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Evolution of Integrity Concept – From Galileo to Multisystem

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1. Introduction

The Galileo navigation system introduced the integrity concept, intended as a continuous control of the information broadcasted by satellites. Although the RAIM technique represents the first example of integrity monitoring, it is able to detect only local errors made at the receiver level. The integrity monitoring applied by EGNOS could instead be seen as the forerunner of the Galileo system. Even if there are many differences in the definition of integrity for the two systems, the aim is the same for both: to protect the user against the failure of the system, warning him in the shortest time and with the greatest precision possible.

The integrity of a navigation system can be defined as follows: "integrity relates to the trust that can be placed in the correctness of information supplied by a navigation system. Specifically, a navigation system is required to deliver an alarm when the error in the derived user position solution exceeds an allowable level (alarm limit). This warning must be issued to the user within a given period of time (time-to-alarm) and with a given probability (integrity risk)" (Oehler et al., 2004).

In the near future a central role will be played by the integrity receiver's capability. This service can be considered essential in the safety critical application domain, particularly in aviation. For these applications, the system's capability of protecting the user against system failure is of primary importance.

Integrity includes the system's ability to supply, at the right time, reliable warnings to the user (alarm). The main problem with this service is how to determine what can be considered safe. This depends on the requirements of the different fields of application. The following parameters are traditionally used to define the safety of the service for a specific application:

- Alarm Limit (AL): the maximum error allowed in the position domain before an alarm is generated.
- Time To Alarm (TTA): the time that elapses between an error's overcoming of the AL and the reception of the alarm by the user's receiver.
- Integrity Risk (IR): the probability that the alarm will not be delivered within the TTA.

Allowable values of AL, TTA and IR depend on the specific application of the navigation system. The Galileo system provides a high level of integrity of the navigation signal. The global integrity concept is the answer to the needs of different types of users who are all looking for different services in terms of signal and performance.

A new concept of Integrity will be introduced in the following paragraphs. In particular, starting from the Galileo Integrity concepts, we will illustrate a few solutions to the integrity problem and describe a new one, in which data of different constellations (GPS/EGNOS and Galileo) are combined in order to improve the accuracy and the availability of the navigation data.

2. Galileo integrity

The integrity concept developed in Galileo has the aim of ensuring the correct computation of the user's position and provide a valid alarm to the user if the error in the position solution has exceeded a fixed threshold - the Alert Limit - relative to the specific application (Martini, 2006). The user can be in one of the following conditions (Table 1):

Case	System Case	System State	System Alert for Satellite	Satellite User Msg.	Comment
1	Fault-Free	Nominal	NO	OK	
2	Fault-Free	Nominal	YES	NOT-OK	False Alert
3	Faulty	Non-nominal	YES	NOT-OK	True Alert
4b	Faulty	Non-nominal	YES	NOT-Monitored	True Alert
4c	Faulty	Non-nominal	NO	OK	Error below Threshold

Table 1. Examples of integrity

In order to estimate all the errors that might occur in different situations, we have adopted a Gaussian model (J. Rife et al., 2004), whose standard deviation derives from the standard deviation of the error distribution and from the accuracy of the system. Moreover, each Gaussian distribution might have a bias, representing the presence of a faulty condition. The following Figure (Figure 1) shows the system's estimate of the error distribution, illustrating the situations displayed in Table 1. The first two cases concern a faulty free condition: the error is modelled with a zero-mean Gaussian distribution. In this case, the system only has an estimation of the error. This estimation could be considered as a sample of the above-mentioned Gaussian distribution, and this sample could be above (1) or below (2) the specific threshold. In case 1, the system is working in nominal condition, whereas case 2 concerns a False Alarm condition. The failure is modelled as the presence of a bias in the error distribution. This bias could be higher than the threshold (case 3), and in that case the system would certainly detect it.

Otherwise, the mentioned bias could be higher than the threshold, but the sample of the distribution could be below this limit (case 4). This case is referred as Missed Detection condition (Martini, 2006).

The Galileo system provides three elements to preserve user integrity:

- Signal-in-Space Accuracy (SISA): this is the expectation of the errors relative to the SW's clock and ephemerides, based on long term observations.

- Integrity Flags (IF): this is a warning relative to a satellite that is transmitting a signal with an excessive error. IF is based on the short term observation of the clock's variations, the ephemerides and the RF signals.
- Signal-in-Space Monitoring Accuracy (SISMA): this is an estimation of the accuracy of the Signal-in-Space Error (SISE).

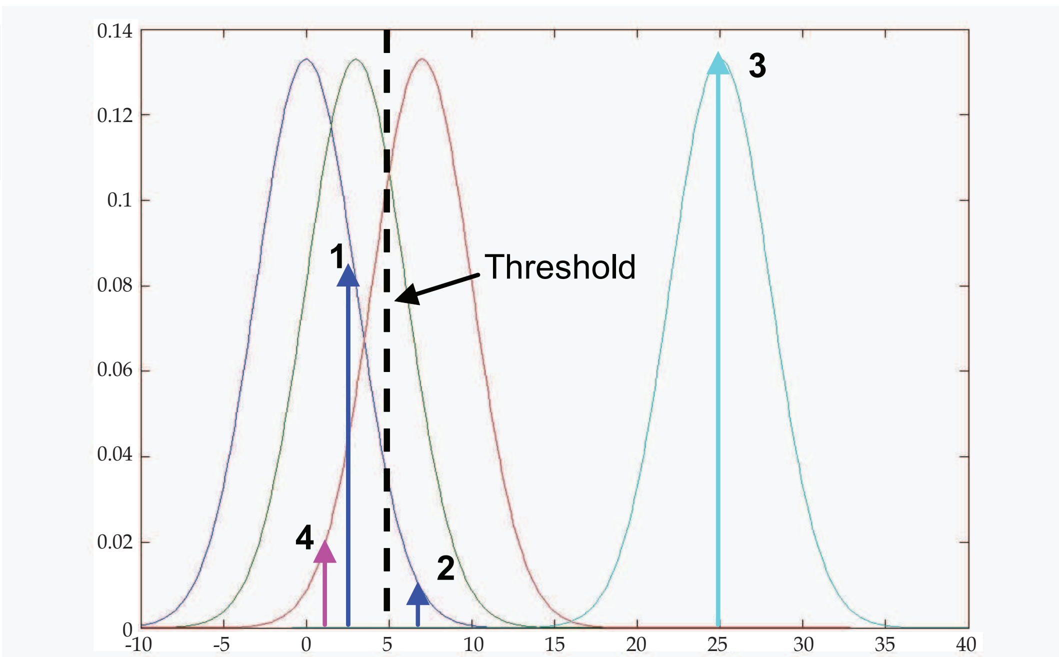

Fig. 1. Integrity events

Using the parameters described above, the user could check the integrity, as follows:

- In a faulty free condition, SISA overbounds the SISE distribution.
- SWs set as NOT OK or NOT MONITORED are discarded from the position computation.
- The user receiver computes the Protection Level using SISA and SISMA parameters.
- PL is compared with the specific AL.

2.1 Faulty free protection level

The Galileo Integrity system is based on the concept of Protection Level. Its main purpose is to calculate the error's bound in the position estimate, in order to be able to control this error with a sufficient level of confidence.

The user receiver judges the accuracy of the computed position solution, typically in term of Horizontal Protection Level (HPL) and Vertical Protection Level (VPL), by means of an estimate of the system errors, an estimate of the local errors and the knowledge of the number and geometry of the SWs used for the positioning algorithm. The computed Protection Level is then compared with a specific Alert Limit, in order to determine the availability of the navigation service.

The original definition of integrity belongs to the position domain, but it can be translated into the Signal-in-Space domain. As a matter of fact, the position error can be replaced by the SISE and the Protection level by the SISA.

2.2 Faulty case

In case of a system failure, the range measurement will be affected by a bias that gets added to the other errors. The aim of the system is to detect this bias. For this reason the Galileo system consists of a Ground Segment (GSS) that is able to monitor range measurements. If the bias exceeds an established integrity threshold, the user will become aware of this via an alarm.

The error detected by the ground segment can be modelled using a zero-mean Gaussian distribution with variance σ^2. Since the false alarm probability can be considered as the area limited by this function between threshold and infinite, we can calculate this threshold as follows:

$$TH = k_{fa} \cdot \sqrt{\sigma_{SISA}^2 + \sigma_{u,L}^2} \tag{1}$$

where k_{fa} derives from the false alarm probability.

The alarm is notified by setting the Integrity Flag relative to the satellite with failure in the information delivered to the users. This satellite must not then be considered by the user in the xPL computation and in the positioning algorithm. The combination between the IF and the PL can ensure the integrity of the information received in the position domain. Moreover, the implementation of a RAIM algorithm comes to the aid of the integrity monitoring, in order to face up to errors caused by local effects (i.e., multipath, interference, jamming and ionospheric effects).

2.3 Evolution of integrity concept

The evolution of the Galileo integrity concept concerns only the verification of system integrity. In particular, based on the above-mentioned definitions, the checking methodology has been modified: the vertical and the horizontal protection levels have been combined in a unique concept, and the user has to compute a probability, named Hazardous Misleading Information Probability (P_{HMI}), which will be compared to the threshold. Once the distribution of the error in the desired reference frame is known (Gaussian overbounding distributions with SISA and SISMA), it will be simple to derive the associated integrity risk both in the faulty and the faulty free conditions appointed to the user equations. Therefore, the error distributions for the vertical (one dimensional Gaussian distribution) and horizontal (Chi Squared distribution with two degrees of freedom) cases need to be derived, and the corresponding integrity risk can be easily computed by analyzing the integral for both distributions with the given alert limits. The integrity risk at the alert limits VAL and HAL are finally computed by adding the vertical and horizontal contributions (Dore & Calamia, 2009).

2.4 Galileo integrity risk

Based on the aforementioned quantities (SISE, SISA, SISMA, IF and TH), the user receiver can derive the integrity risk for the user position solution. This integrity risk is always computed for a given alert limit. Whenever the derived IR at the AL is larger than the allowed IR, the user equipment will raise an alert (Oehler et al., 2004).

The assumptions made for the derivation of the user integrity equation are summarized as follows:

- In a Faulty Free mode, the true SISE for a satellite is zero mean Gaussian distributed with standard deviation SISA.
- In general, a faulty satellite will be flagged as Don't Use.
- For each instance in time, one satellite of those flagged as OK is considered to be faulty but not detected (Faulty Mode). The distribution for the SISE of a faulty satellite is Gaussian with an expectation value TH and a standard deviation SISMA.

Once the distribution of the error in the reference frame is known (Gaussian overbounding distribution with SISA and SISMA respectively), the derivation of the associate integrity risk is straightforward.

