error state vector.  $\epsilon$  is the measurement error vector.

The WLS solution of  $\delta X$  is:

$$\delta X = [H^T W H]^{-1} H^T W \times \delta \rho \quad (6)$$

Where  $W$  is the observation weighting matrix. For the WLS, it is the way to give confidence to the measurements. The smaller the error variance, the more it must be considered in the final solution.

$$W = \begin{pmatrix} 1/\sigma_1^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1/\sigma_m^2 \end{pmatrix} \quad (7)$$

## B. Weighting Schemes

The pseudorange provided by the receiver contains the error contribution like satellite clock error, ionospheric error, tropospheric error, NLOS / multipath, and receiver clock error. The clock errors are directly accounted in the state vector. The other sources of error can be global errors that include atmospheric errors. These are corrected either by applying respective models or by SBAS data. The so-called local errors are due to the local effect (discussed previously) that comes from the receiver-operating environment and can induce disturbances.

The role of the weighting scheme is to contain such effects that bring uncertainty in the measurements. For example, there is a large dependence on the variance and the elevation of the satellite. [25] [26] have shown that global effects and feared local events (multi-path, NLOS) affect each visible satellite differently, low-altitude satellites are the most affected. [27] [28] have proposed a sin-type function for the determination of the variance:

$$\sigma_i^2 = 1 / \sin(el_i)^2 \quad (8)$$

[29][30] investigated the impact of the received signal quality on the error variance and introduced the use of  $CNO$  to weight GNSS observations. This  $CNO$  weighting strategy was extended by [31][32] to respectively develop the sigma- $\epsilon$  and sigma- $\Delta$  models. [33] has proposed a generic formula of sigma- $\epsilon$  that works with all types of receivers:

$$\sigma_i^2 = V_i + C_i 10^{\frac{-CNO_i}{10}} \quad (9)$$

where  $V_i$  ( $m^2$ ), and  $C_i$  ( $m^2 Hz$ ) are a receiver, antenna and frequency-dependent model parameters.

In [34], a comparison of elevation and  $CNO$  based models is given where it is shown that low elevation satellites are more accurately weighted with  $CNO$ . A hybrid model with  $k$  factor as a LOS indicator is proposed [35]:

$$\sigma_i^2 = k \frac{10^{\frac{-CNO_i}{10}}}{\sin(el_i)^2} \quad (10)$$

The models described above take advantage of the knowledge of the elevation and/or the carrier to noise ratio to estimate the variance of GNSS observations. These approaches greatly improved the estimation of the position compared to an approach that would consist of establishing an identical choice of variance for all the observations. Moreover, these models also help in the estimation of measurement uncertainty.

### C. HPL Computation

The HPL is a statistical limit making it possible to guarantee a very high probability (called Integrity Risk Target) that the true position error is contained. There are several proposals for HPL in the literature, such as the Isotropy Based Protection Level (IBPL) developed proposed by GMV [36]. In this study, we implement the classical method consisting of decomposing HPL into two components a noise term  $HPL_n$  and a bias term  $HPL_b$ :

$$HPL = HPL_n + HPL_b \quad (11)$$

The noise term is calculated according to the error propagation [37] as for HPL computed with SBAS data (mostly for aeronautic applications):

$$HPL_n = K(P_{md}) \times d_{major} \quad (12)$$

where  $K$  is an inflation factor allowing to meet the integrity risk requirement. It is generally obtained conservatively, by selecting the 4 degrees of freedom value in the  $\chi^2$  table;  $d_{major}$  is the error uncertainty along the semi-major axis of the error ellipse. More details can be found in [37][38].

The bias term is the most affected by the change in weighting strategy. Indeed, the latter intervenes directly insofar as this term consists in the satellite geometry information and the detectable bias presented in the FDE section:

$$HPL_b = \max_i (Slope_i \cdot \sigma_i) \times p_{bias} \quad (13)$$

where the slope is given as

$$Slope_i = \sqrt{\frac{(H_{N,i}^+)^2 + (H_{E,i}^+)^2}{S_{ii}}} \quad (14)$$

with  $H^+ = [H^T W H]^{-1} H^T W$  and  $S = I - H H^+$ ;  $\sigma_i$  is the standard deviation provided by the proposed model, of the  $i$ th measurement;  $p_{bias} = \sqrt{N S S E}$ , this choice is explained in [35].

