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A New GNSS Integrity Monitoring Based on Channels Joint Characterization

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***Abstract*— Many GNSS (Global Navigation Satellites System) applications need high integrity performances. Receiver Autonomous Integrity Monitoring (RAIM), or similar method, is commonly used. Initially developed for aeronautics, RAIM techniques may not be fully adapted for terrestrial navigation, especially in urban environments. Those techniques use basically the pseudoranges to derive an integrity criterion. In this paper, we introduce a new integrity criterion based on the correlation quality of each channel. This quality assessment is computed from the correlation levels for each channel, all based on a single position and speed. Hence, as the so-called Direct Position Estimation (DPE), we exploit the joint behaviour of all channels to detect any incoherence at an upstream step of the processing. This Direct RAIM (D-RAIM) allows detecting possible integrity problems before it can be seen on a classical RAIM scheme that only exploits the outputs of each channel.**

Keywords*— Integrity; GNSS; receiver; navigation; satellites; DPE; RAIM; DRAIM

I. INTRODUCTION

The satellite navigation systems can be characterized by several Required Navigation Performance (RNP) parameters: accuracy, continuity, availability and integrity which define the required safety level for a navigation system [1]. The integrity concept has been developed for aviation to prevent from the risk of deviation from a predefined flight path [2]. It has been extended afterwards to sea and terrestrial transportation.

Because of its stand-alone capability, Receiver Autonomous Integrity Monitoring (RAIM) is usually chosen in the integrity process at the user segment level. This algorithm performs a consistency check on the satellite measurements. It can detect and exclude spurious pseudoranges, to provide an "*a posteriori*" estimate of the position error. In some specific cases, the performances of RAIM can be dramatically degraded. Indeed, the receiver requires at least four satellites in view to estimate its position and the clock bias. Being based on the measurements redundancy, these performances depend on the number of additional satellites which can be low, especially in urban environment.

We propose in this paper a new integrity criterion based on channels joint characterization which uses all the available information in the reception chain. This parameter estimates the measurements coherence and detects an a priori navigation risk. Indeed, any error or inconsistency between channels impacts this highly sensitive criterion, even if it does not lead directly to a flawed positioning. This parameter can be integrated in a RAIM technique as the main factor to monitor the navigation integrity. Hence, the main objectives of this paper are first to prove the relevance of integrating the new criterion in an autonomous integrity monitoring, and then to exploit it in the navigation solution estimation.

This paper is organized as follows: Section II describes the integrity concept and its monitoring by the RAIM algorithm. Section III introduces the proposed integrity management method based on raw data processing. Section IV brings to light the relevance of the proposed criterion by simulations. Finally, section V suggests several perspectives.

II. INTEGRITY AND RAIM

A. Receiver Autonomous Integrity Monitoring

Integrity is a measure of the trust which can be placed in the correctness of the information supplied by the navigation system. It includes the ability to provide timely warnings to the user in case of hazardous navigation. The presented work focuses on the integrity management at the receiver side, in the context of terrestrial navigation.

Autonomous integrity monitoring is based on the satellite measurements redundancy, which can be augmented by additional sensors. In this study, we focus on RAIM technique, which only bases the integrity assessment on the received satellite data in order to detect, to identify and to exclude faulty measurements. The fault detection and the fault exclusion are then the two main functions of the algorithm. RAIM technique must also predict its ability to protect the user considering satellite geometry and an assumed measurement model [3].

Several RAIM features make this method widespread, as for example:

- Stand-alone capability,
- Compatibility with any GNSS system,
- Flexibility: possibility to develop particular versions, with respect to the chosen application needs.

RAIM requires at least five satellites in view in order to get the fault detection capability. If an unacceptable error is detected, a warning must be sent to the user, indicating that the current GNSS should not be used currently for navigation. Assuming that one or less faulty measurement is present, RAIM requires a minimum of six visible satellites to exclude the faulty one in the navigation solution and to allow an uninterrupted operation. These detection and exclusion functions (FDE) are generally based on the comparison of a statistic test and a defined threshold.

Hence, following the FDE tests, the receiver position is updated using the selected measurements. Most of the time, another step is performed by the RAIM algorithm consisting in horizontal and vertical protection levels computation. These bounds depend on the RAIM threshold and the satellites-received geometry and are defined as areas around the real position of the receiver. RAIM is declared available if these protection levels are grossed up respectively by defined horizontal and vertical alert limits. Further details can be found in [3].

