Received January 21, 2020, accepted February 13, 2020, date of publication March 2, 2020, date of current version March 16, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2977455

A Review of the Evolution of the Integrity Methods Applied in GNSS

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This work was supported in part by the European projects: FR8Rail-II, which received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 826206; and by autonomous indoor and outdoor safety tracking system (AIOSAT), which received funding from the European GNSS Agency under the European Union's Horizon 2020 research and innovation programme under grant agreement No. 776425.

ABSTRACT The use of GNSS technologies has been spreading over time up to a point in which a huge diversity of applications require their use. Due to this demand, GNSS has turned into a more reliable technology, as multiple aspects of it have evolved. Integrity has become a vital aspect of being considered when using GNSS. The following document gathers and shows different aspects of integrity in terms of GNSS. The paper mainly focuses on the description of different receiver autonomous integrity monitoring methods. For this purpose, basic concepts and possible GNSS error sources (and their corresponding solutions) are introduced. Afterward, an explanation and a classification of the integrity monitoring techniques is given, where the fault detection and exclusion methods and different protection level computation formulas are analyzed.

INDEX TERMS Fault detection and exclusion, GNSS, integrity monitoring, protection level, receiver autonomous integrity monitoring.

I. INTRODUCTION

Nowadays, the demanding requirements of industry and society urge positioning systems to be safer, more reliable, and even faster. In this scenario, GNSS technologies are considerably spreading since they emerged. The amount of applications and systems that rely on GNSS PVT solutions is substantially growing [1], [2], and users benefit from the evolutions on this topic.

For the aim of fulfilling the high demanding requirements for positioning applications, multiple technologies and techniques have been developed to increase the confidence of GNSS in terms of accuracy, integrity, and continuity. This paper focuses on the review and explanation of the different fault detection and exclusion (FDE) methods found in the literature to improve the integrity of the estimated GNSS PVT solution. These methods are based on the detection and exclusion, when possible, of faulty satellites for the computation of the PVT solution. According to [3], continuity is "a system's ability to function without interruption." As it is dependent on the positioning system instead of the processing of the data, it will not be discussed in the document. Even if accuracy improving techniques are not discussed in this paper, it is important to mention that the fault detection and exclusion methods can improve the accuracy of the solution. Note that most of the time, position, velocity, and time will be considered as the GNSS solution; nevertheless, the discussed methods will mainly refer to integrity in terms of position.

GNSS integrity methods were developed to improve aircraft navigation. Nowadays, these research branches have spread to multiple ground transportation systems. It is due to this that many references about the topic are focused on ground transportation, as the harsh environments and the movement of these systems lead to more dynamic and changing, thus, challenging scenarios.

According to the last issue of the federal radio navigation plan [4], "Integrity is the measure of the **trust** that can be placed in the correctness of the information supplied by a navigation system. Integrity includes the ability of the system to provide timely warnings to users when the system should not be used for navigation".

The associate editor coordinating the review of this manuscript and approving it for publication was Hayder Al-Hraishawi.

Integrity is connected and defined by a set of parameters that are dependent on the target application. The following list contains the ones that are going to be used in this paper [5], [6]:

Alert Limit (AL) is the error tolerance a system has, which cannot be exceeded without issuing a warning.

Time to Alert (TTA) is the maximum allowable time elapsed from the moment the integrity threshold is crossed until the alert is issued.

Integrity Risk (IR) is the probability that the position error exceeds the Alert Limit.

Position Error (PE) is the difference between the measured position and the real position, also known as ground truth.

Protection Level (PL) is the position error that the algorithm guarantees that it will not be exceeded without being detected.

False alert (FA) is the event in which an alert is issued without surpassing the alert limit.

Missed detection (MD) is the event in which there is a fault that is not detected by the algorithm.

Positioning failure (PF) is the event in which the positioning error exceeds the defined Protection Level.

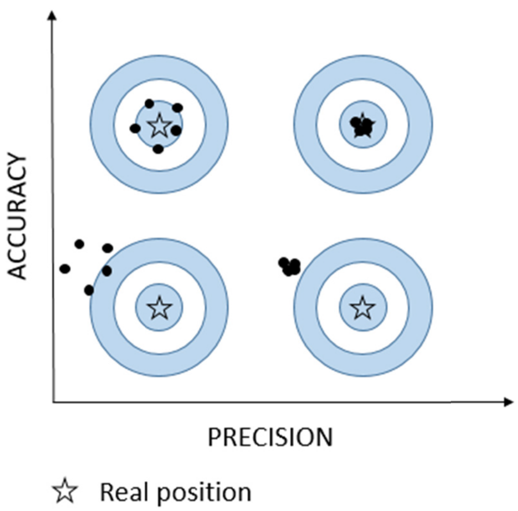

FIGURE 1. Precision vs. Accuracy.

The positioning error is a term that appears in some of the previous definitions. This error is understood as the "**correctness**" of the position. Two terms are commonly used to refer to the "correctness": **accuracy and precision**, which they do not mean the same. As shown in FIGURE 1, the accuracy, on the one hand, is the degree of proximity of the computed solutions to the real position. The precision, on the other hand, is the proximity between the computed solutions between each other. In statistical terms, assuming an undetermined probability distribution characterized by its mean and variance, the accuracy can be understood as the displacement of the distribution's mean from the real position, whereas the precision would be related to the width of the distribution and its variance.