Finally, HPL in our study is chosen as:

$$HPL = K(P_{md}) \times d_{major} + \max_i (Slope_i \cdot \sigma_i) \times p_{bias} \quad (15)$$

## III. EXPERIMENTAL PROTOCOL

### A. Data Acquisition

For this study, we carried out an acquisition campaign to record GNSS measurements from a static position. The acquisition system consists of a multi-frequency and multi-constellation Septentrio (AsterRx4) receiver and PolaNT AT1675-29S antenna placed on the rooftop of the laboratory building. The main purpose of acquiring signals from the roof antenna is to record a relatively clean signal representative of optimal conditions i.e. free from the effects coming from the antenna surrounding environment.

Universal Software Radio Peripheral (USRP 2910) is used to generate the interference signal. A monotone interference signal combined with a GNSS signal captured by the antenna is fed to the receiver over the wired link. The interference is applied at several intervals throughout the complete thirty minutes acquisition duration. In the scenario, the interference source is removed for some time to permit the receiver to return to the nominal situation before the start of another interference instance. At each



instance, two different tones are transmitted to produce interference within the GPS L1 band. The tones are transmitted some few seconds apart from each other therefore are simultaneously present for a very short duration. Similarly, the interference tone continues to hop within 6 MHz of GPS L1 band. The interference profile is presented in figure 2.

We have recorded three scenarios for the comparative study. In each case, the GNSS signals are