Therefore, the error distribution for the vertical (one dimensional Gaussian distribution) and horizontal (Chi Squared distribution with two degree of freedom) cases needs to be derived, and the corresponding integrity risk can be easily computed by analyzing the integral for both distributions with respect to the given alert limit. Finally, the integrity risk at the alert limits HAL (Horizontal) and VAL (vertical) are computed by adding the vertical and horizontal contributions (Oehler et al., 2004).

$$\begin{aligned} P_{HMI}(VAL,HAL) &= P_{IntRisk,V} + P_{IntRisk,H} = \\ &= 1 - erf\left(\frac{VAL}{\sqrt{2}\sigma_{u,V,FF}}\right) + e^{-\frac{HAL^2}{2\xi_{FF}^2}} + \\ &+ \frac{1}{2}\sum_{j=1}^{N} P_{fail,sat_j}\left(\left(1 - erf\left(\frac{VAL+\mu_{u,V}}{\sqrt{2}\sigma_{u,V,FM}}\right)\right) + \left(1 - erf\left(\frac{VAL-\mu_{u,V}}{\sqrt{2}\sigma_{u,V,FM}}\right)\right)\right) + \\ &+ \sum_{j=1}^{N} P_{fail,sat}\left(1 - \chi^2_{2,\delta_u,H}cdf\left(\frac{HAL^2}{\xi_{FM}^2}\right)\right) \end{aligned} \tag{2}$$

where N is the number of satellites used for the positioning algorithm.

The Integrity Risk computed by the user represents the probability of exceeding the specified alert limits, since the system works according to the hypothesis described above. The Integrity Risk guaranteed by Galileo is partially allocated to user computation and partially to the system itself. This means that a proper design and implementation of the system must guarantee that the system have a sufficiently low probability of being in a condition in which the performance relevant assumption is no longer valid. Only this will ensure that the true overall integrity risk is below the required limit, in accordance with the specified level of service when this service is declared available by the integrity system.

2.5 HMI probability computation algorithm (HPCA)

In order to better understand the P_{HMI} formula (Eq. 2) and all the elements contributing to its design, it is necessary to show the main passages leading to the construction of that equation. These passages could be collected into an algorithm leading to the HPCA algorithm (HMI Probability Computation Algorithm) (Luongo et al., 2004).

The objective of HPCA is to compute the predicted HMI probability in any integrity exposure time interval (150 s) for a given GMS integrity by monitoring state and user geometry.

This algorithm includes the following modules:

- UERE Computation Module
- Position Solution Matrix Computation Module
- Fault Free Position Error Computation Module
- Faulty Position Error Computation Module
- HMI Probability Computation Module

Figure 2 shows the block diagram of the HPCA Algorithm.

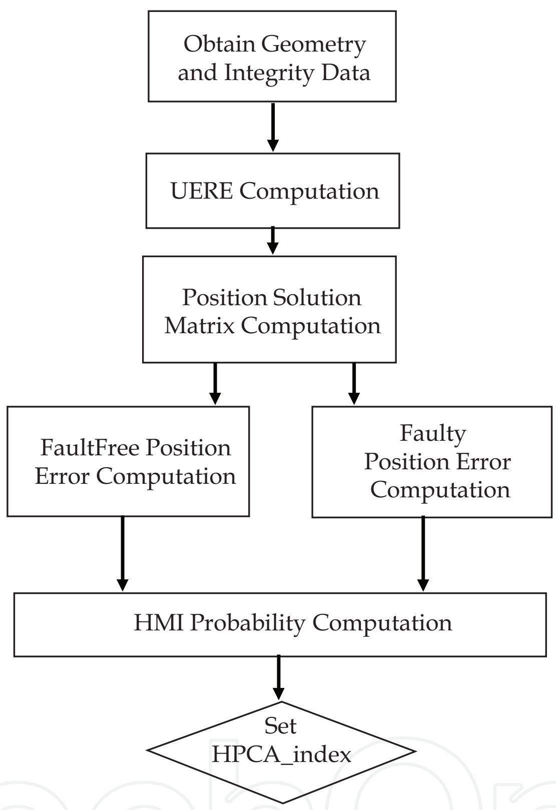

Fig. 2. HPCA algorithm

The "UERE Computation module" computes the predicted standard deviation of total pseudorange error on each signal from visible satellites. The principal formula is as follows:

$$\sigma_{u,RX}[i] = \sqrt{\sigma_{SISA}^2[i] + \sigma_{u,L}^2[i]} \tag{3}$$

It takes into account the signal in space as well as the local errors.

$\sigma_{SISA}[i]$ is the SISA value for the i[th] satellite used at user level; it is equal to the SISA value broadcasted in the navigation message increased by a factor of 1.1.

$$\sigma_{SISA}^2[i] = (1.1 \cdot SISA[i])^2 \tag{4}$$

$\sigma_{u,L}[i]$ is the predicted standard deviation of the local errors (troposphere, noise, multipath) on the i[th] signal. The values of the standard deviation of local errors can be read in the UERE table (Galileo satellites). Typical values are those reported in the following Table (F. Luongo et al., 2004). The computation is performed using the following interpolation function:

$$\sigma_{u,L}(i) = a + b \cdot e^{-10 \cdot EL_i} \tag{5}$$

Where A is a matrix that depends on the elevation angles, σ_i is the standard deviation value of the UERE for the i[th] satellite, while a and b can be computed by the following equation:

$$|a\,b|^T = (A^T \cdot A)^{-1} \cdot A^T \cdot \sigma_i \tag{6}$$

ID	01	02	03	04	05	06	07	08
Elevation [rad]	0.1745	0.2618	0.3491	0.5236	0.6981	0.8727	1.0472	1.5708
σ_i [m]	1.0300	0.7800	0.6700	0.6000	0.5800	0.5700	0.5600	0.5500

Table 2. UERE table

The predicted standard deviation of total pseudorange error ($\sigma_{u,RX}$) is considered an internal variable of the HMI Probability Computation Algorithm (HPCA).

The "Position Solution Matrix" module computes the position solution matrix. The main formula is reported:

$$K = \left(G^T W G\right)^{-1} G^T W \tag{7}$$

where K is the Position Solution Matrix, G is the Observation Matrix and W is the Weighting Matrix obtained by inverting the Covariance Matrix.

The "Fault Free Position Error" module computes the characteristic of the position error in fault free mode (fault free geometry: all the useable satellites). In particular, it evaluates the standard deviation of the distribution that overbounds the vertical position error and the variance of the distribution that overbounds the horizontal position error. The principal formulas are reported as follows:

$$\sigma_V = \sqrt{\sigma_{ZZ}^2} \tag{8}$$

$$\xi_H^2 = \frac{\sigma_{XX}^2 + \sigma_{YY}^2}{2} + \sqrt{\left(\frac{\sigma_{XX}^2 - \sigma_{YY}^2}{2}\right)^2 + \sigma_{XY}^4} \tag{9}$$

where σ_V is the standard deviation of the model (zero-mean normal CDF) used to overbound the vertical position error in fault free mode.

ξ_H^2 is the variance of the model used to overbound the horizontal position error (along the semi-mayor axis of the error ellipse) in fault free mode.

The $\sigma_{m,n}$ components are obtained using this general expression:

$$\sigma_{m,n} = \sum_{i=1}^{N} K[m,i] \cdot K[n,i] \cdot \sigma_{u,RX}^2[i] \tag{10}$$

where "i" indicates the ith satellite, "m" and "n" the reference axis: X, Y or Z.

The "Faulty Position Error" module computes the characteristic of the position error in faulty mode (faulty geometry: one single failure satellite). In particular, the standard deviation of the distribution that overbounds the vertical position error and the variance of the distribution that overbounds the horizontal position error are computed. The principal formulas are reported here:

$$\sigma_V = \sqrt{\sigma_{ZZ\_F}^2} \tag{11}$$

$$\xi_H^2 = \frac{\sigma_{XX\_F}^2 + \sigma_{YY\_F}^2}{2} + \sqrt{\left(\frac{\sigma_{XX\_F}^2 - \sigma_{YY\_F}^2}{2}\right)^2 + \sigma_{XY\_F}^4} \tag{12}$$

where σ_V is the standard deviation of the model (zero-mean normal CDF) used to overbound the vertical position error in faulty mode.

ξ_H^2 is the variance of the model used to overbound the horizontal position error (along the semi-mayor axis of the error ellipse) in faulty mode.

The σ_{m,n_F} components are obtained using the following general expression:

$$\sigma_{m,n\_F} = \sum_{i=1}^{N} K[m,i] \cdot K[n,i] \cdot \sigma_{u,RX}^2[i] + K[m,i_0] \cdot K[n,i_0] \cdot \left(\sigma_{SISMA}^2[i_0] - \sigma_{SISA}^2[i_0]\right) \tag{13}$$

where "i" indicates the i[th] satellite, "m" and "n" the reference axis: X, Y or Z.

The "HMI Probability" module computes the probability of HMI. The principal formulas are reported as follows:

$$P_{HMI} = P_{HMI,Fault-Free} + p_{fail} P_{HMI,Faulty} \tag{14}$$

$$P_{HMI,Fault-Free} = P_{HMI,Fault-Free,V} + P_{HMI,Fault-Free,H} \tag{15}$$

$$P_{HMI,Faulty} = P_{HMI,Faulty,V} + P_{HMI,Faulty,H} \tag{16}$$

3. EGNOS integrity

The GPS system is neither accurate nor reliable enough to be accepted as the only instrument of navigation for critical applications. One of the reasons is that no reliable and quick (within seconds) information can reach the user if any problems with the system occur. As a consequence, the GPS system cannot be used for landing approaches, for instance. Airplanes still have to use ILS-systems (Instrument Landing Systems) in case of poor visibility. But the installation and the maintenance of ILS-systems in every airport is expensive. With the SBAS systems, CAT I approaches (limited visibility) will be possible without additional ILS systems. For CAT III approaches (zero visibility), even the SBAS will not suffice, and ILS is still required.

EGNOS provides a European-wide, standardized and quality-assured augmentation service suitable for different fields of applications. Integrity is a key quality and safety parameter, and it alerts users when the system exceeds tolerance limits. EGNOS broadcasts wide-area differential corrections to improve accuracy, and alerts users within six seconds if something goes wrong (integrity).

The receiver combines satellite/user geometry information, with EGNOS-corrected pseudo-ranges, and internal estimates of the tropospheric delay to compute the user position. Ideally, the user would like to have the difference between the computed position and the true position - the true position error (PE) - to be less than the AL. However, since the true position is not known, the PE cannot be determined, and an alternative approach is required.

In fact, the receiver continuously estimates a predicted position error, known as the protection level (PL), for each position solution. The PL can be estimated using the UDRE and GIVE parameters and other local error-bound estimates. It is scaled for compatibility with the probability of non-integrity detection so that the PL should always be larger than PE.