When talking about positioning systems, a combination of precision and accuracy is usually pursued. Nevertheless, systems are not ideal; thus, positioning errors are always present. These errors, as seen in FIGURE 1, are usually bounded by the accuracy rather than by the precision, as low accuracies often lead to bigger distances from the ground truth than what low precision does. Consequently, positioning systems tend to define and set an error tolerance threshold (AL) that should not be surpassed by the error in order to maintain the integrity of the system.

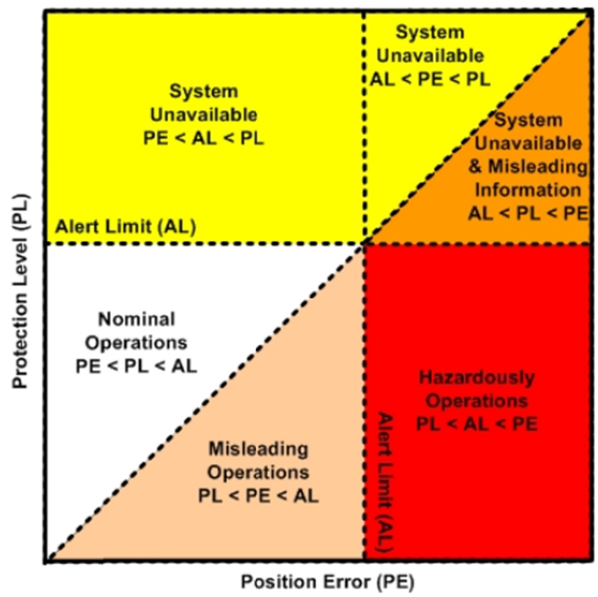

FIGURE 2. The Stanford diagram [7].

The Stanford diagram shown in FIGURE 2 specifies the integrity and availability criteria that describe the performance of a system, as a function of a user-defined alert-limit. It describes the system's state according to the relation between the tolerable error, the estimated error, and the real error.

The expected nominal operation mode, according to the diagram, implies having a positioning error smaller than the calculated protection level and a protection level which is smaller than the alert limit.

II. INTEGRITY FOR GNSS POSITIONING

Incorrect integrity monitoring could lead to devastating consequences for safety-critical applications scenarios. This means that integrity is dependent on the quality of the input information/signals and the detection and mitigation techniques implemented in the positioning algorithm for the multiple error sources that receivers need to handle. The following section mentions the different error sources that could degrade the input signals together with multiple error mitigation techniques that are used. Afterward, different kinds of integrity systems are discussed in section B, with further details on the autonomous method, as it is commonly found in transportation systems and intelligent transport system (ITS) applications. Finally, due to the relevance of the mentioned method, a classification of these techniques is carried out in section C.

A. CHARACTERIZATION AND REDUCTION OF THE MEASUREMENT ERROR SOURCES

As it is known and referred to in the literature, GNSS signals suffer from multiple error sources before reaching the receiver's antenna. Some of the most common error sources found are random noise, shadowing, multipath, NLOS (Non-Line-Of-Sight), interferences and attenuation due to signal in space and the receiver's surroundings (e.g., skylines, canyons, tunnels, etc.). These phenomena are closely linked to GNSS position performance and integrity evaluation.

Consequently, a wide variety of techniques have been developed in order to reduce or mitigate the aforementioned error sources:

1) SIGNAL WEIGHTING METHODS

These methods are commonly used as criteria of signal reliability, giving proportional weights to each measurement according to certain criteria (e.g., received signal to noise ratio) intending to relay more in better quality signals. This weighting is usually done by modifying/introducing a covariance matrix according to the mentioned criteria. This covariance matrix reflects the errors that affect each satellite's signal and, as it is assumed that the errors that affect each satellite do not affect the rest of them, it tends to be diagonal

$$\begin{pmatrix} \sigma_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_m \end{pmatrix},$$

where σ_m is the variance of pseudorange measurement errors, and m is the number of observations [8].

These values can be computed according to models that consider different physical parameters to weight the variance. The author shows in [9] a method that employs the inherent information in the carrier-to-noise-power-density ratio (C/N0) in order to estimate the random errors. This model represents the variance of an undifferenced phase observation as

$$\sigma_i^2 = V_i + C_i 10^{-\frac{C/N_0}{10}}, \tag{1}$$

where $V_i[m^2]$ and $C_i\left[m^2\ Hz\right]$ are parameters proper to the model that must be estimated and may vary according to the scenario. Further C/N0 based research is found in literature in [8]–[11].

Together with C/N0, satellite elevation can also be used to estimate the quality of the received signal, assuming that the higher the elevation, the more trustworthy it is. This is represented as [13]

$$\sigma_i^2 = \frac{1}{\mathrm{SIN}\,(\theta)^2}, \tag{2}$$

where θ is the satellite elevation angle.

The paper in [9] presents a novel hybridization weighting model that takes into account satellite elevation, the signal C/N0 and a LOS/NLOS indicator obtained from the Urban Trench Model (UTM)

$$\sigma^2 = k \cdot \frac{10^{-0.1 \cdot \frac{C}{N0}}}{\mathrm{SIN}\,(\theta)^2}, \tag{3}$$

where k is the LOS/NLOS indicator; $k = 1$ for LOS signals and $k = 0.5$ for NLOS signals.

The author performs in [13] a comparison between the presented weighting methods.

2) MULTIPATH AND NLOS RELATED TECHNIQUES

Multipath and NLOS mitigation and exploitation techniques are especially used in urban areas, where signal LOS is usually blocked, and signal beam rebounds are commonly found (multipath).