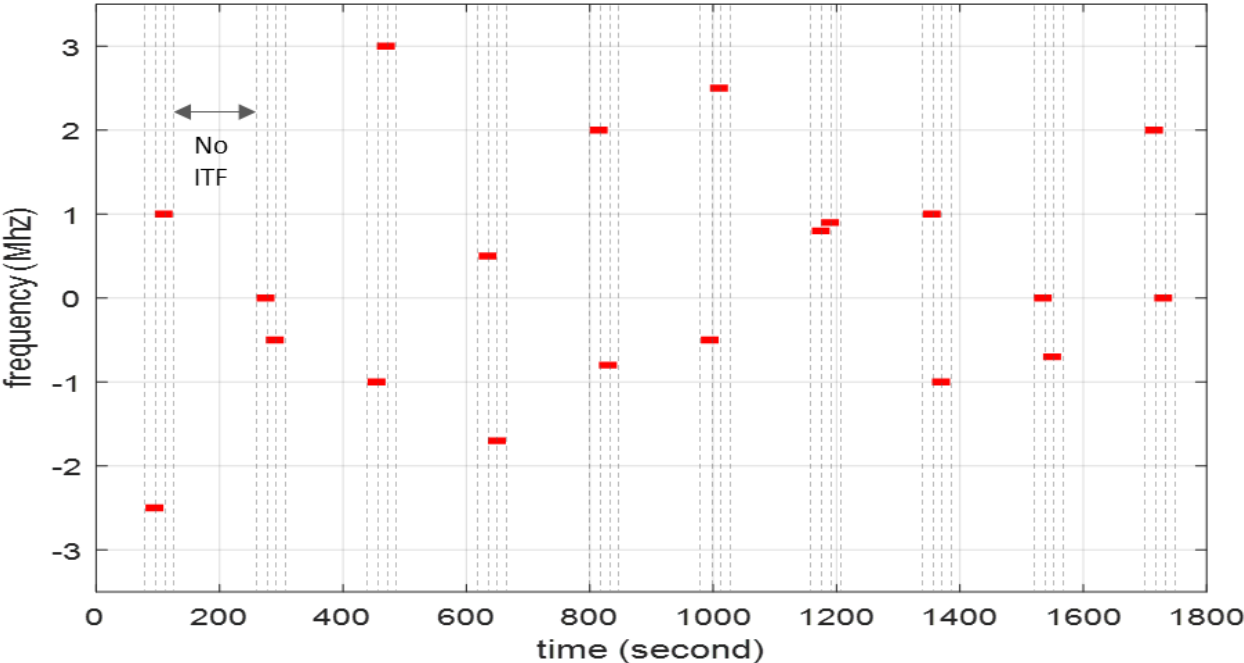


Figure 2. Interference profile at the baseband frequency vs time. The tones (red) continue to hop randomly within  $\pm 3$  MHz around the GPS L1 frequency. The dashed vertical lines highlight the regions where interference is active. Each tone is active for 30 seconds.

acquired; 1) in the absence of an interference signal. 2) in the presence of interference without applying any mitigation technique and 3) in the presence of interference and with an active mitigation technique.

We have selected the mitigation technique provided by the receiver itself to filter the effects of the interference signal. The 2 notch filters are activated and are set to auto mode. Each notch filter is dedicated to track different tones that could be present at the same time at a different frequency to properly suppress the interference signal.

The purpose of this study is to evaluate the impact on KPI's for the three cases presented previously. In this first study, we successively recorded the measurements to avoid time synchronization constraints among the different cases. It would either require a synchronization system to harmonize the interference injection in the same scenario replayed over again or would require parallel acquisition with multiple receivers. We assume that the configuration of the satellite would generally remain identical as the measurements are collected in very optimal conditions. Figure 3. shows the configuration of the satellite for the three scenarios.

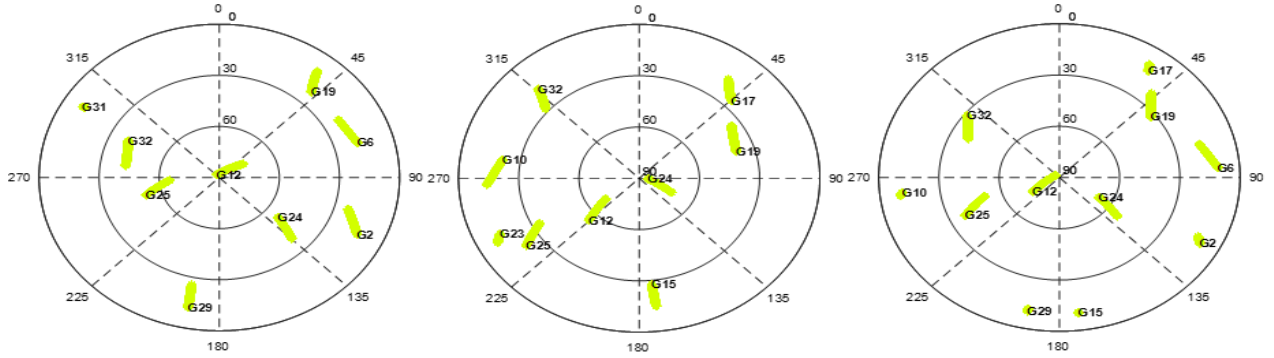


Figure 3. Sky plot to show satellite configuration for the three cases; Reference (Right) without interference, interference with no mitigation applied (center), and interference with active mitigation block.

## B. Results and Analysis

The objective of this study is to analyze the impact of interference and the mitigation technique on the KPIs. We present three cases for this purpose where the satellites signals are acquired; 1) without interference, 2) with interference but no mitigation applied and 3) interference with active mitigation technique and the performance indicators such as accuracy, availability and integrity are analyzed.

Figure 4 and Figure 5 clearly show the impact of interference and the importance of a good mitigation technique in the accuracy of the positioning system. From the Stanford diagram, it can be seen that in the absence of interference, the errors are very small ( $< 2$  meters) as the points are much more concentrated. This is a very obvious case as the measurements are collected in very optimal conditions, therefore, show high accuracy. In the case of interference and without mitigation technique the impact of interference is very much evident as the large number of points representing error greater than 10 m. When interference mitigation is applied, we can see that the accuracy in the position is greatly improved. Unexpectedly, the results show that the weighting models do not significantly affect the positioning accuracy in our case.