Integrity assessments are based on PL and AL. A new PL is estimated for each computed position solution, then it is compared with the required AL, and an integrity alert is triggered if PL>AL. There is an underlying assumption, that PL>PE, when assessing integrity, and this corresponds to the “safe” zone to the left of the leading diagonal in Figure 3. In the nominal operation case, PL<AL and the system is available. If PL>AL for a particular operation, the EGNOS integrity cannot support the operation, and the system is unavailable.

There is also an “unsafe” zone to the right of the leading diagonal where PL<PE and the integrity assessment provide misleading information (Figure 3). The case at the bottom left corner of the diagram (PL<PE<AL) is also “safe,” theoretically, because the AL has not been exceeded, but it should be noted that EGNOS also protects against these out-of-tolerance situations (ESA, 2005).

Different parameters, used in the XPL computation, must be elaborated by the ground segment (Roturier et al., 2001):

- the variance $\sigma^2_{UDRE,i}$ of a zero-mean normal distribution that describes the user differential range error (UDRE) for each ranging source after the application of fast and long-term corrections and excluding atmospheric effects and receiver errors;
- the variance $\sigma^2_{UIRE,i}$ of a zero-mean normal distribution that describes the L1 residual user ionospheric range error (UIRE) for each ranging source after ionospheric corrections have been applied. This variance is determined from the variance ($\sigma^2_{GIVE,i}$) of an ionospheric model based on the broadcast grid ionospheric vertical error (GIVE).
- the variance $\sigma^2_{local,i}$ of a zero-mean normal distribution that relates the pseudo range error due to local receiver noise and multipath;
- the variance $\sigma^2_{tropo,i}$ of a zero-mean normal distribution that defines the residual pseudo range error of a tropospheric correction model.

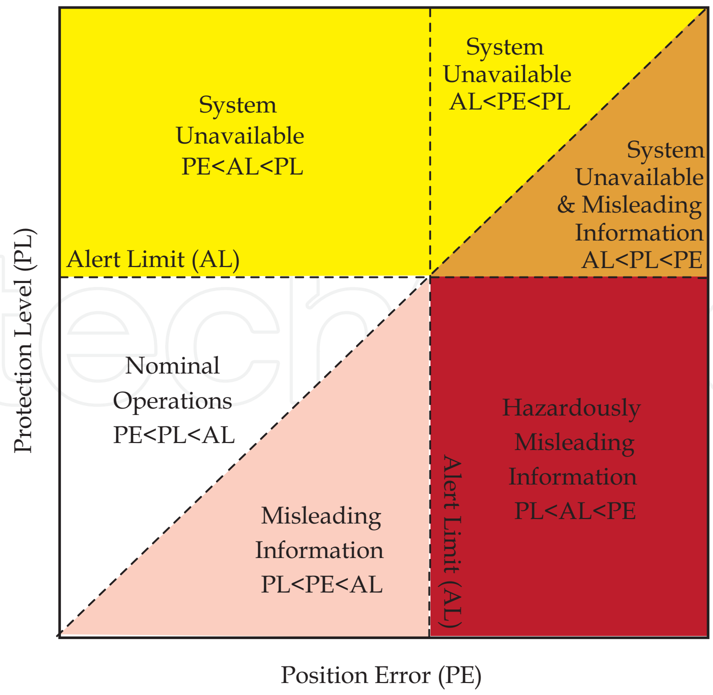

Fig. 3. EGNOS protection level

Assuming that the error in the range domain can be overbounded by a zero-mean Gaussian probability density function, the variance of that distribution is:

$$\sigma^2{}_i = \sigma^2{}_{i,flt} + \sigma^2{}_{UiRE,i} + \sigma^2{}_{air,i} + \sigma^2{}_{tropo,i} \tag{17}$$

where the variance $\sigma^2_{i,flt}$ may be easily derived from $\sigma^2_{UDRE,i}$. From Eq. (17) and for a given user/satellite geometry, it is quite simple to derive the vertical (horizontal) protection level VPL (HPL) equation by:

1. passing from the pseudo range variance domain to the position variance domain, noting that the integrity definitions are all in the position domain;
2. scaling the position domain variance to the integrity requirement. VPL (HPL) is scaled for compatibility with the probability of non integrity detection so that the VPL (HPL) should always be larger than PE.

Compared to the first step, the variance in the position domain residual error is a linear combination of σ^2_i and is also representative of a zero-mean normal law.

$$\sigma^2{}_{Vposition} = \sum_{i=1}^{N} s^2{}_{V,i}\sigma^2{}_i \tag{18}$$

where $S_{V,i}$ are geometrical parameters.

The second step is achieved by multiplying the position domain variance by a factor k that propagates this variance to a level compatible with the integrity requirement.

$$VPL_{EGNOS} = K_V \sqrt{\sum_{i=0}^{N} s^2{}_{V,i}\sigma^2{}_i} \tag{19}$$

Integrity assessments are based on XPL and XAL: a new XPL is estimated for each computed position solution. It is compared with the required XAL, and an integrity alert is triggered if XPL > XAL.

4. RAIM integrity

The integrity of a navigation system can be checked by using external systems such as SBAS to monitor the correctness of the signals used to calculate position. One of the main drawbacks to this approach is the inherent delay that is introduced when an error is detected, due to the time taken to uplink the information on errors. This section will focus on internal monitoring, and in particular on RAIM. RAIM stands for Receiver Autonomous Integrity Monitoring and is used to denote a monitoring algorithm that uses nothing but the measurements of one particular navigation subsystem, usually a GPS receiver. Conventional RAIM algorithms are designed to protect users from a single satellite failure at a time. However, recent developments have shown that RAIM has the potential to provide integrity even in case of multiple failures for challenging flight categories such as LPV-200 and APV-II (Ciollaro, 2009).

Measurement information is used to compute a position. A test statistic is derived from this position computation. It gets passed to an error detector that will warn the user whenever something is wrong. The error detection procedure will have to obey navigation requirements, and it is important to determine the detection power (or 'error detectability'). It depends on the measurement quality and the configuration, and it is this detection power computation that monitors the system's integrity, determining whether the system has the ability to provide timely warnings when the system is in error. If this is not the case, it will inform the user that it might be unsafe to use the system. It should be noted that position computation algorithms always assume that noise on the measurements has a zero mean. An error or bias, as it is commonly called, is therefore defined as the non-zero mean of measurement noise.

4.1 Satellite slope

The slope, which relates the induced position error to the test statistic, can be calculated directly from geometry and is different for each satellite. The satellite with the largest slope is the most difficult to detect. It produces the largest position error for a given test statistic (Figure 4) (Ciollaro, 2009).

Fig. 4. Satellite slope

The slope is a geometric parameter that can be directly computed from the specific satellite-user geometry, based on the following equations, in the horizontal and vertical planes respectively:

$$Hslope_i = \frac{\sqrt{K_{1i}^2 + K_{2i}^2}\sigma_i}{\sqrt{1-P_{ii}}} \tag{20}$$

$$Vslope_i = \frac{|K_{3i}|\sigma_i}{\sqrt{1-P_{ii}}} \tag{21}$$

where $K = (G^T \cdot W \cdot G)^{-1} \cdot G^T \cdot W$ is the weighted pseudo-inverse of the design matrix, where W the inverse of the covariance matrix, while $P = G \cdot K$. The geometric contribution to the slope is given by the K and P matrices.

4.2 RAIM protection levels

The Protection Levels in the vertical and horizontal planes can be described by the following equations (Walter & Enge, 1995), for the vertical and horizontal cases, respectively:

$$VPL_{FD} = \max\{V_{slope}\}T(N, P_{fa}) + k(P_{md})\sigma_V \tag{22}$$

$$HPL_{FD} = \max\{H_{slope}\}T(N, P_{fa}) + k(P_{md})\sigma_H \tag{23}$$

where:

- V_{slope} and H_{slope} are the satellite error slope in the vertical and horizontal planes
- $T(N,P_{fa})$ is the test statistic threshold, and it is a function of the number of satellites (N) and the desired probability of false alarm (P_{fa}). Given the probability of false alarms, the threshold can be found by inverting the incomplete gamma function:

$$1 - P_{fa} = \frac{1}{\Gamma(a)} \int_0^{T^2} e^{-s} s^{a-1} ds \tag{24}$$

where a is the number of degrees of freedom divided by two, or, in terms of the number of measurements N and unknowns M:

$$a = \frac{N-M}{2} \tag{25}$$

- $k(P_{MD})$ is the number of standard deviations corresponding to the specified Probability of Missed Detection. The smaller the P_{MD} value, the higher the number of standard deviations should be considered, since longer tails for the Gaussian distribution should be taken into account.
- σ_V and σ_H are the standard deviations of the error in the position domain in the vertical and horizontal planes.

It should be noted that, when using RAIM, it is common to allocate the whole Integrity Risk, and so the whole Pmd is confined to only one plane (vertical or horizontal) according to the specific operation. For example, for LPV-200, the whole Integrity Risk is allocated to the vertical domain, since this is the most demanding requirement.

4.3 RAIM tst statistic

It is not possible to obtain a direct measurement of the position error. Therefore, the overall consistency of the solution has to be investigated (Walter & Enge, 1995). As long as there are more than four measurements, the system is overdetermined and cannot be solved accurately. This is why a least squares solution is performed in the first place. Since all of the conditions cannot be met realistically and exactly, there is always an error residual to the fit. Therefore, we need to be able to estimate the fit and assume that, if there is a good fit, the position error is most likely small.

An estimate of the ranging errors from the least squares fit and the basic measurement equation is given by:

$$\varepsilon_{wls} = y - G \cdot x_{wls} = (I - G \cdot K) \cdot y = (I - P) \cdot y \tag{26}$$

where:

$$P = G \cdot K = G(G^T \cdot W \cdot G)^{-1} \cdot G^T \cdot W \tag{27}$$

From these error estimates it is possible to define a scalar measure, defined as the Weighted Sum of the Squared Errors (WSSE):

$$WSSE = \varepsilon_{wls}^T \cdot W \cdot \varepsilon_{wls} = [(I - P) \cdot y]^T \cdot W \cdot [(I - P) \cdot y] \tag{28}$$

which is equivalent to:

$$WSSE = y^T \cdot W \cdot (I - P) \cdot y \tag{29}$$

The square root of WSSE plays the role of the basic observable, because it yields a linear relationship between a satellite bias error and the associated induced test statistic. The test statistic can be defined in both the horizontal and vertical planes.

Typically, a certain threshold, which depends on the required probability of false alarm, is selected. If the statistic exceeds that threshold, then the position fix is assumed to be unsafe. On the other hand, if the statistic is below the threshold, then the position fix is assumed to be valid.