Four different strategies are employed to deal with these phenomena: **ignorer** and **avoidance** of the mentioned beams [14], **mitigation** of these through HW design (correlator modifications [15], correlator banks [14], [16]–[18], diverse polarization antennae [19]–[21], spatial diversity [22]–[24], etc.) or using quality parameters [25] and the **identification** of the NLOS beams for the later elimination or exploitation.

Elimination oriented identification techniques are more commonly used in cases where an LOS component is correctly received, and NLOS components can interfere with it, whereas the exploitation ones are more useful when no LOS beam is received and, thus, NLOS beams are the only information input [26].

The mentioned methods can be sub-classified into three main groups according to the required input: the ones that require a physical signal (usually implemented in HW), the ones that require the parameters obtained from processing the signals such as pseudorange, C/N0, Doppler, etc. (usually implemented in SW) and those which combine both GNSS data and external aid methods such as INS, map aiding, ray tracing, etc. (usually implemented in SW).

Despite the efforts to mitigate the effect of the error sources, the possibility of faulty measurements remains. These faults could imply misleading positions; consequently, error detecting and solving methods have been developed to ensure the integrity of the system.

B. INTEGRITY SYSTEMS

Integrity was originally developed for the aeronautical domain, where a single failure could cause severe fatalities. As mentioned in the introduction, integrity provides the user with timely warnings regarding the reliability of the navigation system through its navigation message. The employed health reporting of the GNSS system may not be well-timed to be considered appropriate for a real-time application that requires a quick failure reaction; thus, two different approaches have been developed to provide integrity: an autonomous one based on self-consistency check of redundant measurements, and a ground-station network-based one [8], [27]. The diverse needs have resulted in the development of two different external-aid-based approaches.

Satellite-Based Augmentation Systems (SBAS), on the one hand, rely on the integrity-related information provided by geostationary satellites, as they improve the accuracy, reliability, and integrity of the GPS signal [28]. The geostationary satellites also provide ranging capabilities, so that they can be used as GNSS satellites to increase the availability [27].

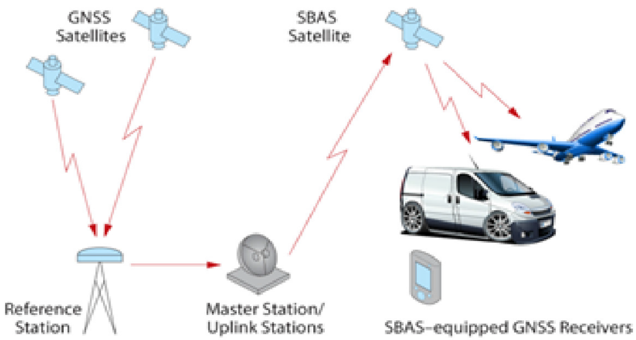

FIGURE 3. SBAS architecture [74].

These systems (FIGURE 3) are based on regional networks of strategically distributed reference stations that measure GPS signal-in-space (SIS) for the purpose of computing the error estimates at the master stations [29].

Ground-Based Augmentation System (GBAS), on the other hand, provide integrity-related information data based on a locally located ground elements. In contrast to SBAS's regional distribution, GBAS employs a small number of reference stations that perform measurements and later corrections at just one location, which is why these systems can be usually found at airports [5], [27].

While providing integrity assurance is the aim of GBAS, it also increases the accuracy and precision below 1 m.

Receiver Autonomous Integrity Monitoring (RAIM) is a technology developed to estimate the integrity of, originally, the GPS. The main aim is to provide the receiver with the ability to perform a self-contained fault detection by comparing each GPS measurement to the other available measurements [27]. It is, thus, based on the consistency check of redundant range measurements [30]. There are two possible pseudorange error scenarios, the fault-free scenario and the faulty one, being the first one affected only by the nominal errors that are modeled as zero-mean independent Gaussian distributions, whereas, in the second ones, a bias is added to some of the range measurements [30].

According to [31], the inputs to RAIM algorithms are the standard deviation of the measurement noise, the measurement geometry, and a threshold that defines the probabilities for a false alert and a missed detection. The main outputs of RAIM algorithms are the protection levels (PL) and the ability to provide an alert.

Although there are many RAIM schemes (see section C), most RAIM algorithms include an error measurement and its corresponding bound in the form of a protection level (PL).

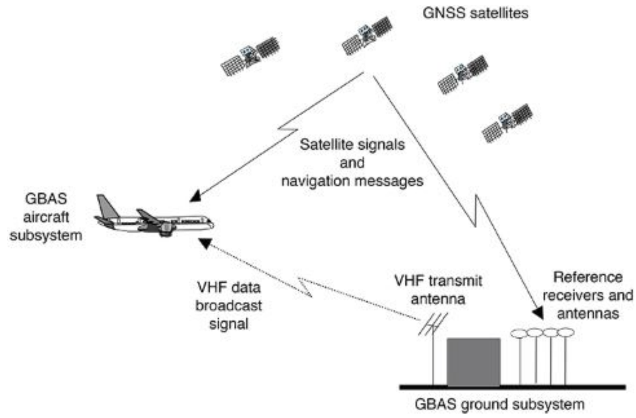

FIGURE 4. GBAS architecture [75].

These PL can be computed in different ways and can even be calculated without applying RAIM, as it will be discussed in Subsection 2.

As RAIM can only bound the positioning error with an *a priori* estimation, the previously mentioned FDE methods have been developed as an extension of RAIM to reduce the positioning error.

The following section will first explain the classical RAIM method, followed by different ways to compute PL. Together with this, the fault detection and exclusion methods will be explained.