We believe that it is probably since the acquisition is done in very optimal conditions. Moreover, the presence of the interference has a nearly similar impact on every satellite. This behavior has to be further investigated therefore is not discussed.

It is very obvious from Figure 4 and Figure 5 how the choice of the weighting scheme could impact the performance requirement of the localization system focusing on the three cases presented above. Figure 4 provides a more insight view by taking into consideration the variation of some of the parameters (carrier to noise ratio, elevation, satellite visibility) that play an important role in the estimation of performance parameters with the time evolution. We consider time analysis also very important for several reasons;

- 1) The three scenarios are recorded successively within 2 hours period. It is evident from the sky plot presented before that the configuration of the satellites has changed over time. Note that the purpose of time analysis is not to draw a comparison between the different scenarios since they were recorded at different times but it can help to analyze the impact of weighting schemes on the protection level for the same scenario.
- 2) The interference and the mitigation case will also play a role in the variation of PL therefore both cases have to be analyzed separately.

In figure 4 and figure 5 we can observe the significance of the weighting scheme in the estimation of the protection level for all three cases. When interference mitigation is not applied, PL estimated from the CN0-based weighting scheme seems to closely follow the variation of the CN0 measurements as can be seen in figure 5c and figure 5d. The presence of interference has a direct impact on the CN0, as a

result, it brings normal operation to 81.751% with 321 unavailable points. Moreover, it ensures completely the safe operation without any HMI. After the recovery of CN0 due to the mitigation technique, the normal operation increases to 98.333% and with 30 unavailable points. In general, it is seen that CN0 model appears to be very conservative whenever interference or the residual of interference are present.

The sine model takes into consideration the elevation of the satellites. It gives a large weightage to the high elevation than the satellite at low elevation. It does not take into account the signal quality that is important in the case of interference. In the presence of interference and without mitigation, it resulted in more normal operations 93.462% compared to CN0 model but at a cost of 19 HMI points and 4 MI points. When mitigation is applied the model becomes very conservative. This results in reduced normal operations 80.722% with 347 unavailable points.

The Hybrid model is the combination of the elevation and CN0 models. Therefore, it is expected that the hybrid scheme is the most conservative in comparison to other models. The results clearly show that in case of interference without mitigation, the normal operations are reduced to 74.474% and 449 unavailable points. Similarly, in the case of interference with active mitigation, 67.611% of the points are in normal operations and with 583 unavailable points.