The statistic-vertical error plane is thus broken up into four regions consisting of: normal operation points, missed detections, successful detections and false alarms. Ideally, there would never be any missed detections or false alarms. In reality, a certain number of missed detections and false alarms are allowed, based on the P_{md} and P_{fa} requirements, respectively.

5. Multisystem integrity

With the advent of Galileo, users will be provided with multiple signals coming from different satellite systems. This will improve position accuracy, because the number of satellites in view per user will be almost doubled. Moreover, the higher measurements redundancy will help guarantee a safer position and the detection of errors. This will also result in an improved availability as well as meet the requirements for more demanding flight categories. Therefore, it is necessary to introduce a base-line for a combined system, defining new parameters, a new integrity algorithm and possible ways to combine the two independent systems.

With the term "Multisystem", we intend the improvement of the accuracy and availability of the navigation solution using the combined Galileo and GPS signals. In this context, it is essential for the user to be able to take advantage of the integrity information coming from both Galileo and GPS satellite constellations, in order to prevent users from making errors that might represent an excessive risk. The multisystem integrity algorithm has to establish a link between the two generations of GNSS, defining the relation for integrating different integrity monitoring schemes (Pecchioni et al. 2007) (Ciollaro, 2009).

5.1 Definition of a new integrity algorithm (EGNOS + Galileo)

Two different approaches have been studied to define the new integrity algorithm. They represent two opposite ways of solving the problem of how to combine different integrity concepts: the first one has been called "One-System-Based Integrity," and the second one "Parallel Integrity" (Dore & Calamia, 2009).

The first approach is based on the use of only one algorithm for both systems with an a priori definition of integrity inputs. The integrity analysis can be made either by converting the EGNOS integrity message into an equivalent Galileo integrity message or vice versa, by using the inverse transformation from a Galileo to an EGNOS-like message. In the first case, known as Galileo-Based-Integrity-Algorithm (GBIA), the Galileo Integrity is used as a baseline; in the second case, called EGNOS-Based-Integrity-Algorithm (EBIA), the One-System Integrity is the EGNOS algorithm.

The second approach is based on the use of independent (parallel) algorithms, one for each System, and on an a posteriori integration of the integrity results. The integrity analysis can be performed by monitoring the values assumed by both the Integrity Risk and the Protection Level. If the IR is used as monitored variable, the scheme will be called IR-PIA; otherwise, if the monitored variable is the PL, the method will be called PL-PIA. It is worth noting that the computational load for the IR/PL conversion is expected to be higher than the PL/IR conversion, because an iterative method must be applied (Ciollaro, 2009).

5.2 Galileo based integrity algorithm

The approach chosen for this study is GBIA. The integrity data in fact arrives from the two systems, Galileo and EGNOS, and is implemented inside the Integrity Risk equation of Galileo, in order to estimate the HMI Probability.

Figure 5 shows the block diagram of a GBIA system. The fundamental block of this diagram is the EGNOS/Galileo converter, which has the aim of converting the EGNOS Integrity message into a message that can be used by the Galileo Integrity Algorithm.

The main functions implemented by the EGNOS-Galileo converter are the following (Ciollaro, 2009):

$$\sigma_{SISA,GPS} = f_{SISA,GPS}\sigma_{UDRE} \tag{30}$$

$$\sigma_{SISMA,GPS} = f_{SISMA,GPS}\sigma_{UDRE} \tag{31}$$

Taking into account the different integrity allocation between the Galileo concept, which implies the use of four failure mechanisms, and the EGNOS concept, based on a failure assumption, the contribution of the GPS satellite to IR computation is reduced only to the faulty free mode.

Then it is possible to assume $f_{SISMA,GPS} = 0$ and $f_{SISA,GPS} = 1$, that is:

$$\sigma_{SISA,GPS} = \sigma_{UDRE} \tag{32}$$

Moreover, in order to estimate the standard deviation of the error, the following equation can be used:

$$\sigma^2_{u,L,GPS} = \sigma^2_{UIRE} + (\sigma^2_{Air} + \sigma^2_{Tropo}) \tag{33}$$

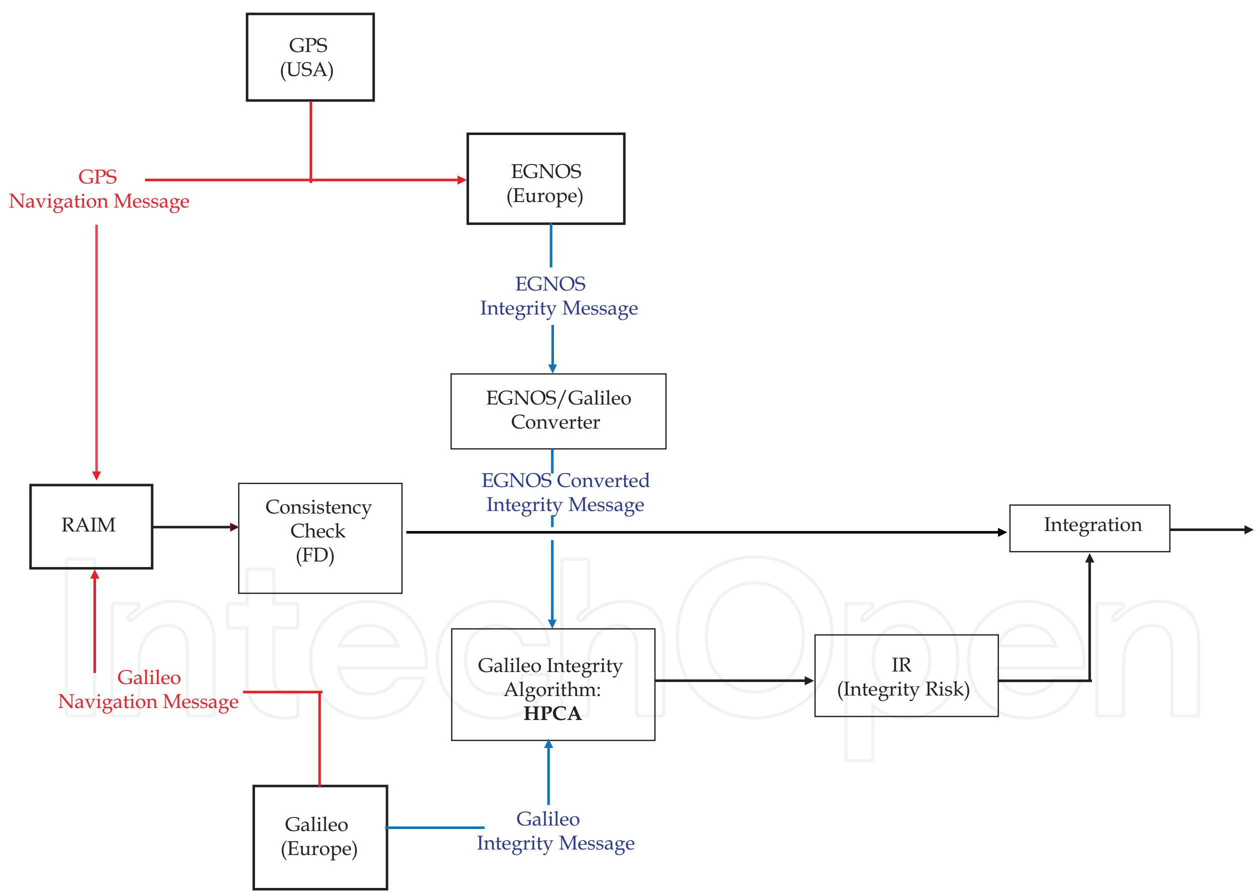

Fig. 5. Galileo-based integrity algorithm

5.3 Multisystem integrity (MSI) algorithm implementation

In this section, we describe a new proposed multisystem integrity algorithm. The algorithm merges integrity data originated by the Galileo and EGNOS systems and employs a Receiver

Autonomous Integrity (RAIM) technique (Weighted RAIM). One of the potential uses of this algorithm consists in the combination of the IR algorithm with the RAIM technique. RAIM is able to detect failures that have not been detected by the IR algorithm. In case of multiple failures, when the WRAIM technique fails, the IR algorithm triggers an alarm.

In this Section we describe the characteristics of this innovative algorithm, pointing out the reason for using the IR equation for the combined constellation Galileo/EGNOS and the reason for taking advantage of a RAIM technique. The EGNOS integrity equation provides a way to measure the integrity based on the incoming signal variances and the satellite geometry. The same is also true for the Galileo IR equation, obviously bearing in mind which data is the Galileo integrity data.

This algorithm is supposed to enable the user to take advantage of the data transmitted by the Galileo and EGNOS systems: the user receiver must consider a single and large constellation in order to strengthen the positioning algorithm and improve the accuracy. This idea is simply in need of the definition of a new integrity concept, which would be able to combine the techniques mentioned above.

5.3.1 IR equation

First of all, we have to explain why the protection level concept turns into the integrity risk concept in a Galileo environment. In an EGNOS domain, IR is the probability that the horizontal (vertical) PL exceeds the horizontal (vertical) AL without the user receiving any alarm whatsoever. This definition requires a clear distinction between the horizontal and vertical cases. Therefore, it is necessary to split IR into two a priori fixed quantities.

On the contrary, as far as a Galileo integrity equation is concerned, the users do not have to evaluate the horizontal and vertical protection levels, but the global IR directly, without making any strict allocations. In fact, different applications need distinct integrity requirements for the horizontal and vertical situations: for example, for a ship the vertical component of the error is not that important for a ship, but it is instead essential for a plane. This last observation leads us to choose the Galileo integrity equation to perform the multisystem integrity algorithm.

The first step in the definition of a new integrity algorithm concerning a combined constellation (Galileo+GPS), is the characterization of the equivalent elements belonging to the two navigation systems. In order to perform the test on the position solution, we opted for the relationship between σ_{SISA}^2 of Galileo and σ_{UDRE}^2 of EGNOS. First of all, these are quantities defined in the same domain SIS. Secondly, they are related to the same typology of error (clock and ephemeris).

The local contribution to the variance of the error in the SIS depends on the elevation angles of the satellite belonging to the two constellations considered. As mentioned before, in order to consider a single constellation composed by both GPS and Galileo SW, we have considered the variance of the error in the SIS as follows:

$$\sigma_i^2 = \sigma_{SISA/UDRE,i}^2 + \sigma_{u,L,i}^2 \tag{34}$$

where the first term, in the case of an EGNOS satellite, derives from Eq. 32; the second term instead represents the local error contribution and can be estimated via the following equation:

$$\sigma_{u,L,i} = a + b \cdot e^{-10El_i} \tag{35}$$

where a and b are parameters that depend directly on El_i (Luongo, 2004). This estimation was performed for both cases, the Galileo and GPS satellites.