Several classes of RAIM techniques exist, with distinct statistic tests and processes. They are still all based on the pseudoranges redundancy and they all aim at determining the self-consistency of measurements. Several RAIM versions are listed below, with corresponding references:

- Least Square Residual (LSR) method (the conventional technique): the sum of squares of the measurement residual defines the current decision variable. The computations are described in [3]. In addition, the Weighted LSR (WLSR) is also useful to improve the algorithm performances.
- Parity Method (PM): The test variable is based on a parity vector, resulting from the projection of the measurement vector on the parity space [4]. The Generalized Likelihood Ratio (GLR) has been developed and is detailed in [3]. Its main objective is to detect only fault leading to a positioning failure.
- Range Comparison method (RCM): The test variable is based on the comparison between the predicted measures from a 4-satellites navigation solution and the received data [5]. In addition, LSR, PM and RCM provide similar performances at different computation costs according to [6].
- Novel-Integrity Optimized RAIM (NIORAIM): In this method, a pseudoranges weighting is presented. It tends to decrease the protection levels, and then to improve the availability of the system. [7]
- Maximum Solution Separation (MSS): This technique is based on the separation between the position estimation using all the satellite measurements and those using satellite subsets [3]. Based on this principle, a Multiple-Hypothesis Solution Separation (MHSS) algorithm has been developed and is described in [8].
- Advanced-RAIM (ARAIM): In order to fulfil the requirements of the new LPV-200, the GNSS Evolutionary Architecture Study (GEAS) developed an Advanced-RAIM, based on the MHSS method. The description of the ARAIM architecture is detailed in [9]. This algorithm will provide many improvements, such as the system availability under a single fault assumption; moreover, it will permit to detect a constellation-wide satellite faults (which is impossible using only one constellation). As a reference, [10] presents an ARAIM airborne algorithm description, bringing to light the capability of protection against a multiple fault threat model.

This non exhaustive list shows the diversity of the algorithms based on the conventional RAIM. The recent techniques, particularly ARAIM, provide near optimal performances for aviation. For terrestrial navigation, especially in urban environments, the required performances differ from the aviation case. Hence, the developed RAIM versions may not be adapted for the chosen context. This observation has motivated the search of other RAIM process.

In this paper, we assume that no augmentation system or external data is available. The E5a signal of the Galileo system is used. Galileo being here the only navigation system used, the integrity parameter is crucial.

B. *Toward a joint estimation approach*

In the chosen navigation context, the conventional RAIM technique can present several major drawbacks. Indeed, this algorithm focuses on the navigator output, using potentially a pseudo-ranges weighting method. In an urban environment, many problems can occur, such as:

- Spurious signals reception as multipath (MP), radio-frequency interferences (RFI),

- Masking: the low number of satellites in view in order to estimate a quite large number of unknowns: the Position, Velocity, Time (PVT) and the navigation integrity. The estimation of the measurements noise can then be flawed, even impossible with only four channels,

- Weak satellites geometry and generation of high error bounds.

In order to improve the navigation performances in harsh environments, particular positioning techniques have been developed and have proved their efficiency and robustness. The Direct Position Estimation (DPE) method is directly based on the received GNSS signal: it estimates the PVT from the maximum likelihood (ML) technique. This joint approach has shown an important contribution in the context that we chose in this paper, in comparison with the conventional navigation method (see section III.B for further details). The performances provided by this joint characterization have motivated the development of a new integrity assessment called Direct-RAIM (D-RAIM), as presented in the next section.

