Analyses of Integrity Monitoring Techniques for a Global Navigation Satellite System (GNSS-2)

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BIOGRAPHIES

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ABSTRACT

A GNSS-2 has to overcome the basic deficiencies, i.e. the lack of integrity, availability, continuity and accuracy in the Signal-In-Space (SIS), of present satellite navigation systems as the U.S. Global Positioning System (GPS) and the Russian Global Navigation Satellite System (GLONASS). Thus, the European contribution to GNSS-2 (Galileo) with the current baseline of reusing the European Geostationary Navigation Overlay Service (EGNOS) requires that the SIS provides already integrity for Category I (CAT I) precision approach and landing.

The integrity of a system refers to the assurance that all functions of this system perform within the operational limits where the integrity risk is the probability of undetected failures resulting in the loss of specified accuracy. Analyses of appropriate integrity monitoring techniques for a GNSS-2 must be performed in order to demonstrate whether or not this performance requirement can be met by the proposed GNSS-2 architectures. In addition to this, these analyses have to show the advantages and limitations of these techniques as well as the achievable service integrity monitoring levels for the different integrity monitoring concepts.

The paper discusses basic integrity monitoring concepts as Receiver Autonomous Integrity Monitoring (RAIM) like methods for the Galileo users and the contribution of the Galileo ground-based integrity monitoring as well as the first results of an adapted RAIM algorithm availability simulation. This discussion takes also several Galileo hybridization techniques, e.g. the combination of Galileo with other navigation systems (GPS, LORAN-C, etc.) and/or with further sensors (barometric altimeter, etc.), into account.

INTRODUCTION

The general purpose of integrity monitoring is the protection of a service provided by a system against errors, which exceed a specified bound. This protection of a system service can be achieved by several methods, where redundant information is used by either a single independent autonomous subsystem or by a combination of independent autonomous subsystems in order to check the correctness of this service and/or the total system is monitored by an external independent monitoring system.

The objective of the independent autonomous integrity monitoring, which is performed by a Galileo user receiver, is the protection of the navigation solution provided by this user receiver against position errors exceeding the alarm limit. For this reason, the integrity monitor of a user receiver must provide a timely warning when a failure exists (i.e. when a position error exceeds the alarm limit). In addition to this, if a user receiver utilizes additional information from the Ground Integrity Channel (GIC) of Galileo, from further navigation systems and/or from other sensors, then the integrity of the navigation solution, which is provided by this user receiver, increases.

The following discussion with regard to the navigation solution integrity monitoring by the user receiver gives a first preliminary qualitative assessment of the integrity monitoring level, which can be achieved at user level, as well as of the impact of the GIC on the integrity monitoring level. Moreover, the hybridization of Galileo with other navigation systems and/or with further sensors is considered too.

USER AUTONOMOUS INTEGRITY MONITORING BASICS

All measurements, which are used by the user receiver for the determination of the navigation solution, are also used by the integrity monitor of this user receiver in order to check the consistency of this navigation solution. In general, the independent autonomous integrity monitoring, which is performed by a Galileo user receiver, is structured as follows:

(i) **User integrity monitor availability check** (checks whether or not the number of used measurements as well as the relative geometry of the user receiver position and the satellite positions are sufficient for the determination of a correct navigation solution, which meets the user performance requirements)
(ii) **Hypothesis test** (checks whether or not one of the measurements, which are used by the user receiver, is incorrect when the integrity monitor of this user receiver is available where it is assumed that only one of these measurements is incorrect at a time)