The IR equation has been implemented by means of a numerical code in a computer. FF and FM, in Eq. 2, suggest the faulty and faulty free modes. In fact, the Galileo system assumes two separate scenarios: one in which the satellites are all set as use, and the other in which one of the satellites set as use is supposed not to be functioning. When you are in the faulty mode, in the case of Galileo satellites, the SISMA element comes out; in an EGNOS case, only the faulty free mode is instead expected and, because we could not find an equivalent for the Galileo SISMA in its navigation message, we are going to consider the following situation:

- Faulty free: for the Integrity Risk computation we consider all satellites in view, GPS and Galileo are set as OK.
- Faulty mode: the involved satellites are only those belonging to the Galileo constellation; hence the index of the sum concerns only those satellites.

5.3.2 Inputs of the implemented algorithm

The information available a priori for the new algorithm consists of two text files containing position (X,Y and Z components) and velocity (X,Y and Z components) of the SV belonging to the two constellations considered, and obtained through a constellation simulator.

Pseudoranges are obtained by the true satellite-user distance, adding a zero-mean Gaussian noise with variance depending on SISA and the elevation angles of the satellites.

Regarding the SISA and SISMA evaluation, we have considered actual values, adding a Gaussian noise:

$$\begin{aligned} SISA &= 0.87 + N\left(0, \sigma_{SISA}\right) \\ SISMA &= 0.7 + N\left(0, \sigma_{SISMA}\right) \end{aligned} \tag{36}$$

In this case, $\sigma_{SISA} = \sigma_{SISMA} = 0.01$, in order to simulate a sort of degradation on the signal received. We must also describe the behaviour of the positioning algorithm in the combined constellation case. Generally speaking, if we define X^k, Y^k and Z^k as the coordinates of the K-th satellite and X, Y and Z as the coordinates of the user position, we are able to compute the distance between the satellite and the user (d^k) and the pseudoranges (ρ^k) as follows (Misra & Enge, 2001):

$$d^k = \sqrt{(X^k - X)^2 + (Y^k - Y)^2 + (Z^k - Z)^2} \tag{37}$$

and

$$\rho_c^{(k)} = d^{(k)} + c\delta t_u + \tilde{\varepsilon}_\rho^{(k)} \tag{38}$$

where:

ε_ρ^k : residual error on k-th satellite. b : clock's offset.

Applying a linearization to the (38), we get the expression of the pseudo range model:

$$\Delta\underline{\rho} = G\Delta\underline{X} + \underline{\varepsilon}_\rho \tag{39}$$

The matrix G is named Design Matrix, and it consists of the linear coefficients obtained by the partial derivatives of the observation's equations with respect to the estimated coordinates. This matrix characterizes the user-satellite geometry. The number of the columns of G agree with the number of unknowns to be determined (X,Y,Z and b), while the rows equal the number of the available observations (number of satellites in view for both navigation systems). The union of the Galileo and the GPS constellations causes a change in the G matrix. The number of unknowns in fact become five, in order to compute the clock's offset for both systems. In order to estimate the user position's ($\Delta\tilde{X}$) we have to apply the weighted least mean square method to the pseudo range model, organizing the weight matrix (W) with the information contained in the navigation message sent by EGNOS or by the Galileo satellites (considering only SWs in view, or those with an elevation angle greater than 10°):

$$\Delta\tilde{X} = \left(G^T \cdot W \cdot G\right)^{-1} \cdot G^T \cdot W \cdot \Delta\rho \tag{40}$$

where G and W are two matrices of dimension N×5 and N×N respectively, with N representing the number of the satellites used in the positioning algorithm.

5.3.3 Outputs of the implemented algorithm

In this Section we will describe the characteristics of the implemented multisystem integrity algorithm. We will discuss the results of a few simulation tests organized by different typologies (with or without failure) and different durations, in order to test the validity of the proposed algorithm and confirm the expected results.

A peculiarity of this algorithm is the allocation of the Integrity Risk, valid for the computation of the P_{HMI} , and the P_{FA} (False Alarm Probability), required to estimate the RAIM statistics. The false alarm probability of RAIM and the Integrity Risk of Galileo are related to the time required for a specific flight operation. For example, in the case of safety of life applications, this time is equal to 150 seconds. Our study refers to these applications.

The proposed algorithm elaborates the position computation, the RAIM statistics and the IR equation in every second. It is therefore useful to refer to the probability mentioned above as to one second. In order to perform this conversion, we use the binomial distribution, obtaining the value of P_{HMI} and P_{FA} , both initially set[1] at 0.5×10^{-7} , referred to as one epoch (second).

The failures have been reproduced in two different ways:

- Introduction of a step function, at a given test epoch, on the pseudo range of a satellite in view.

[1] Equally split between the two integrity requirements from the initial value of 1×10^{-7} / 150s as defined by the ICAO for the avionic integrity requirements.

- Bias on SISA and SISMA.

We chose the step function because it is able to characterize a lasting failure on a satellite. In fact, when we are looking at aeronautical applications, any failures lasting more than six seconds (TTA) are relevant. SISA results from the predictions on a satellite clock and ephemeris errors, and these error estimations are based on long term observations: SISA increases mark out long term failures. SISA derives from a large data batch, so the anomalous behaviour of just one sample is not relevant. On the other hand, pseudorange variations point out instantaneous failures. In case of failures, the new algorithm is able to protect users from:

- long term bias due to errors from the clock and ephemeris data (IR equation);
- long term bias and short term bias due to local errors (multipath, receiver noise) and errors caused by the SV, the SV payload and the navigation message (i.e. ephemeris data, clock) (RAIM algorithm).

5.3.3.1 No failure mode

In a "no failure" condition we are able to judge the behaviour of the new algorithm compared to the single constellation case, and we can also evaluate the performances offered by the code in term of probability of false alarm and missed detection.

Figure 6 illustrates the RAIM statistic in normal operations (Vertical case), without failure, and the correct functioning of this part of the algorithm. In this case the RAIM algorithm has been simulated independently from the IR algorithm, in order to estimate how it behaves with many samples in an epoch.

We tested the IR algorithm in the same way, for the two constellations and in absence of failures (Figure 7).

Figures 6 and 7 show that the RAIM statistic presents some samples that exceed the threshold. In particular, these samples do not exceed the VPL (Vertical Protection Level), therefore they are in the False Alarm zone. This tells us that the RAIM statistic presents a low probability of triggering an alarm, whenever it is not necessary (the main reason for this behaviour of the WRAIM could be seen in the largest sensibility to the outliers of this integrity algorithm). Instead, the IR algorithm has a lower false alarm probability than the previous case, consequently to the fact that the threshold is never exceeded, and the system does not trigger any alarms when the SIS is not affected by any bias.

5.3.3.2 Error on pseudoranges

We simulated the local error by adding a bias (fixed value) to the pseudoranges. Our intent was to emulate the contribution of some types of errors (i.e. multipath) that are not present in the SIS transmitted (local errors) and consequently are not detectable by the ground segment of EGNOS or Galileo, but only by a RAIM technique.

The pseudoranges are calculated by using the true distance between the satellites and the receiver, adding a Gaussian noise that depends on the variance σ_i^2 (Eq. 34). In addition to the noise, in order to simulate the malfunctioning in the biased case, by a certain epoch we added a fixed value to the range measurement. Since the IR algorithm is not able to detect these kinds of errors, we present the results of the WRAIM part of the proposed algorithm for this first model of failure.