III. DIRECT-RAIM

A. *Signal Model*

The received signal is considered to be a superposition of plane waves. Considering N snapshots, the digitized received complex baseband signal model can be written as:

$$x = \sum_{k=1}^{K} \alpha_k a_k(\Theta) + n \qquad (1)$$

With:

- $x \in \mathbb{C}^{N\times 1}$ the received signal,

- K the number of SiV (Satellites in View),

- $\alpha_k \in \mathbb{C}$ the k-th signal amplitude,

- $a_k(\Theta) = \begin{bmatrix} c_k\big(t_0 - \tau_k(\Theta)\big)e^{-i2\pi f_k(\Theta)t_0} \\ \dots \\ c_k\big(t_N - \tau_k(\Theta)\big)e^{-i2\pi f_k(\Theta)t_N} \end{bmatrix} \in \mathbb{C}^{N\times 1}$ the vector of transmitted unitary signals,

- Θ the PVT vector,

- $c_k$the k-th signal code (the transmitted navigation signal spread by the pseudo-random noise (PRN) code)

- $[t_0, \dots, t_N]$ the vector of time samples,

- N the number of snapshots for the digitized received signal,

- τ_k the k-th signal delay,

- f_k the k-th Doppler deviation,

- $n \sim N(0, \sigma^2) \in \mathbb{C}^{N\times 1}$ the assumed zero-mean additive white Gaussian noise.

The vector format of the signal model is given by the following equation:

$$x = A(\Theta)\alpha + n \qquad (2)$$

With:

- $\alpha \in \mathbb{C}^{K\times 1}$ the vector of complex amplitudes,

- $A(\Theta) \in \mathbb{C}^{N\times K}$ the matrix in which each column represents the k-th satellite signal, with respect to the current PVT. For the sake of simplicity, it will be written as A.

B. *Direct Position Estimation*

To estimate the real-time PVT $\widehat{\Theta}$ of the receiver, the conventional method consists in a two-steps procedure: first, the parameters of each satellite signal are estimated separately (delay, Doppler, etc); then, the trilateration step provides $\widehat{\Theta}$ from the previous estimations. In a harsh environment, the performances of this method can degrade: for example, the reception of spurious signals can lead to a flawed positioning.

As explained in II.B, another method has been introduced in [11], which consists in a direct estimation of the PVT using the ML. It has been called DPE. Fig. 1 shows the principle of the DPE method, compared with the conventional two-steps procedure.

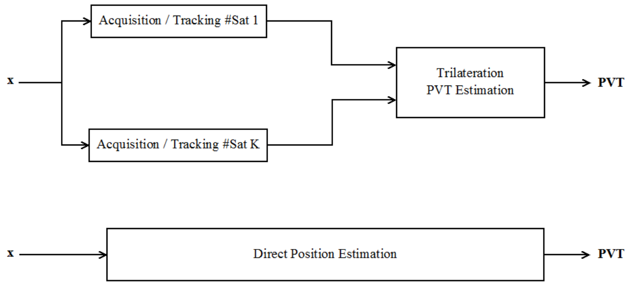

Figure 1: Block diagram of the conventional two-steps procedure (top) and the DPE (bottom)

The solution of the ML method is provided by the maximization of the following cost function:

$$\Theta_{ML} = argmax_{\Theta}(x^H P_A(\Theta)x) \tag{3}$$

With :

- $P_A = A(A^HA)^{-1}A^H$ the projection matrix on the signal subspace.

A comparative study of the DPE and the conventional two-steps method performances has been realized and is explained in [12]. It proves that the DPE outperforms the conventional method, especially in harsh environments.

Hence, in the context of terrestrial navigation, we base our integrity assessment on the channels joint characterization defined in the DPE method: the study of the GNSS signal likelihood, depending on the PVT estimation provided by the navigator, called Direct-RAIM. Such a method has been motivated by the RAIM limitations, which are derived from the fact that the integrity management in RAIM is based on the correlator outputs and the estimated pseudoranges. The following integrity criterion is developed to bring information about the measurements likelihood for the integrity monitoring.

C. *Integrity criterion based on channels joint characterization*

The major objective of any integrity process is to quantify the probability that the distance between the real position and the estimated one exceeds a pre-defined threshold. In order to estimate the reliability of the information provided by the navigator, we propose to focus on the probability density function (pdf) of having observed the received signal and depending on PVT vector Θ. This likelihood is expressed in the following equation:

$$p(x;\Theta) = \frac{1}{(\pi\sigma^2)^N} exp\left(-\frac{\|x-A(\Theta)\alpha\|^2}{\sigma^2}\right) \tag{4}$$

All unknowns should be estimated in maximizing the likelihood:

- <u>Complex amplitudes</u>:

$$\hat{\alpha} = (A^HA)^{-1}A^Hx \tag{5}$$

- <u>Noise variance</u>: Deriving this entity and replacing the complex amplitudes by the equation (5), we have:

$$\hat{\sigma}^2 = \frac{\|x-A\alpha\|^2}{N} = \frac{x^H P_A^{\perp} x}{N} \tag{6}$$

With $P_A^{\perp} = I - P_A$ the orthogonal projection on the signal subspace.