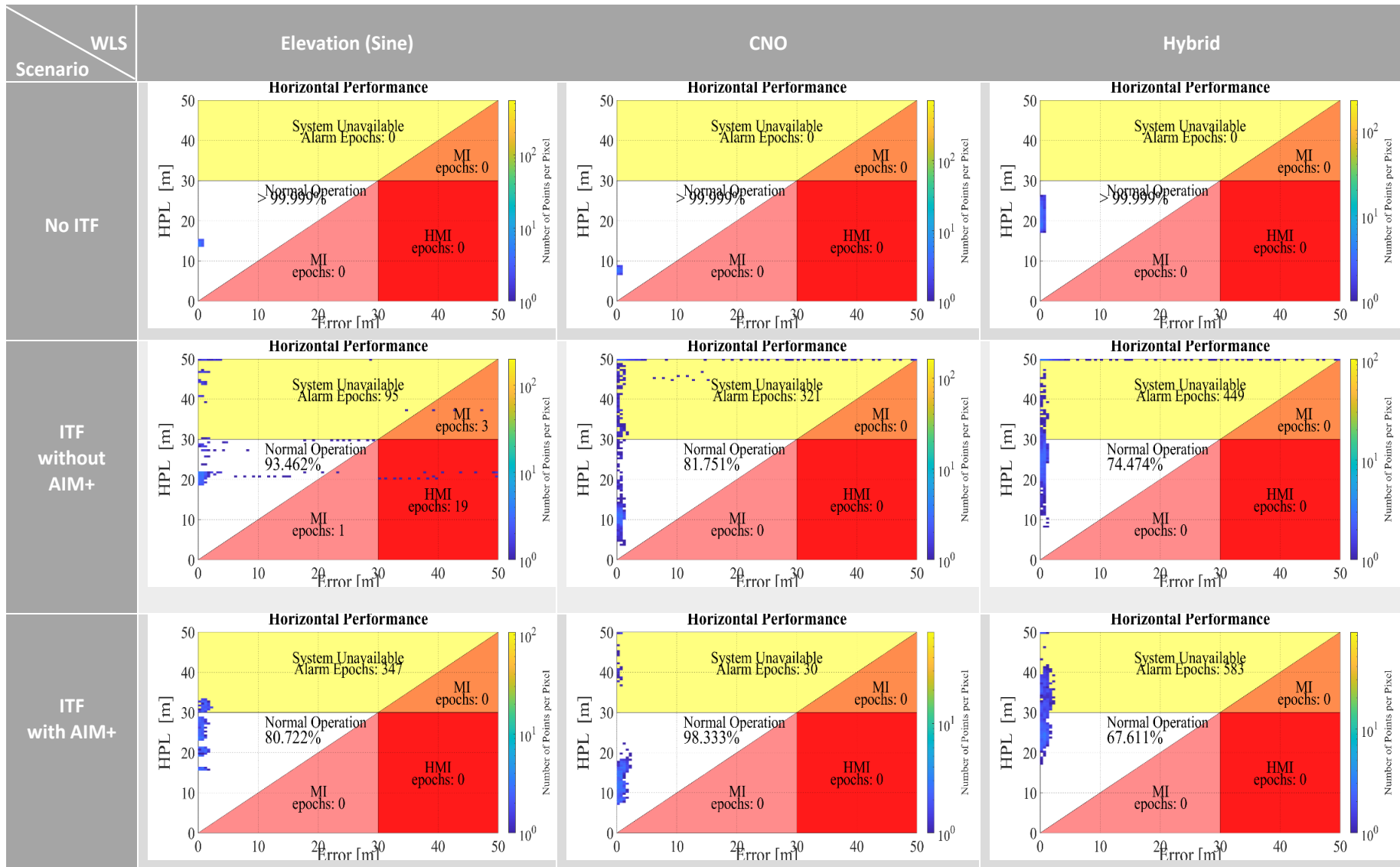
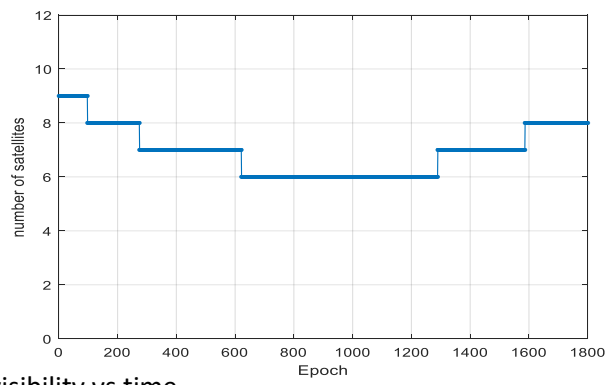
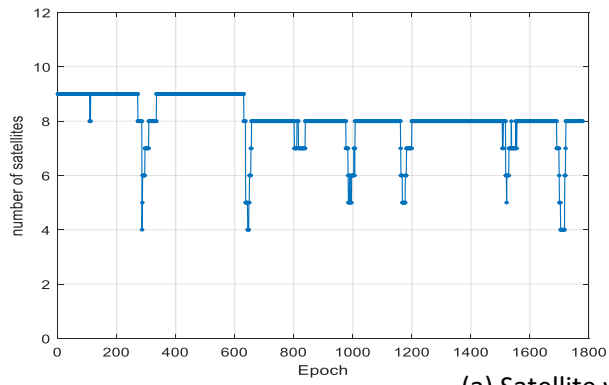
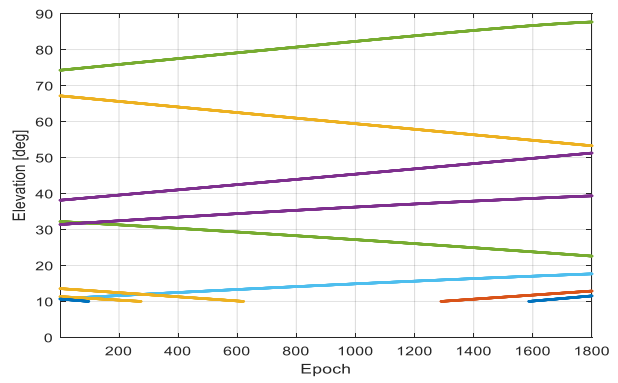
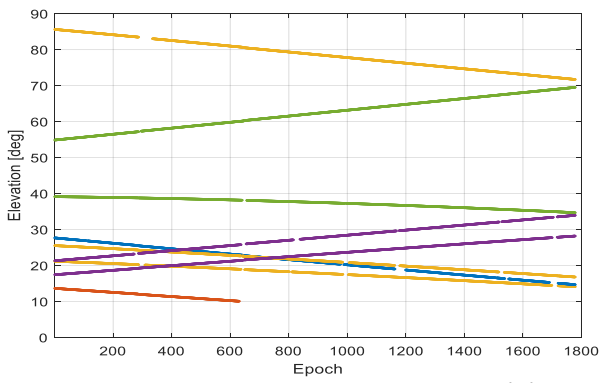