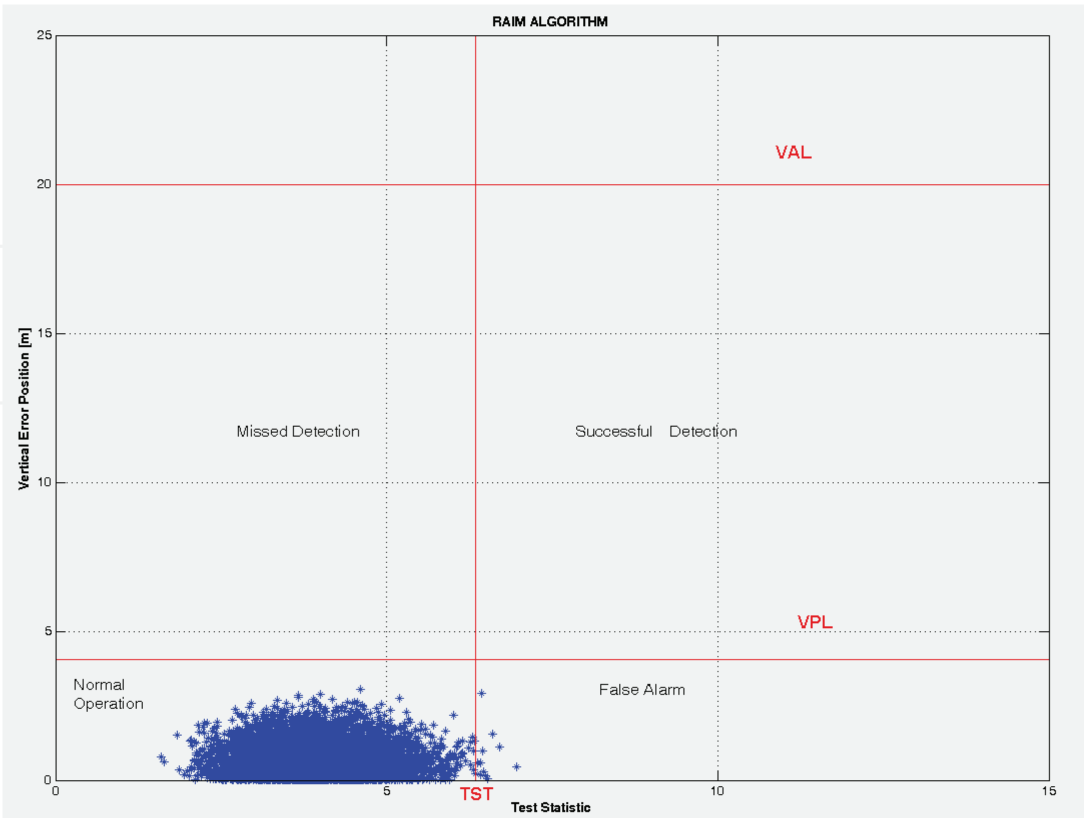

Fig. 6. WRAIM in faulty free condition

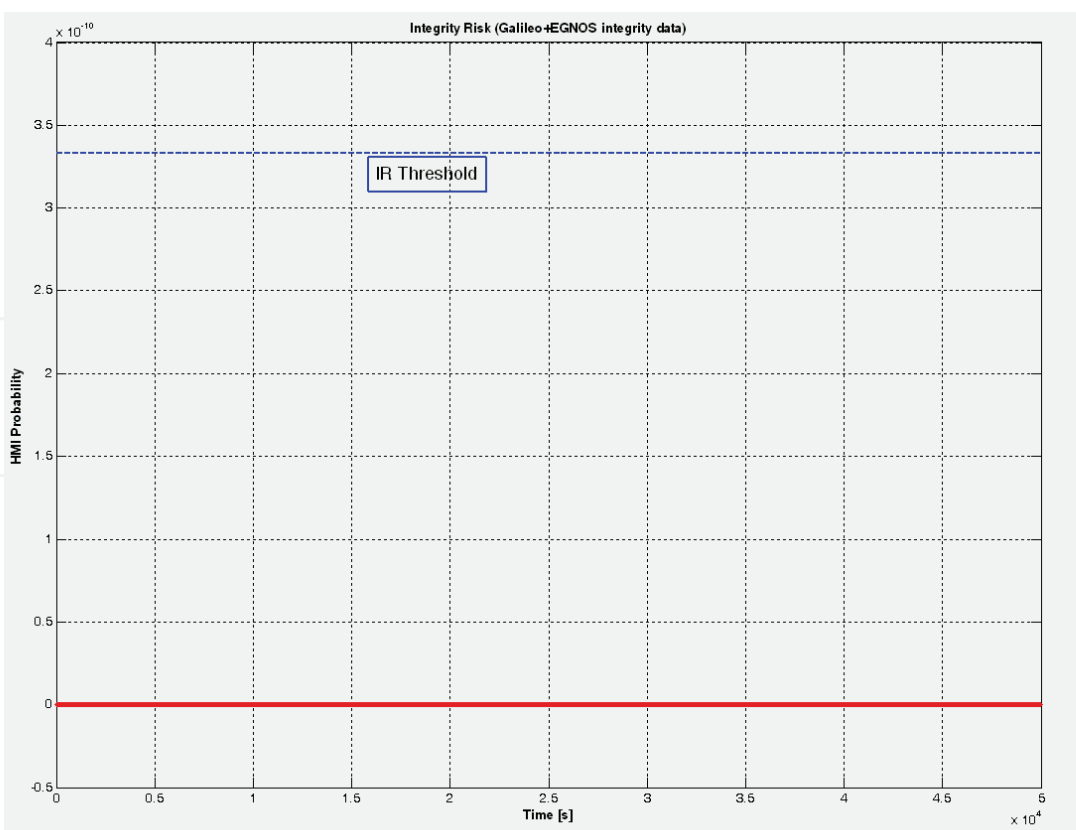

Fig. 7. IR algorithm in faulty free condition

Figures 9 and 10 show how the RAIM statistic behaves in the presence of a bias of 20 meters inserted from the 30-th epoch in a satellite belonging to the Galileo constellation, and a bias of 10 meters, from the 50-th epoch, in a GPS satellite. In both cases the RAIM statistic (green and blue curves) exceeds the Test Statistic Threshold by a probability of 100%. The Figures show the instantaneous behaviour of the RAIM. This way of representing the RAIM process

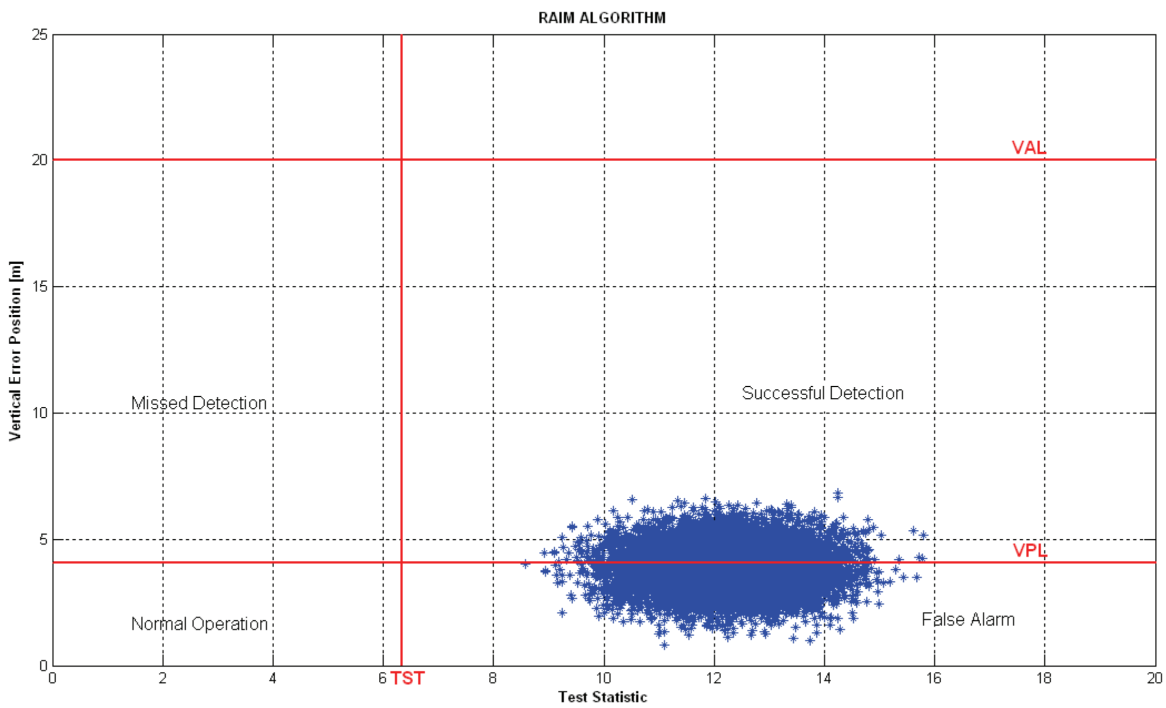

Fig. 8. RAIM and bias on pseudorange – satellite Galileo PRN 4 – RAIM algorithm

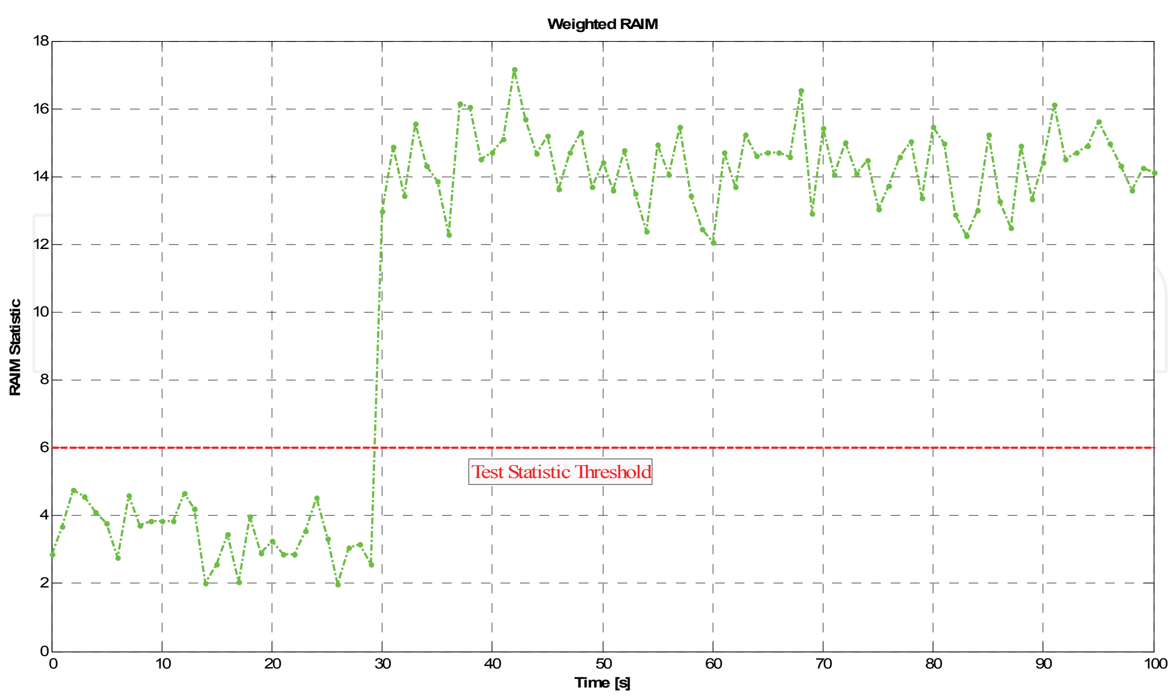

Fig. 9. RAIM and bias on pseudorange – satellite Galileo PRN 4 – Multisystem Integrity Algorithm