1) CLASSICAL RAIM

The principle of the classical RAIM method is shown in FIGURE 5. Each of the diagonal slopes is related to each observable satellite, where the bigger the gradient of the slope, the bigger the position error caused by the ranging error from the said satellite. It is assumed that, in the worst-case scenario, a failure could remain after the FDE test. Consequently, the PL is expected to be such that overbounds the error caused by a faulty measurement at the biggest sloped satellite [32].

In the case in which there was one only faulty measurement and the rest were ideal, the protection level should be located at PR_0, at the point in which the slope crosses the threshold used in the FDE test (T_D) [32].

Nevertheless, as the rest of the measurements are not ideal, they introduce an error that can be modeled as zero-mean Gaussian variables (gray ellipses) around a new mean value. This value is called p_{bias}, and it is a deterministic value that depends on the number of visible satellites [33].

Taking into account the mentioned matters, the PL should be set so that the probability of misdetection (P_{md}) is as small as possible or, in other words, such that reduces the Integrity Risk.

2) COMPUTATION OF THE PROTECTION LEVEL (PL)

The PL is an upper bound estimation of the positioning error. This estimation is used to raise an alert flag whenever a predefined threshold is surpassed.

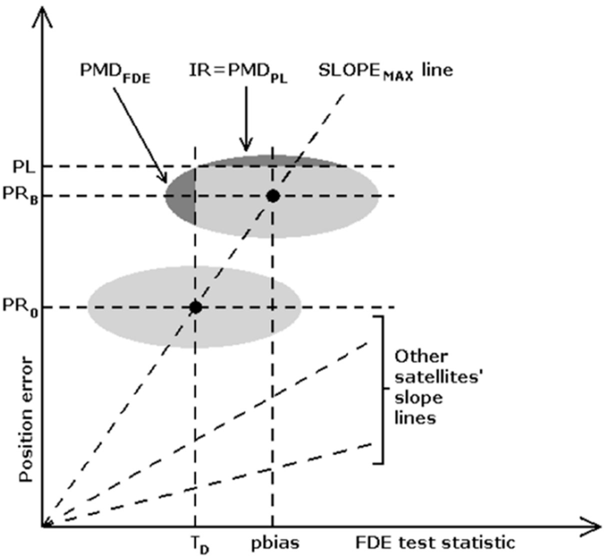

FIGURE 5. Classic RAIM scheme and the corresponding protection level computation [32].

Even though different definitions of PL can be found for the different applications, all of them are used for integrity purposes [20], [21]. The protection level is usually found broken down into its two components: the Vertical Protection Level (VPL) and the Horizontal Protection Level (HPL).

The PL is computed weighting different parameters according to the application or the scenario. Depending on the characteristics of the error source, the weight of this in the solution error may be different; for example, the PL can be decomposed into a noise component usually calculated according to the propagation error and a biased error part that can be computed in different ways according to the chosen model [12]:

$$PL = K(P_{md}) \cdot d_{major} + \max{}_i(SLOPE_i) \cdot p_{bias}. \quad (4)$$

The former term of the sum, which corresponds to the measurement noise, is computed according to the error propagation with external SBAS data aid [34]. K is an inflation parameter related to integrity risk, dependent on the probability of misdetection (P_{md}). d_{major} denotes the error uncertainty described by the semi-major axis of the error ellipse and it can be computed with the 2D elements of the variance matrix as

$$d_{major} = \sqrt{\sigma_e^2 + \sigma_n^2} \quad (5)$$

The $SLOPE_i$ parameter is a characteristic line, particular to each satellite, result of plotting the Horizontal Positioning Error (HPE) against a test statistic, as can be seen in FIGURE 5 [33].

Brown's method [36] or any of its variations are usually used to compute the $SLOPE_i$ parameter, which guarantees integrity by only accepting geometries that provide adequate redundancy to determine if there is an error on any channel of the receiver [37].

Variations of this method are found in the literature. Nevertheless, plenty of them show a similar structure, with the same slope-based method as a base [38].

Three different methods for the computation of the PL are discussed in [31]. These methods are the Brenner's method [34], which equals the PL to the largest error in the horizontal plane but does not identify the faulty satellite; Brown's method (previously mentioned) and Lee's method [39], which takes into account the fact that the missed detection probability depends on the bias error magnitude, and the maximum occurs before the bias error reaches the value that determines HPL in these methods [31]. Together with this, it also proposes a new method that contains the deterministic part defined by Brown's method's SLOPE and the stochastic part defined by noise. This method differs from (2) in the first term (the noise component) in the use of the integral of a statistic noise distribution instead of external SBAS data.

The computation of the PL can also be found to be based on the real-time processing of the SBAS broadcast data, as augmentation systems as EGNOS provide correction information for all pseudoranges. For this purpose, the RTCA standard differentiates two modes of operation; the non-precision approach and the precision approach. The author in [28] computes the PL as following:

$$PL = K_H \cdot d_{major} = 6.18 \cdot d_{major} \quad (6)$$

where the K_H is computed by the Rayleigh cumulative distribution function, assuming a non-precision approach as [40]

$$\begin{aligned} K_H &= RayleighCDF^{-1}(1 - P_{md}) \\ &= RayleighCDF^{-1}(1 - 5 \cdot 10^{-9}). \end{aligned} \quad (7)$$

a: ISOTROPY BASED PROTECTION LEVEL

This patented method is based on the hypothesis of the entropy on the measurement residuals, what is to say, that this vector can point in any direction equiprobably [30], [41]. This method, unlike others, does not assume any gaussianity on the measurement distributions [42]. According to this method, the PL is computed as follows [30], [41], [43]:

$$PL = k \cdot \|r\| \cdot XDOP. \quad (8)$$

The first parameter, k, is the isotropy confidence ratio (ICR), a parameter that ensures a bound of the error estimation by a confidence level (1-α) and the size of the residual vector, being α the integrity risk. r is the residual vector of the least square estimation. The later parameter, XDOP, is the employed type of dilution of precision (HDOP if HPL is computed and VDOP in the case of VPL).