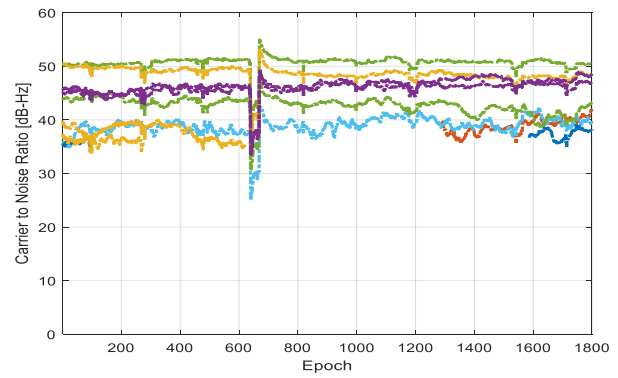
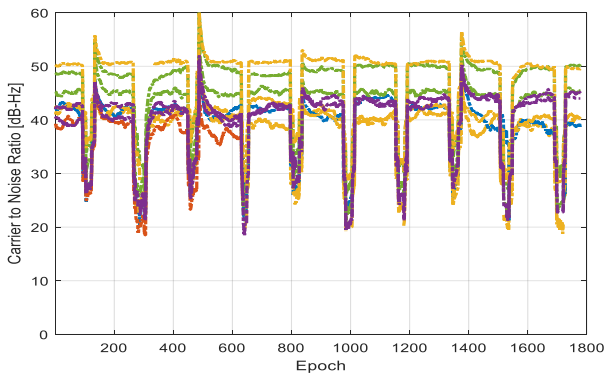
Figure 4. Stanford diagram of each weighting scheme representing the scenarios of acquisition; in the absence of interference (ITF) (upper row), in the presence of ITF but without mitigation (middle row), and in the presence of ITF and with active mitigation (lower row). Here the ITF mitigation (AIM+) provided by the Septentrio receiver is applied.