Replacing the expressions (5) and (6) in the probability density function (4), we have:

$$p(x;\Theta) = \frac{N^N e^{-N}}{\left(\pi x^H\left(I-A\left(A^HA\right)^{-1}A^H\right)x\right)^N} \tag{7}$$

The signal codes being approximately decorrelated, the columns of A are almost orthogonal to each other, leading to $A^HA \simeq N.I_K$. Hence, (7) reduces to:

$$p(x;\Theta) \simeq \frac{N^N e^{-N}}{\left(\pi\left(x^Hx-\frac{x^HAA^Hx}{N}\right)\right)^N} \tag{8}$$

So, finally:

$$p(x;\Theta) \simeq \left(\frac{Ne^{-1}}{\pi\left(x^Hx-\frac{1}{N}\sum_k|a_k^Hx|^2\right)}\right)^N \tag{9}$$

The pdf derived in (9) only depends on the "correlation residual": the difference of energy between the received signal and the output of the correlators (matched filtering): $x^Hx - \frac{1}{N}\sum_k|a_k^Hx|^2$. Hence, any channel inconsistencies will generate a large residual and will tend to decrease $p(x;\Theta)$. Any error on the estimated PVT, because of MP on one channel for instance, will lead to a decrease of the likelihood due to a fall on many output correlation channels.

This pdf enables the evaluation of the coherence between the received signal and the estimated PVT. This criterion provides an *a priori* estimate of the navigation error: any bias on the PVT or any spurious signal will have a strong impact on the density.

D. *Relevance of the pdf for the navigation problem detection*

In order to bring to light the legitimacy of using the defined pdf as an integrity criterion, we give below some examples of potential navigation events. In an optimal case, the correlators provide a maximum coherence between the received signal and the estimations, which is reflected by a maximum correlation residual, and a maximum pdf. In harsh environments, several problems can occur, such as:

→ *<u>Spurious signal reception without negative impact on the PVT</u>*:

In this case, the PVT is not impacted, which means that the parameters estimations are not biased. Hence, the correlation residual is not affected by the spurious signal reception. Nevertheless, because of the reception of the additional unwanted signal, the signal energy $x^H x$ increases, and the pdf tends to decrease.

Note that the pdf brings information even if there is no error on the PVT estimation: it permits to raise an alert and to send a warning to the navigator in order to anticipate potential problems.

→ *Navigation problem causing a bias on the PVT*:

The PVT bias is caused by inaccurate estimations provided by the correlators, especially on signal delays and dopplers. This significant difference between the real and estimated parameters leads to a decrease of the correlation residual $\frac{1}{N}\sum_k |a_k^H x|^2$, and a decrease of the pdf.

The following paragraph intends to test these expectations and to show the pdf behavior in particular scenarios.

IV. SIMULATIONS AND RESULTS

The presented simulations have the same global configuration:

- 1 reception antenna
- Tracking loops: DLL/PLL/FLL
- E5a Galileo Signal
- Sampling Frequency: 30 MHz

A. *Impact of a PVT bias on the pdf*

In order to show the influence of a PVT bias, a 100 meters-bias is forced over a given period of time. The chosen configuration is detailed is the Table 1. The PVT $\widehat{\Theta}$ is estimated using a Least Squares method. Fig. 2 shows the error of the PVT estimation. The PVT bias impact is also reflected on $p(x;\widehat{\Theta})$ by a density decrease. Knowing the real position and velocity vector $\widetilde{\Theta}$, it is possible to compare the density functions computed from the estimated PVT $p(x;\widehat{\Theta})$ and from the real PVT $p(x;\widetilde{\Theta})$. $p(x;\widetilde{\Theta}) - p(x;\widehat{\Theta})$ is shown on the Fig. 3.