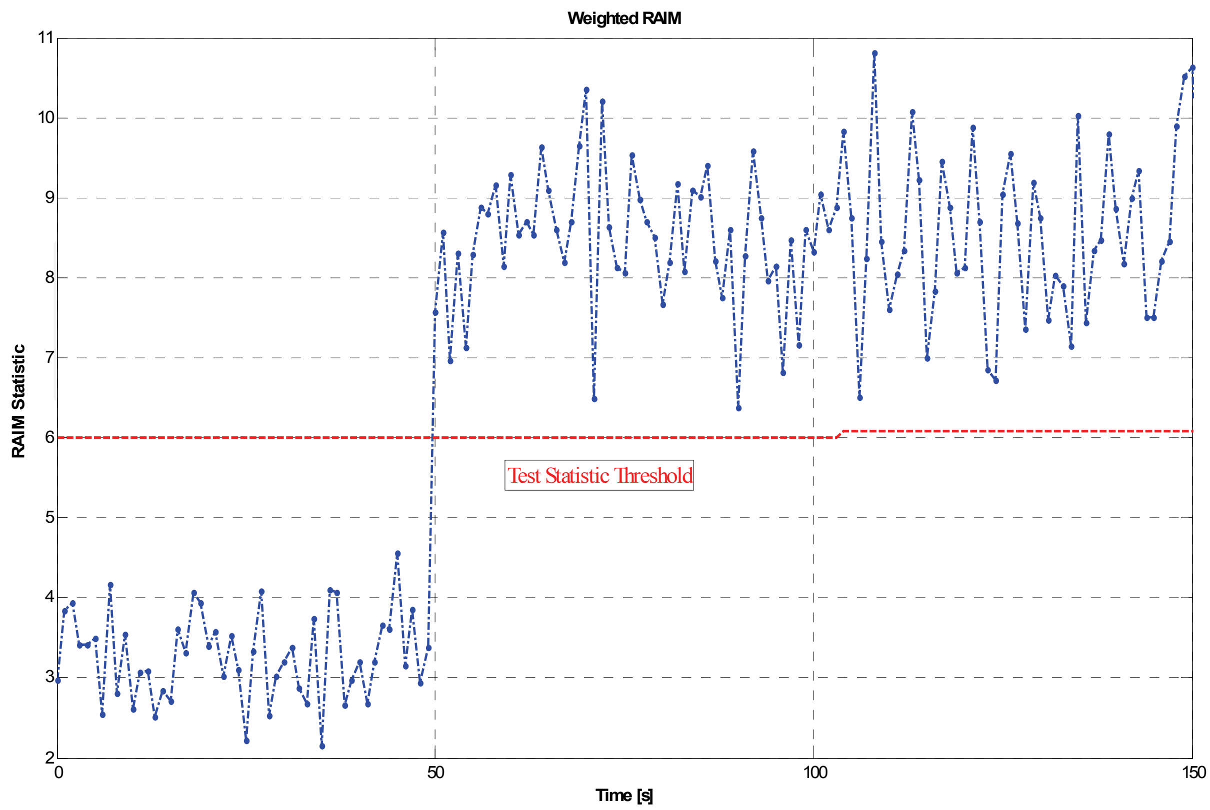

Fig. 10. RAIM and bias on pseudorange – satellite GPS PRN 8

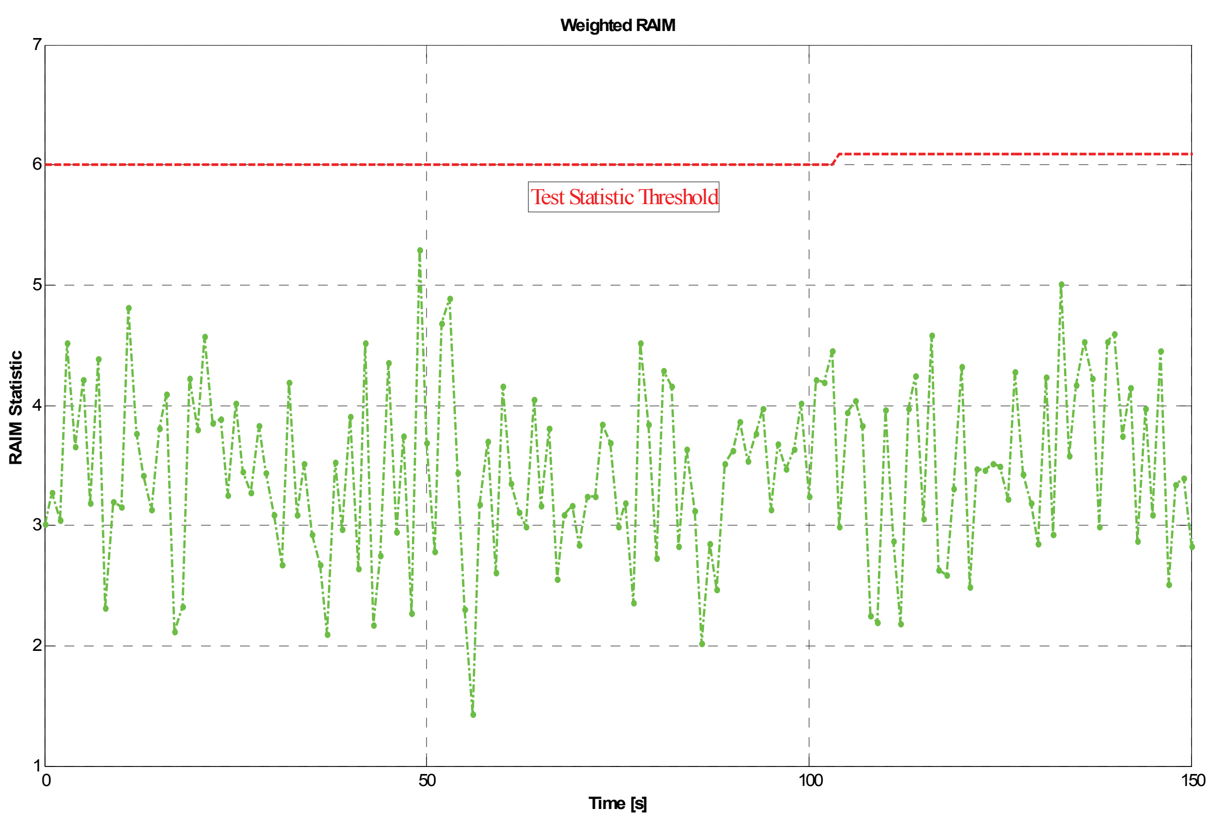

Fig. 11. RAIM and bias on all pseudoranges

is not typical; in fact, in the example depicted in Figure 6, different samples of one epoch[2] are considered in order to obtain an estimate of the proper functioning of the algorithm. Figure 8 shows this kind of analysis made for the biased case (Galileo satellite, Vertical case). The RAIM technique clearly detects the error in the pseudorange; in fact, the ellipse of point leaves the normal operation region exceeding the TST. The same result can be achieved also in the GPS biased case.

We can obtain different results by adding a bias on all pseudo ranges relative to all satellite in view. Through this kind of simulation we can reach the results shown in Figure 11.

In Figure 11, the RAIM statistic remains around zero value: the receiver assigns the 10 metres bias entirely to the two temporal unknowns, the GPS time clock's offset and the Galileo time clock's offset.

In conclusion, we figured out that the RAIM statistic is not able to detect the failures on more than one satellite at the same time. This is a limit for this algorithm, which leads us to conclude that the RAIM algorithm does not work properly when used as single integrity system.

5.3.3.3 Error on the SISA/SISMA value

We simulated the error on the signal in space by adding a bias on the standard deviation of the noise considered in the SISA and SISMA computation of two random satellites belonging to one of the two constellations considered. In this failure mode, SISA and SISMA values have been implemented as in Eq. 36, assuming the following value for the respective standard deviation:

$$\begin{aligned} \sigma_{SISA} &= 10 \\ \sigma_{SISMA} &= 7 \end{aligned} \tag{41}$$

Figure 12 shows the behaviour of the implemented algorithm, in particular the IR equation, when the bias on SISA and SISMA is considered in two Galileo satellites. In this case the algorithm triggers alarms with a probability of 2%.

Comparing this with a single constellation case (only a Galileo satellite), Figure 13 shows the behaviour of the Integrity Risk algorithm in the Galileo case, considering the same size of bias for the same satellite. What is clear from this comparison is the decrease of alarms (~10%, in the second case) triggered by the system achieved by using the combined constellations. This means that in a dual constellation the combined system provides a safe position for the user.

As described in the previous Section, since these disturbances are not related to a variation in the pseudoranges ($\Delta\rho$), we are not able to detect those errors through the RAIM statistic. The trend of the statistics is similar to that in Figure 11, in which the curve never exceeds the Threshold; for the sake of brevity we didn't report this picture.

In conclusion, Figure 14 shows the behaviour of the described algorithm when the bias is applied to the SISA value belonging to two GPS satellites; in this case the biased SISMA is

[2] the satellite configuration remains the same during the simulation; however, the noise added to the pseudoranges varies.

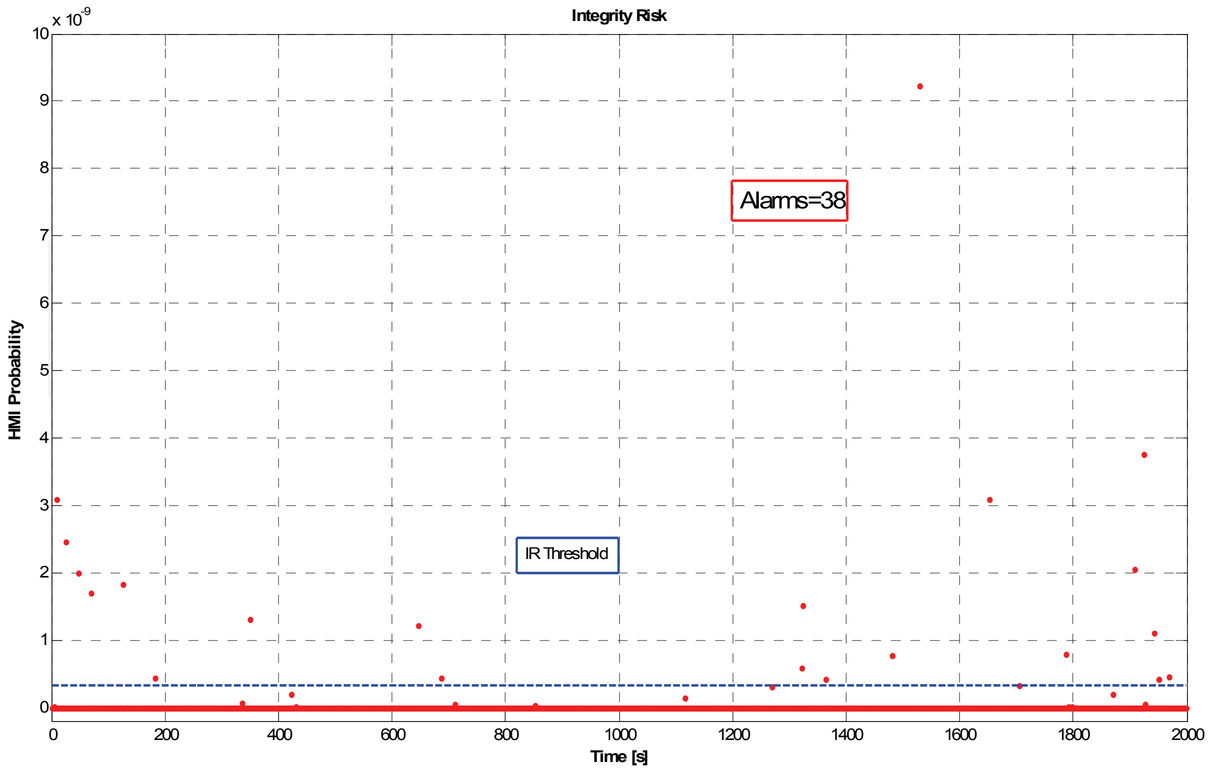

Fig. 12. IR algorithm combined constellation and bias on SISA and SISMA, satellites Galileo PRN15 and PRN22