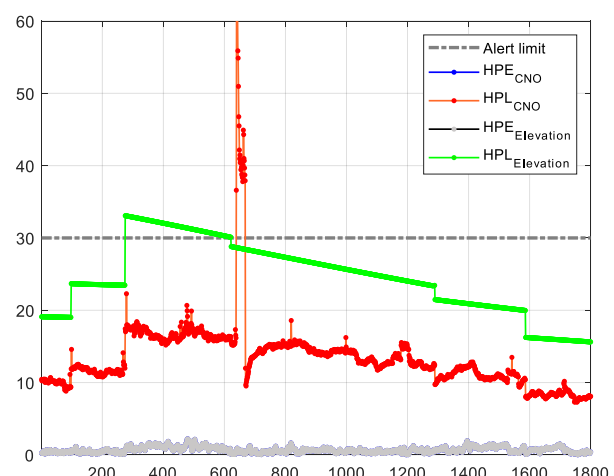
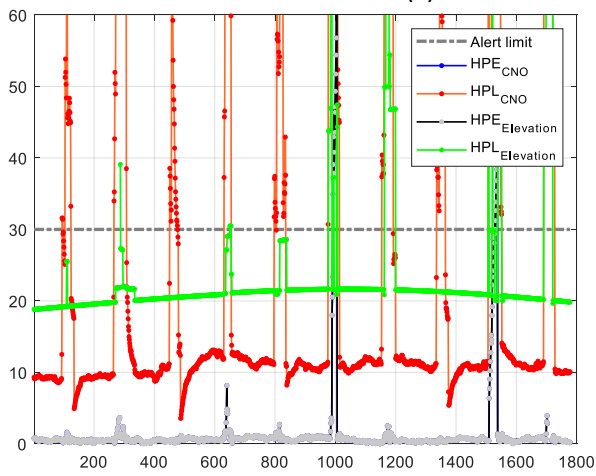
(a) Satellite visibility vs time



(b) Elevation vs time



(c) Carrier to Noise ratio vs time



(d) HPE and HPL vs time

Figure 5. The assessment of different parameter (carrier to noise ratio, elevation and satellite visibility) contributing in the estimation of the HPE and HPL vs time. The interference scenario without mitigation (Left) and after applying mitigation technique (right)

## CONCLUSION

With the proliferation of communication systems in an increasingly connected world and the development of sophisticated jamming means, interference is a major issue for a location function integrated into a land transport system. In this study, we set up an experimental protocol to assess the impact on the usual performance indicators of a localization function using only GNSS. We presented three scenarios: 1) no interference is applied, 2) in the presence of interference but without mitigation, 3) the interference is mitigated. We also studied the behavior of the usual weighting models (elevation based, CN0 based and hybrid model) for each scenario. It has been observed, as expected, that interferences when they are not mitigated, can have a bad impact on the availability of the system. Additionally, they cause hazardous misleading information (HMI) which questions the integrity of the provided solution. However, in this same case where the interferences are not mitigated, the different possibilities of weightings react differently. The weighting model based solely on elevation is found to be the least effective since it is not considering the impact of interference. So elevation is no longer the predominant criterion for weighting in our case. CN0 based weighting model turns out to reduce the number of HMIs while compromising the availability. Finally, the hybrid model turns out to be the most conservative weighting model when dealing with interference. The same observation had been made in previous studies concerning NLOS and multipath.

In the case when mitigation is applied the first observation made is that there is no more HMI. For the scenario played (frequency hopping) and the simulated intensity of the interference, the filtering technique of the receiver seems very effective. However, some unavailability is noted for the three weighting models proposed. This unavailability is much more dominant in the weighting model based on elevation and the hybrid model.

These results presented here are very much representative of interference scenarios and the characteristics of the interference signal. In addition, the three scenarios were recorded sequentially, which does not permit us to compare the three scenarios.

This study with informative results will continue to improve the experimental protocol to guarantee a perfect synchronization of the different scenarios either by recording the three scenarios via a single antenna, a splitter and three identical receivers dedicated to recording in parallel the three cases. Otherwise, it would require a single acquisition that can be playback multiple times in the same scenario. In the future, this constraint could be relaxed with the GNSS simulator and interference simulator (thanks to the Stella HIL simulator provided by M3Systems). A larger amount of data with more diverse scenarios (different jammers at different distances/powers, different types of interference signal chirp, DME like, frequency hopping etc ...) will then be implemented. Finally, the same study on a multi-sensor localization system could also be carried out.

## ACKNOWLEDGEMENTS

The present work benefits from the financial support of the ANR French Research Agency within the project LOCSP No 2019-CE22-0011

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