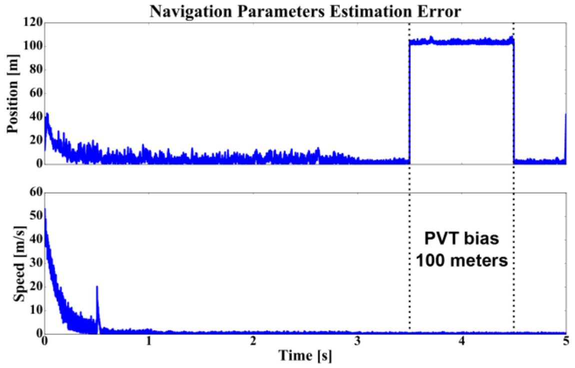

Figure 2: Error of the PVT estimation

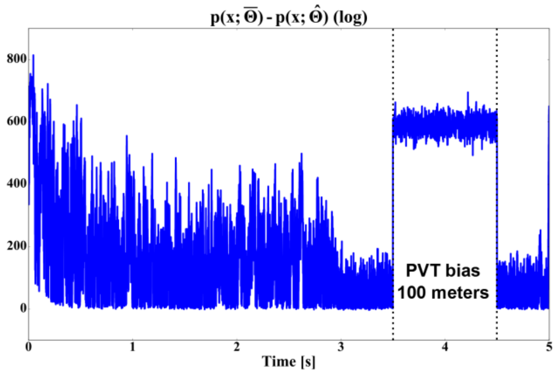

Figure 3: Impact of a PVT bias on the density

The decrease of the pdf depends on several parameters such as the importance of the navigation error or the satellite-receiver geometry. A signal exclusion system can be then set up to identify the signal which causes the greater density decrease thus compromising the navigation integrity. Fig. 4 shows the integration of such an exclusion management in the reception chain. An example is detailed further in the IV.C) Note that a 1 ms integration time has been chosen all along the simulation to bring to light the impact of a PVT bias on the density, but it could be increased in order to set up a system of error detection.

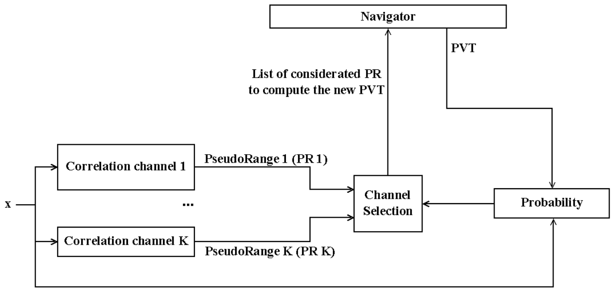

Figure 4: Navigation management according to the new integrity criterion

The difference of pdf, shown in the Fig. 3, decreases over time. This is due to the fact that synchronizations of frequency, phase, and code are successively made over time. It makes the tracking more accurate. Hence the estimated PVT $\widehat{\Theta}$ moving towards the real PVT $\widetilde{\Theta}$, the difference of probabilities is decreasing. The tracking configuration is described in the Table 2.

Table 1: Navigation configuration

Configuration	
Signal	Galileo E5a
Number of Satellites in View	5
Conditions of navigation	Clear-Sky
Type of simulation	Dynamic
Average speed of the mobile	10 meters per second

We have compared the current pdf value $p(x;\widehat{\Theta})$, computed from the estimated PVT, with the $p(x;\overline{\Theta})$ density, computed from the real PVT. Theoretically, $p(x;\overline{\Theta})$ is computed from the real navigation solution and takes the maximum pdf values. This maximum $p(x;\overline{\Theta})$ is found at the expected abscissa:

$$\overline{\Theta} = argmax_{\Theta}\big(p(x;\Theta)\big) \tag{9}$$

It represents the solution provided by the DPE. $p(x;\overline{\Theta}) - p(x;\widehat{\Theta})$ represents the difference between the maximum density and the density computed from the estimated PVT. Fig. 5 shows the probability density value computed around the real position. Note that the figures show the log-pdf; the observed values are extremely high, due to the fact that the criterion is a probability density function on the received raw data x whose values are very low.

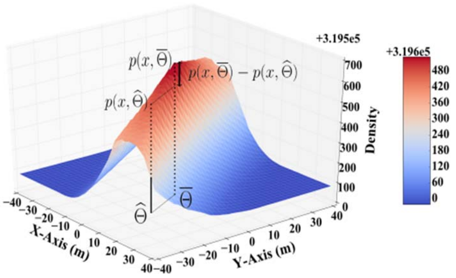

Figure 5: Pdf around the real position of the receiver

B. *Impact of a MP on the pdf*

The pdf contains all the information needed for the integrity management: inconsistencies or errors are detectable. As explained previously, even if the navigation is not impacted, the pdf is useful to anticipate possible problems; the navigator can then manage the navigation integrity by taking into account potential threats detected by the pdf.