Reference [42] shows a variant of this method as

$$PL = k \cdot \|r\| \cdot \sqrt{\lambda_{\max}^{(H^T H)^{-1}}}, \quad (9)$$

where the XDOP parameter is substituted by the largest eigenvalue of $H^T H$ (H is the observation matrix used in the linear observation equation).

The PLs mentioned previously were all based on GNSS measurements. Nevertheless, other sensor observations can be added to the equation in order to obtain an estimation closer to reality. An (ITS) application focused PL is shown in [44]. This method adds IMU and vehicle odometer measurements to the RTK positioning and the corresponding integrity monitoring.

b: KALMAN INTEGRATED PROTECTION LEVEL

This patented method is an extension of the IBPL that allows both the use of GNSS-standalone and GNSS/INS navigation [45]. It estimates the error using a zero-mean multivariate Student distribution instead of a Gaussian one to improve the robustness against outliers [42]. It takes into account the temporal correlation of measurements, which, according to its author, is a requirement in order to compute a correct bound to the Kalman solution errors [46]. The results of this method, when applied to the case of a GNSS low-cost multi-constellation receiver, are also shown in this publication.

3) FAULT DETECTION AND EXCLUSION (FDE) METHODS

FDE methods are extensions of RAIM used not only to detect faulty satellites but also to exclude them from the navigation solutions so that the system's operation is not interrupted due to an incorrect PVT solution. The FDE scheme is divided into a global and a local test, where the global test (GT) is used to check if there is any fault (for which a minimum of five satellites is required) and the local test (LT) is used to identify it (for what six satellites are needed). A common approach to performing the global test is to use a test statistic, based on the Normalized Sum of Squared Error (NSSE), and check if this variable, multiplied by a variance factor and by the degrees of freedom (n-p), follows a centrally chi-squared distribution or not [47]. This test statistic is computed as

$$t = \widehat{r}^T \Sigma^{-1} \widehat{r}, \qquad (10)$$

where r represents the range residual of the measurement and Σ represents the covariance matrix of the measurement errors.

In a failure-free situation, in other words, in case the global test passes the predefined threshold, the test statistic will follow a central chi-squared distribution (H_0) (FIGURE 6). This would mean that the solution would be computed without faulty satellites, obtaining, as a consequence, a reliable position estimation. On the other hand, if the global test is failed, which means that a failure has been detected, the test statistic will be non-centrally chi-squared distributed (H_a), with a non-centrality parameter called λ [47]. FIGURE 6 shows a statistical view of the GT and the behavior of the test statistic in both the faulty (H_a) and non-faulty (H_0) scenarios. α and β are the probabilities of detecting correctly and incorrectly the failure in the system, respectively. n is the number of satellites that are observed, and p is the number of parameters to be estimated.

There are multiple FDE schemes in which GT and LT are combined in different ways [12], [30]. In case of detecting a failure during the GT, the next FDE techniques can be carried out [12]:

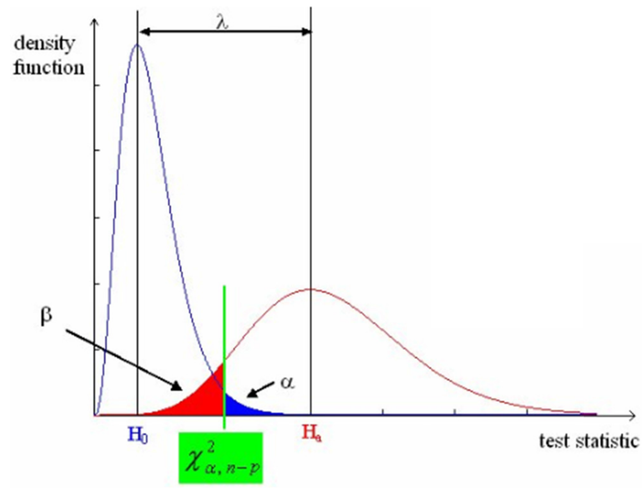

FIGURE 6. A central and a non-central chi-square distribution used for failure detection during the global test [47].

–**Subset testing (ST)** [13], [47], [48]: the GT is recomputed using subsets of more than four satellites, and the one with the most satellites and the smallest test statistic from the ones that pass the GT is selected.

–**Sequential local test (SLT)** [13], [47]: in each iteration of the LT, the one that further exceeds a given threshold with the biggest LT statistic will be eliminated.

–**Forward-backward test (FB)** [13], [48]: The forward loop performs the sequential local test while the backward one reintroduces the eliminated satellites to find the optimal combination from all the possibilities.

–**Danish method** [13], [48]: an iteratively reweighting is performed on the pre-estimated measurement variance based on the ration between an LT statistic and the local threshold. A point that should be emphasized is that there is no exclusion in this method and, if the algorithm cannot converge after iterating, the solution is considered unreliable.

Although all the mentioned FDE methods are based on the same GT – LT principle, each introduced variation has a different result. The following table summarizes the results shown in [13] and classifies these methods from 1 to 4 as a function of seven different aspects, being 1 the best and 4 the worst.