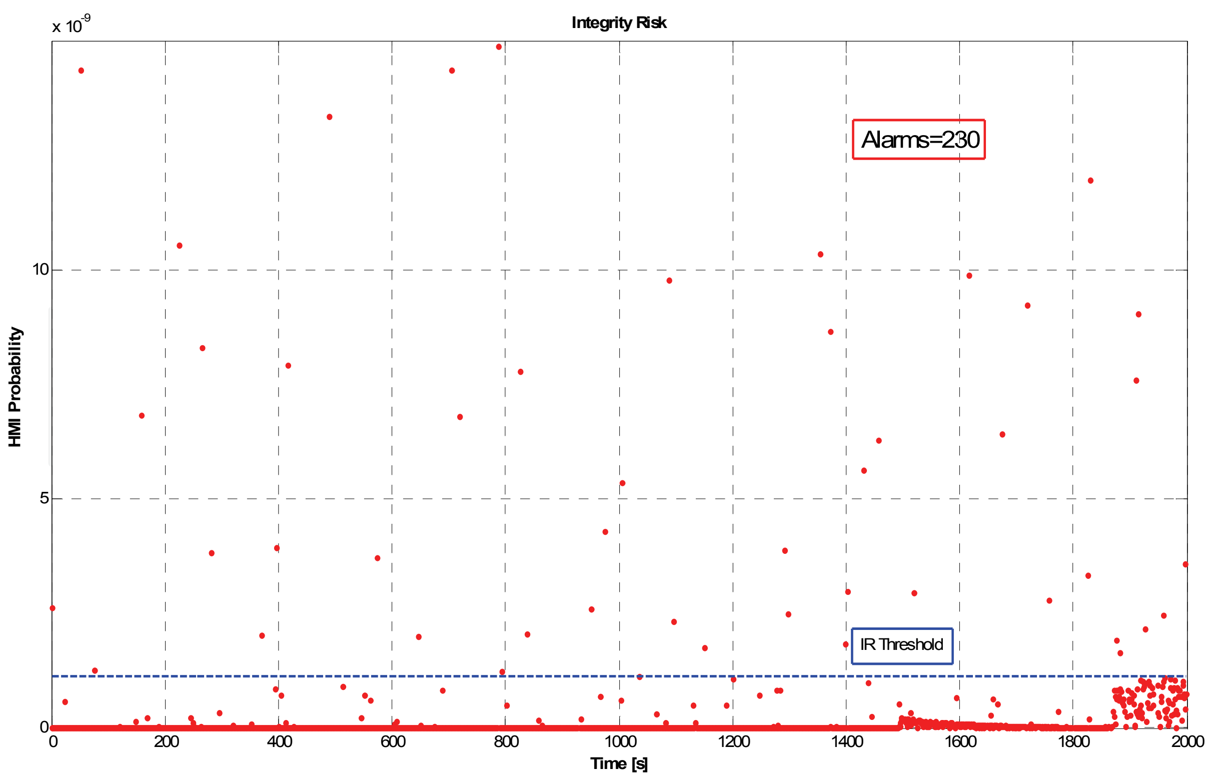

Fig. 13. Galileo IR algorithm and bias on SISA and SISMA, satellites Galileo PRN15 and PRN22

not present because this quantity is not broadcasted by the GPS satellite and, as we stated previously, the integrity data delivered by these satellites does not alter the Faulty section of the P_{HMI} equation. For this reason, in this context, the above-mentioned probability does not reach high values. Indeed, the statistics never exceed the Threshold.

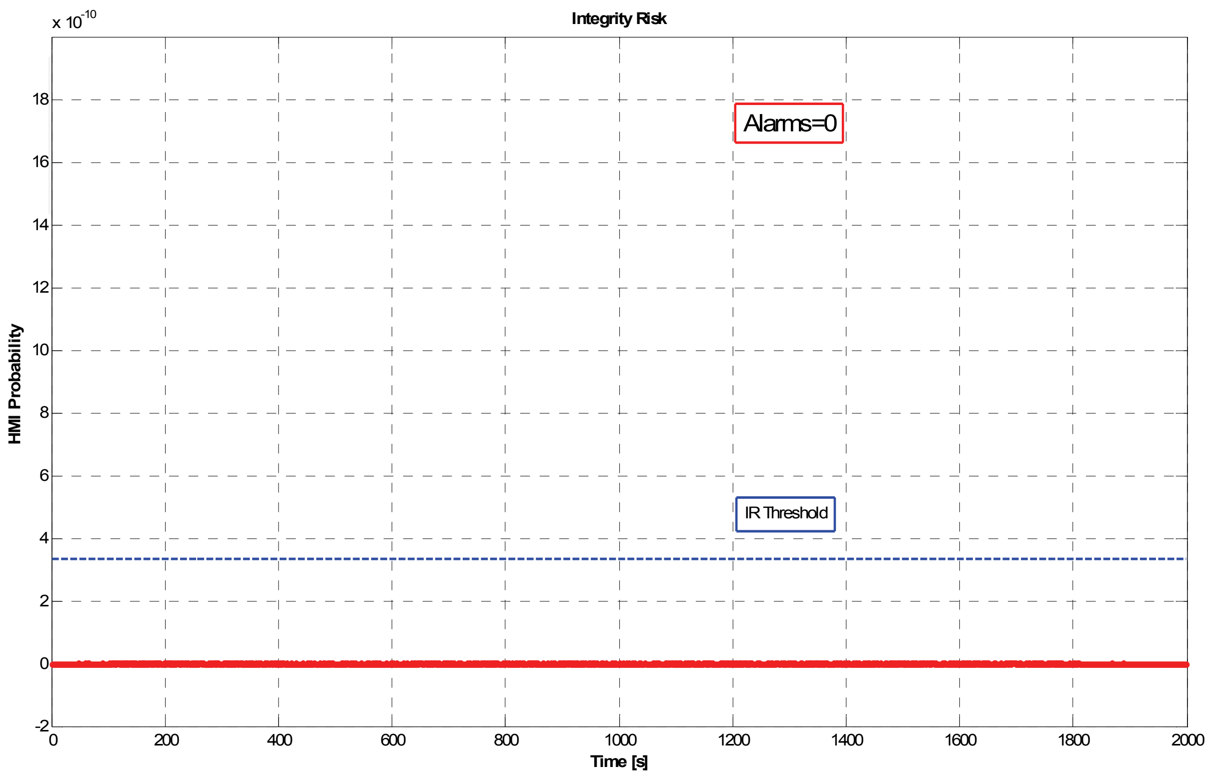

Fig. 14. IR algorithm combined constellation and bias on SISA, satellites GPS PRN3 and PRN10

6. RAIM evolution: ARAIM

An interesting development of the described study is the analysis of the new RAIM technique, the Advanced RAIM. ARAIM, proposed in 2010 by the GEAS (GNSS Evolutionary Architecture Study), could be considered as an evolution of the classical RAIM. This new solution takes advantage of the availability of different new navigation systems (i.e. Galileo) in order to improve receiver performances.

ARAIM is an extension of the single-frequency RAIM. Both are based on an airborne comparison of each satellite measurement to the consensus of the other available satellite measurements (GEAS, 2010). However, the differences between the two techniques are also important. ARAIM should be pursued for the worldwide vertical guidance of civil aircraft based on two or more GNSS constellations radiating at two ARNS/RNSS frequencies (L1 and L5). The main characteristic of the Advanced RAIM would support vertical guidance to decision heights of 200 feet (LPV-200), whereas single-frequency RAIM only supports LNAV guidance. As such, ARAIM must protect vertical errors at levels of 35 meters, while RAIM only needs to detect lateral errors of 200 meters or so. In addition, LPV-200 corresponds to a severe major hazard level (10-7), and LNAV is only major (10-5).

The proper functioning of this system does require some assistance from the ground; for example, the ISM (Integrity Support Message), which is a message developed using reference receivers on the ground, is communicated to the aircraft. The ISM message conveys the safety assertions associated with each of the underlying satellite systems to the sovereign responsible for a given airspace. These messages would contain performance estimates for each satellite to be used for navigation. ARAIM therefore uses a multiplicity of satellites in a dual-constellation environment to take responsibility for all faults that arise between dispatch and the completion of approach.

As described in the previous Section, one of the potential uses of the Multisystem Integrity algorithm is represented by the combination of the IR algorithm with the RAIM technique. ARAIM is still in a feasibility status, and a comparison—in order to test and verify the requirements and highlight the differences between the two approaches—between its results and Multi System Integrity cannot yet be performed. Indeed, the two systems have the same aim: to improve the reliability of the position solution provided by the system in particular conditions (LPV-200 for ARAIM), taking advantage of different navigation systems.

7. Conclusions

The totality of the tests made on the implemented code has been planned with the aim of characterizing the performances of the algorithm respectively in faulty free and in faulty mode. The use of the Galileo and EGNOS system as a single and augmented constellation allows us to develop the positioning algorithm and improve the position accuracy. Furthermore, the combination of the two SVs systems enables us to obtain some benefits from the RAIM point of view.

Our proposed solution starts from the integrity equation defined for the Galileo system and adapts it to the combined Galileo + EGNOS system, or rather, it combines the integrity data supplied separately by the two navigation systems, with the aim of computing the Hazardous Misleading Information Probability. We focused our attention on the IR equation: the implemented code reproduces the IR equation as it is presented in literature, that is, with the SISA values relative to Galileo and GPS satellites, and SISMA relative only to the Galileo ones, in faulty free and faulty mode, respectively. The results obtained testing the algorithm in the presence of failure have provided positive indications on the implemented IR equation: in these cases, the HMI probability increases with the value of the bias.

Alhough the IR protects the user against extended failure, whose effects revert on the SISE estimation, the RAIM technique could instead highlight instantaneous errors on the distances measured by a Galileo or a GPS satellite. RAIM and IR compensate each other, or rather, the RAIM indicates failure unperceived by the IR and vice versa; therefore the combination of the RAIM technique with the integrity equation has proved to be a good idea. This technique is based on a very different concept than protection levels and leads to different results. However, the Galileo integrity concept is more complete than the GPS/SBAS and RAIM integrity concepts and offers more protection from failures. However, this concept needs to be investigated further, in particular regarding the assumptions to be used for the error distributions and the parameters to be considered in the integrity equation. Indeed, although more complete, the new integrity concept introduced by Galileo is more complex and less intuitive than SBAS and RAIM protection level concept.

A possible development of the proposed algorithm could be the definition of SISMA analogous for the GPS satellites in order to contribute to the IR equation under faulty conditions.

The present study is only a preliminary analysis. In order to better evaluate the performances of the proposed algorithm, we need to use realistic data (i.e. pseudoranges measurements obtained through a real GNSS receiver) as inputs of the implemented code.

8. Acknowledgements

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- PEGASUS (Platform of Enhanced Gnss receiver for Application in Sol User Segment), December 2010 – December 2011, financed by the Italian Space Agency (ASI) under the contract. ASI I/024/10/0.

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Global Navigation Satellite System (GNSS) plays a key role in high precision navigation, positioning, timing, and scientific questions related to precise positioning. This is a highly precise, continuous, all-weather, and real-time technique. The book is devoted to presenting recent results and developments in GNSS theory, system, signal, receiver, method, and errors sources, such as multipath effects and atmospheric delays. Furthermore, varied GNSS applications are demonstrated and evaluated in hybrid positioning, multi-sensor integration, height system, Network Real Time Kinematic (NRTK), wheeled robots, and status and engineering surveying. This book provides a good reference for GNSS designers, engineers, and scientists, as well as the user market.