In order to show another example, the previous configuration, detailed on the Table 1, is chosen. A static MP impacts one of the 5 satellites in view during 1 second. This satellite is called SatX. The Table 3 shows the characteristic of the SatX: the parameters of the static MP and those of the Line of Sight (LOS) signal, on average.

In this configuration, the error of the PVT estimation is shown on the Fig. 6. According to the tracking configuration, we observe an improvement of the accuracy over time, and no bias is detected. The synchronization steps (zones 1, 2, 3 and 4) are indicated on this figure. Fig. 7 shows the corresponding pdf computed from the estimated PVT. Note that the PVT cannot be estimated without the navigation message data, which provides satellites position, transmission time, clock correction parameters, etc. We assume that the navigation message is known in order to permit the estimation of the receiver speed and position from the beginning of the simulation.

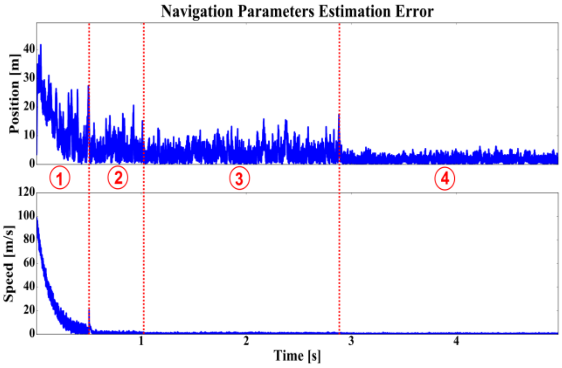

Figure 6: Error of the PVT estimation

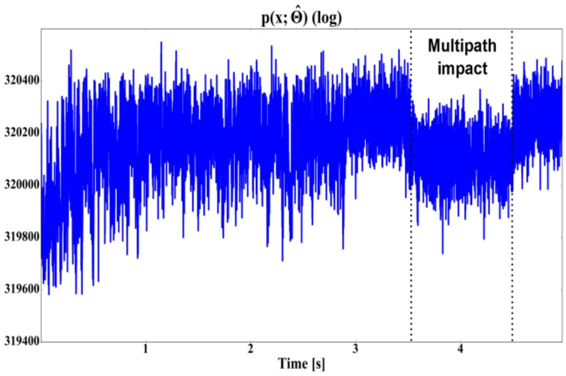

Figure 7: Pdf computed from the estimated PVT impacted by a MP

The presence of this spurious signal is visible on the pdf: we observe a decrease over the period when the MP affects the receiver antenna; indeed, it impacts the coherence of the measurements. Despite of this observation, the navigation is not biased by the MP. The high sensitivity of the integrity criterion is brought to light in this example. Note that the 1 ms-integration makes impossible the spurious signal detection. In order to set up a detection system, longer integrations should be taken.

Table 2: Tracking configuration of the synchronization step

Synchronization steps	Frequency ①	Phase ②	Codes ③	Demodulation ④
Time segment (in seconds)	[0; 0.5]	[0.5; 1]	[1; 3]	[3; 5]
Number of integration (in ms)	1	1	1	1
Carrier Tracking Band (in Hz)	50	25	15	10
Code Tracking Band (in Hz)	5	3	3	1
Code Tracking Gates (in Chips)	[-0.5; 0.5]	[-0.5; 0.5]	[-0.25; 0.25]	[-0.1; 0.1]

Table 3: Characteristics of the SatX

SatX	Elevation (°)	Azimuth (°)	Relative Delay (Chips)	Doppler (Hz)	Relative Power (dB)
LOS (average)	21	-142	0	0	0
MP	50	60	2.0	200	0

C. *Channels selection*

The previous examples have been introduced in order to bring to light the consistency of the pdf study in the navigation integrity. In this subsection, we propose one of the several uses of this integrity criterion: the channels selection for the PVT estimation. Indeed, being based on the measurements likelihood, a decrease of the pdf can be equated to a potential risk on the navigation. Even if, as previously proved, a decrease of this pdf is not always related to a bias on the estimated PVT, it can still permit to send a warning to the user.