The fact that the results shown in TABLE 1 have been taken from a single measurement implies that some of the values can change between scenarios, as a single sample is not enough to make proper statistical statements. Nevertheless, it is still useful to have an early idea about the behavior of each of the methods and performance of each of them according to the application.

The mentioned methods may not be robust enough, as it is assumed that one outlier cannot be spread into the rest of the residuals. The author shows in [49] a possible solution to the mentioned issue by the Leave One Block Out approach. When possible, the observations are decomposed into uncorrelated blocks, so that the effect of a faulty observation is isolated.

TABLE 1. Comparison of the FDE methods.

		ST	SLT	F-B	Danish
Availability		1	4	2	3
Computation time		4	3	1	2
HPE	Min.	1	2	2	4
	Max.	1	4	2	3
	Mean	1	4	2	3
	Median	2	1	3	4
	Std. Dev.	1	4	2	3

Real-time applications, for example, could require lower computation times, as the detection of faults (and the consequent improvement in solution) and the recalculation of the solution should be done fast enough not to exceed the reaction time.

Life involving applications, on the other hand, could require high availability of the method, as a faulty measurement could imply an error that could lead to fatal consequences. Note that, according to [3], availability is "the percentage of time a signal fulfills the above accuracy, integrity and continuity criteria."

C. CLASSIFICATION OF NOVEL RAIM TECHNIQUES

Originally, the RAIM method was developed for airplane integrity monitoring. In this original scenario, GPS was just employed in an environment where the only signal failure could happen due to the malfunctioning of a satellite. Nowadays, multiple constellations are used, which implies a considerable amount of satellite combination. Moreover, as GNSS positioning and RAIM methods are commonly used on ground applications, where multiple error sources can be found, the RAIM methods have been improved to deal with the mentioned issues.

These techniques, which primary emphasis is the failure detection and exclusion, can be classified in multiple ways according to different parameters. When talking about the required amount of observations for the computation, one can distinguish two categories [27]:

–**A recursive scheme.** Typically a Kalman or a particle filter, which uses the history of the measurement data. Kalman filters are linear-quadratic estimators; thus, they are best for estimating linear systems with Gaussian noise [50]. They have much lower computational requirements than particle filters but are less flexible. Particle filters, on the other hand, can handle almost any kind of model, by discretizing the problem into individual "particles." This process may have as drawbacks high computational requirements.

–**A snapshot scheme.** A scheme in which the estimation of the position and the time of the receiver are based on the current measurements and satellite data. The main advantage of this scheme is that it allows an instantaneous position fix as it does not depend on more data than the corresponding to that same epoch [9]. Regarding its performance, nevertheless, it is usually outperformed by the recursive scheme. This scheme is usually used to calculate the initial position in the recursive scheme, based, often, on the Least Squares Estimation (LSE). E.g: LS background [48], Parkinson's LS residual method, Sturza's parity method [51], Brenner's parity method [52], Maximum residual method [48], solution separation method [53]–[55] etc.

The recursive scheme gives a more accurate position estimation than the snapshot one; therefore, the first is commonly used to detect rapidly growing measurement errors by monitoring the residuals. These residuals, also called innovations, are the differences between the current measurements and the predicted ones based on the history of the measurements. The recursive scheme, nevertheless, using innovations as test statistics, fails to catch slowly growing measurement errors called soft failures or ramp type because of attempting to adjust the solution to match faulty past measurements. Soft failures can be detected by the snapshot scheme. Two schemes should be used in parallel to achieve better fault detection.

No Classical RAIM implementation could fulfill the demanding vertical navigation requirements that were needed in aviation. Therefore, the second generation of RAIM techniques was developed that could ensure integrity in both lateral and vertical navigation. An example of this are the ARAIM and RRAIM methods that were presented as a possible solution [56]. According to GEAS [27], ARAIM with MHSS was decided as the principal architecture. RRAIM, on the other hand, was decided to be used whenever ARAIM was not available. In the following section, these two methods will be discussed, among other novel RAIM methods.

1) ADVANCED RAIM (ARAIM)

With the deployment of multiple new constellations, new RAIM methods have emerged. The Advanced Receiver Autonomous Integrity Monitoring (ARAIM) method expands the RAIM method to more constellations than GPS. This combination of constellations contributes to a better performance of horizontal guidance than RAIM based just on GPS [49], [57], [58].

The ARAIM has been developed from the solution separation, as this method turns out to be easier to modify for providing the improved competencies wanted for ARAIM [27], [59]. The solution separation method is based on the estimation of the position by means of computing it with all the available satellite measurements on the one hand and, on the other hand, computing the solution with all satellites except one. This solution separation method relies on three threshold test for each fault mode, one for each coordinate [55], [60]. ARAIM algorithms assume the possibility of having multiple-signal faults, not as in classical RAIM. The algorithm shown in [27] considers that the probability of multiple-signal fault threat is small, as it assumes that these are mitigated by other methods such as core-constellation design, ground monitoring, or separate airborne evaluation of broadcast data. In [38], on the other hand, the author assumes that the possibility of suffering multiple failures is not negligible and, as a consequence, it discusses how should be the algorithm configured to detect them.

This approach takes advantage of the multi-frequency signals to compute an ionosphere-free combination to obtain higher accuracies. Moreover, it can use carrier-smoothed code measurements for both fault detection and positioning [61].

One of the main differences between ARAIM and RAIM is the capacity of ARAIM to adjust its operation to different requirements. Integrity parameters, fault probabilities, and even the probability of missed detection are fixed in RAIM, whereas in ARAIM, these parameters vary according to the requirements [62]. The authors describe in [62] the minimum operational performance standards.

The airborne algorithms for ARAIM are already mature enough for their use [63]. The full architecture for its deployment, on the other hand, is still being developed and standardized to support a correct operation [57]. Consequently, developing this architecture will be the current and future work in this area for the use of this technology.

2) RELATIVE RAIM (RRAIM)

The relative RAIM (RRAIM) is a technique that was developed to handle the GPS data latency problem [56], [64].

It is based on the propagation of older pseudoranges forward in time by using precise carrier phase measurements [61]. For this purpose, integrity measurements are performed periodically, when available, and during these intervals (called coasting time), RRAIM takes the difference between the accumulated carrier phase and the original value to estimate the new positions [64]. The accumulated uncertainty during this interval can be split into three main sources; the change of noise and multipath levels, the change in the tropospheric error, and the satellite clock drift [56].

Two main variants of the RRAIM algorithms are found in literature: a Range Domain RRAIM that is based on a Chi-square (χ^2) RAIM method (introduced in [56]), and a Position Domain RRAIM based on a solution separation RAIM method (introduced in [64]).

3) EXTENDED RAIM (ERAIM)

Due to the fact that satellite navigation depends on radiofrequency signals, degradation of these could lead to a faulty PVT solution or even to no solution scenario. As a consequence, multiple transportation systems in the ITS world have started to integrate multiple sensors (such as INS or odometers) to complete and improve the performance of GNSS only systems.

Thus, the purpose of adapting RAIM to GNSS/INS integrated systems gave rise to the creation of ERAIM. This method is based on the least-squares theory, which is used to find the best estimators of the state parameters in a Kalman Filter [55], [56]. Once having characterized the filter, and based on the new measurement, integrity monitoring is performed, including outlier detection and identification, reliability, and separability [55], [56].

The term reliability is used to quantify the minimum detectable bias that stipulates, with a high confidence level, the lower bound for detectable outliers [66].

Separability, on the other hand, is the capacity of separating measurements, in the case of a faulty one, so that good measurements are not incorrectly understood as a fault [65].

References [65] and [66] show empirical results of the method; the first one does, nevertheless, a comparison for ERAIM vs. RAIM and its corresponding analysis.

A different meaning is given to ERAIM in [27], where ERAIM means RRAIM-Extended ARAIM. The main goal of this method is to use RRAIM's coasting during ARAIM's unavailability intervals. Together with improving availability, this method leads to tighter detection thresholds as the carrier-phase is added via RRAIM. The tighter detection results in smaller protection levels than using just ARAIM.

4) CARRIER BASED RAIM (CRAIM)

Even if most RAIM methods are based on code measurements, other architectures exist, such as the Carrier-Phase based RAIM (CRAIM) [46], [47]. This method's main characteristic is the use of the carrier-phase, which is much more precise than code measurements, as it is more robust against noise. Nevertheless, it is not always available as an absolute measurement without external aid, due to its ambiguities, especially difficult to compute in harsh environments.

The CRAIM method proposed in [67], which is a carrier-phase based algorithm for high-accuracy positioning based on Kalman filtering, only allows failure detection and does not provide failure identification. This is why [68] introduces a new variation of this method that permits both failure detection and failure identification using extended w-test detectors. These detectors are based on the use of two test-statistics for the EKF, which are respectively presented for the code (c) and carrier phase (p) double-difference (DD). These statistics can be deduced as follows:

$$w_{ij} = \left| \frac{e_j^T R_i^{-1} r_{ik}}{e_j^T R_i^{-1} W_{ik} R_i^{-1} e_j} \right|, \quad i = c, p \tag{11}$$

where the unit vector represents the use of a certain measurement or, in other words, if $e_i = 1$, the i_{th} measurement is used. R_i represents the measurement noise covariance and W_{ik} is the reduction of W_k, a parameter that represents the variance-covariance of the innovation r_{ik}. W_k is a weighting matrix that considers the covariance and measurement noise of the measurement residual.

In a faulty-free case, the test statistic follows a standard Gaussian distribution. In a faulty case, on the other hand, it follows a non-central Gaussian distribution [69]. These statistics can be used to define a threshold using the P_{FA} in order to detect a fault in both the carrier phase and the code.

This innovation, which makes this method efficient for multi-failure scenarios, improves integrity and reliability.

Both papers [67], [68] provide an extensive analysis of their algorithms and the behavior of the employed

TABLE 2. RAIM technique classification and characteristics.

RAIM type	References	Measurement	Algorithm	FDE type / Tolerated faults	External input	Navigation	Constellations	Frequencies
Classical RAIM	[32][38][39] [45][46]	Code	LS / WLS methods	FDE / Single fault	No	LNAV	GPS	1
Advanced RAIM	[47][48][49] [18][30][42]	Code	Solution separation (SS) or Mulitple hypothesis Solution Separation (MHSS)	Real time FDE / Multiple faults	Integrity data from Integrity Support Messages	LPV-200	Multiple	Multiple
Relative RAIM	[50][47] [48][49]	Carrier	Chi-square method or SS method	FDE / Multiple faults	External monitors	LPV-200	GPS	-
Extended RAIM	[18][51][52]	Code	Least square initialized EKF	FDE / Multiple faults	Multiple sensors	-	Mulitple	-
Carrier based RAIM	[46][47] [53][54]	Carrier	Ambiguity Resolution algorithms (LAMBDA) Extended Kalman Filter (EKF)	FD (no exclusion) / Multiple faults	No	LNAV	Mulitple	Multiple
Time RAIM	[55][56][57]	Code and doppler	WLS and variations	Forward backward FDE / -	No	-	Multiple	-
Vision-Aided RAIM	[58]	Code	Real Time Kinematics (RTK)	Fault detection / single fault assumption in [58] but multiple faults could be detected	Vision system provided landmarks and RTK required corrections	LPV-200	GPS	-

test statistics. Furthermore, the author shows in [67], an example result of the obtained protection level during some measurements.