In order to make a consistent channels selection to estimate the PVT, we focus on the impact of each satellite on the computed pdf. As the RAIM principle, it is possible to create satellite subsets and to compute the corresponding pdf on each subset. Hence, any error on a channel can be detected and the corresponding measurement can be excluded from the navigation solution. The following example intends to prove it.

The scenario defined in the Table 1 is taken over, as the Table 2 tracking configuration. In order to reduce the estimation noise, we focus here only on the demodulation step with a 10-ms integration time. The 5 SiV are called Sat1, Sat2, Sat3, Sat4, and Sat5. Nevertheless, the 5th satellite Sat5 is here in a non-Line of Sight (nLOS) situation during a period of 0.3 second. Its channel is impacted by a MP, whose characteristics are defined in the Table 4. Hence, the Sat5 tracking is not loose, but the non-reception of the LOS impacts the navigation. Note that the relative delay, Doppler and power values are computed from the LOS parameters used in the previous simulation. Fig. 8 shows the estimated position over time from the 5 satellites. A bias is logically observed, derived from the MP tracking on the Sat5 channel. Fig. 9 shows the corresponding pdf.

Table 4: Characteristics of the MP from Sat5

Sat5	Elevation (°)	Azimuth (°)	Relative Delay (Chips)	Doppler (Hz)	Relative Power (dB)
MP	50	60	0.5	100	0.0

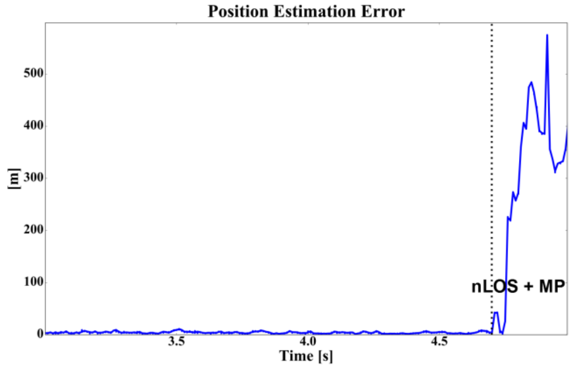

Figure 8: Position Estimation error with the 5 SiV

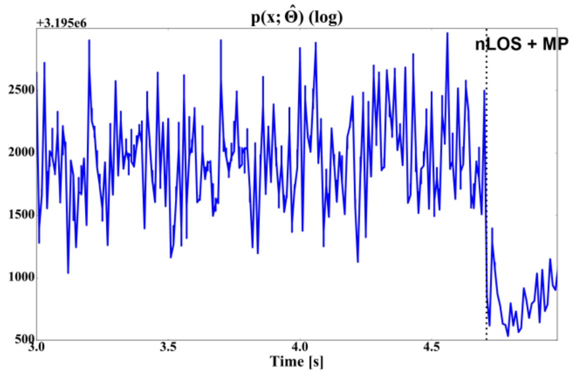

Figure 9: Pdf computed from the estimated PVT

5 subsets of 4 satellites are created, with one excluded satellite each time. The corresponding parameters of interest are:

- ➢ $\widehat{\Theta}_k$ the estimated PVT from the kth subset, in which the kth satellite is excluded

- $p(x;\widehat{\Theta}_k)$ the computed pdf from the k^{th} subset

Fig. 10 shows the computed pdf on the created subsets. Contrary to the pdf computed from the other subsets, $p(x;\widehat{\Theta}_5)$ does not decrease over time. The red curves represent computed sliding averages. A risk derived from the satellite Sat5 is then detected. Indeed, in this example, the risk turned out to be outstanding and is visible on the estimated PVT from the subsets $\widehat{\Theta}_k, k \in [1, \dots, 5]$, shown in Fig. 11. The consideration of Sat5 in the navigation solution estimation generates a potential hazardous bias.