5) TIME RAIM (TRAIM)

The RAIM concept is usually related to positioning; however, it can also be applied to time matters. The addition of a new level of system reliability to timing applications is proposed in [70]. The author presents an algorithm that detects and removes the satellites that exceed a previously defined time residual threshold. It is also mentioned that the algorithm allows the end-user to predict the overall system time accuracy and that the algorithm is able to predict the time error performance of the receiver both in faulty and fault-free scenarios.

A potential T-RAIM approach for a multi-constellation scenario is discussed in [71]. According to the author, the benefits of multi-constellation T-RAIM are shown in hard environments.

Experimental proof of the performance of T-RAIM is given in [72].

6) VISION-AIDED RAIM (VA-RAIM)

It is mentioned in [73] that the performance of existing RAIM methods could not be acceptable during the landing phase of a flight as a consequence of the lack of observations. This is why it proposes a new RAIM method called Vision-Aided RAIM (VA-RAIM), which employs computer vision systems to match landmarks with photographs in order to obtain additional measurements. This method improves availability, as it introduces the landmarks as pseudo-satellites so that the vision system can model the landmark-receiver distance in an analogous way as done in the GPS. These vision measurements are used to expand the GPS measurement equations in order to improve integrity. This is a concept that is easily transferable to other transport means.

This method assumes that the test statistic defined by the NSSE follows a chi-squared distribution. As shown in

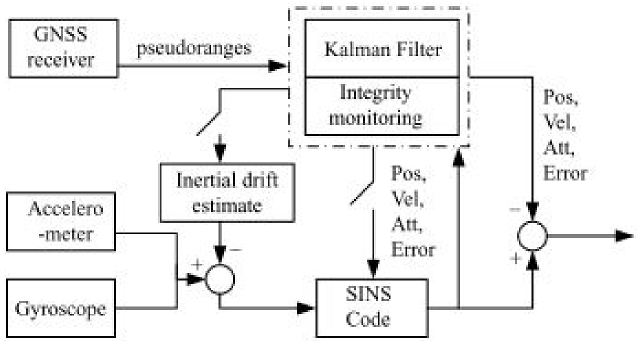

FIGURE 7. GNSS/INS integrated system block [65].

Classical RAIM, this test-statistic is compared to a user-defined threshold T_{NSSE} that is dependent on P_{FA}; so that whenever it exceeds the threshold, a fault will be detected.

The author states that simulation results show that the proposed method outperforms classical RAIM both in terms of fault detection rate and in terms of availability.

III. CONCLUSION

Positioning accuracy is a vital requirement in multiple subjects inside society. As a consequence, so it is the failure detection and the computation of an accurate upper bound of the positioning error.

GNSS techniques have been developed up to a point in which the classical RAIM scheme may not be able to fulfill its duty. As a consequence, research is being carried out on new RAIM schemes that cover the aspects that classical RAIM does not consider, such as multiple faults, multiple frequencies, or augmentation systems.

This paper shows an up to date introduction to GNSS positioning integrity and the respective concept definitions. Together with these explanations, multiple error sources that could cause an incorrect position have been discussed and classified.

Moreover, a statistical approach to the main fault detection and exclusion techniques has been shown in Section B. Besides this summary, a classification (TABLE 2) and an explanation of the principal among these methods found in the literature are done. Finally, as it is a relevant measurement for navigation (together with the GNSS PVT solution), different error upper bounds or protection levels have been shown.

To sum up, this survey gathers and discusses the main receiver autonomous integrity monitoring methods found in the literature. This initial study can be understood as a state of the art chapter on the matter and may be useful for creating a knowledge base about this topic. Future work can be done both in the development of each of the presented techniques and in the empirical comparison of these. This future research should especially focus on the computation of the protection level, as current models use to overbound the error in a loosely way, not being able to properly adapt to the error. In an ideal case, the PL's curve would be tangent to the error at every moment, tightly bounding the error.

ACRONYMS

AL	Alert Limit
C/N0	Carrier to Noise Ratio
DOP	Dilution of Precision
FA	False Alarm
FB	Forward Backward
FDE	Fault Detection and Exclusion
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GT	Global Test
HPE	Horizontal Positioning Error
HPL	Horizontal Protection Level
HW	Hardware
IBPL	Isotropy Based Protection Level
ICR	Isotropy Confidence Radio
IM	Integrity Monitoring
IMU	Inertia Measuring Unit
INS	Inertial Navigation System
IR	Integrity Risk
ITS	Intelligent Transport System
KIPL	Kalman Integrated Protection Level
LOS	Line of Sight
LT	Local Test
MD	Misdetection
NLOS	Non Line of Sight
NSSE	Normalized Sum of Squared Errors
PE	Positioning Error
PF	Positioning Failure
PL	Protection Level
PVT	Position, Velocity and Time
RAIM	Receiver Autonomous Integrity Monitoring
RTCA	Radio Technical Commission for Aeronautics
RTK	Real Time Kinematics
SBAS	Satellite Based Augmentation System
SIS	Signal in Space
SLT	Sequential Local Testing
ST	Subset Testing
SW	Software
TTA	Time to Alert
UTM	Urban Trench Model
VPL	Vertical Protection Level

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