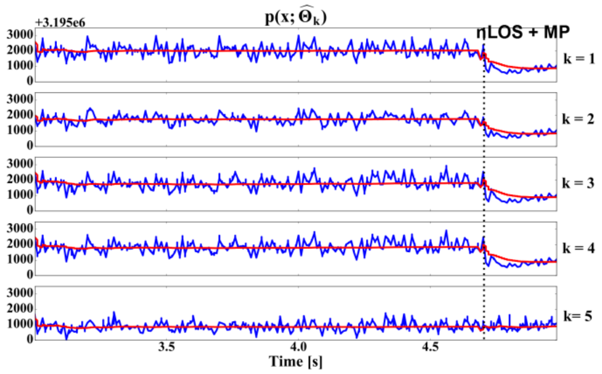

Figure 10: Computed pdf from the 5 satellite subsets

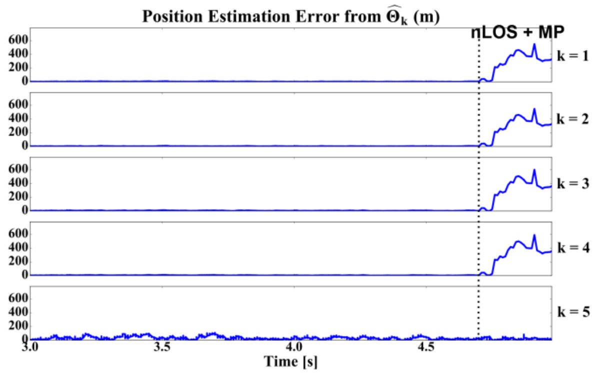

Figure 11: Estimated PVT from the 5 satellite subsets

This example intends to bring to light a potential utilization of the pdf in the navigation solution. An error on a channel is here detectable by the pdf $p(x;\widehat{\Theta}_k)$ computed on the satellite subsets. In addition, this principle could be extended for errors impacting several channels. Hence, even if a decrease of the pdf is not necessarily related to a PVT bias, this criterion can be used to highlight navigation risks, detected from the measurements likelihood. For instance, a decrease of the pdf computed on a subset may not translate an error on the PVT estimation. Nevertheless, the navigator must take the decision to keep or not the corresponding channel, according to the number of SiV and the values of the pdf computed on the other subsets.

Another use of this pdf can be based on the channels weighting: it could be difficult to quantify any decrease of the pdf, and then to detect a potential faulty measurement. Hence, channels weighting derived from the computed pdf on each subset can be a practicable way to bring the likelihood information to the navigation solution.

V. CONCLUSION AND PERSPECTIVES

The proposed method is based on the received raw data, and has been called Direct-RAIM (D-RAIM). Contrary to the *a posteriori* methods, based on the computed pseudoranges, D-RAIM is an *a priori* approach which computes the pdf of having observed the received signal depending on the presumed PVT. In other words, this new integrity criterion estimates the raw data likelihood. Being based on this density, the main objective is to detect any navigation risk, any inconsistency between channels in order to send a warning to the user. This integrity criterion is here defined as a parameter that evaluates the coherence between the received data and the estimations provided by the navigator. This paper intends to bring to light the relevance of the pdf utilization in an integrity monitoring, as an upstream criterion. Hence this pdf can be integrated into a RAIM technique.

The presented simulations have shown the defined integrity criterion sensitivity. Indeed, mainly depending on the correlation residual, the pdf behavior tends to translate the measurements coherence. Being based on an a priori, the pdf has a high sensitivity: a decrease of the pdf is not necessarily related to a PVT bias; nevertheless, it permits to send a warning in order to anticipate potential problems. Thereafter, the navigator has to manage this threat, according to the defined integrity criterion behavior: the base of the D-RAIM is set up.

The way to use the pdf must be defined to develop the complete D-RAIM. We have proposed several options in the previous paragraph. A channel error can be detected by computing the pdf on satellite subsets. It is then possible to detect faulty measurements which potentially lead to a PVT bias and a hazardous navigation. However, the detection of a pdf decrease is not ensured (e.g. because of the estimation noise). Hence, channels weighting derived from the computed pdf over the created subsets can be an optimal way to bring the measurements likelihood information.

Several perspectives are considered for future works: the integration of array antennas for instance. This technique has been already used for the DPE [13], and provides high performances, especially in harsh environments. The array antenna could permit to bring useful supplementary information in order to detect navigation problems. On the other hand, the use of robust estimation could be considered to improve the navigation performances and then to refine the detection of our new integrity criterion.

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