If the integrity monitor of a user receiver is not available (e.g., due to insufficient relative geometry of the user receiver position and the satellite positions), then the user performance requirements cannot be met by the integrity monitoring performed by this user receiver. Therefore, the navigation solution consistency check, i.e. the hypothesis test, cannot be performed by the integrity monitor of a user receiver when this user integrity monitor is not available. The user has to use measurements from other navigation systems or sensors in order to determine a correct navigation solution, which meets the user performance requirements, in this case. Note that the user cannot compute a correct navigation solution meeting the user performance requirements when the integrity monitor of the Galileo user receiver is not available and when no measurements from other navigation systems or sensors are available. On the other hand, a hypothesis test (i.e. the calculation of a test statistic and the subsequent comparison of this test statistic with the concerning threshold) is performed by the integrity monitor of a user receiver in order to decide whether or not an incorrect measurement exists when this user integrity monitor is available. If no incorrect measurement is thereby detected (i.e. this test statistic is smaller than or equal to this threshold), then it is assumed that the navigation solution calculated by the user is a correct navigation solution, which meets the user performance requirements. Otherwise an incorrect measurement is detected (i.e. this test statistic is greater than this threshold) and the navigation solution computed by the user is assessed as incorrect. The user has to perform further operations in order to obtain a correct navigation solution meeting the user performance requirements in this case. After the detection of an incorrect measurement, a user can proceed as follows:

(i) Determination of a correct navigation solution, which meets the user performance requirements, by using only measurements, which are not used by the user for the determination of the navigation solution that is assessed as incorrect, from other navigation systems or sensors
(ii) Isolation, i.e. identification, and/or exclusion of the incorrect measurement from the navigation solution, which is assessed as incorrect

It must be noted that fault isolation/exclusion is only required for primary means of navigation as well as for sole means of navigation. Moreover, the relative geometry of the user receiver position and the satellite positions is not always sufficient for the fault isolation/exclusion purpose. Therefore, the user cannot compute a correct navigation solution meeting the user performance requirements when an incorrect measurement is detected and when fault isolation/exclusion cannot be performed as well as when no other measurements than those used by the user for the determination of the navigation solution, which is assessed as incorrect, are available.

ADAPTED RAIM ALGORITHM

Several methods can be used for the integrity monitoring at user level where RAIM like techniques, which check the correctness of the navigation solution provided by the user receiver, are usable for the integrity monitoring performed by this user receiver. Assuming that the least squares adjustment is used by the user receiver in order to determine the navigation solution, then the RAIM method proposed by Brenner [1] can be modified in order to obtain an adapted RAIM algorithm, which can be used by the integrity monitor of this user receiver and which is also applicable when Galileo is hybridized with other navigation systems and/or with further sensors. This adapted RAIM algorithm is the basis for the following analyses of the navigation solution integrity monitoring performed by the user receiver and is denoted as the parity method with aligned coordinate systems.

Mathematical Model

The mathematical model, which is used by the adapted RAIM algorithm (i.e. by the parity method with aligned coordinate systems), bases on the assumption that at a given point of time n measurements are available at the user receiver. It is additionally assumed that $n > m$ for fault detection as well as $n > m+1$ for fault detection and isolation/exclusion, where m is the number of unknowns. The unknowns are the three user receiver position coordinates and the user receiver clock offset with respect to the Galileo network time (i.e. the number of unknowns is equal to four when the user receiver uses only Galileo satellite measurements). Note that the hybridization of Galileo with other navigation systems and/or with further sensors generally results in additional unknowns (e.g. user receiver clock offsets with respect to the network times of other navigation systems when Galileo is hybridized with further navigation systems). The linearization of the nonlinear functions, which belong to the n measurements, of the unknowns yields the relationships between these n measurements and the unknowns in the form of the following system of linear algebraic equations:

$$\boldsymbol{y}_M = \boldsymbol{G}_M \boldsymbol{x} + \boldsymbol{\varepsilon}_M \tag{1}$$

with

$\boldsymbol{y}_M$	$n\times1$ residual vector
$\boldsymbol{G}_M$	$n\times m$ design matrix with $\mathrm{rank}(\boldsymbol{G}_M) = m$
$\boldsymbol{x}$	$m\times1$ vector of the deviations of the unknowns from the predicted values of the unknowns
$\boldsymbol{\varepsilon}_M$	$n\times1$ error vector

The residual vector consists of the differences between the values of these nonlinear functions at the unknowns and the values of these nonlinear functions at the predicted values of the unknowns. Furthermore, the elements in each row of the design matrix are the first order partial derivatives of the corresponding nonlinear function at the predicted values of the unknowns. The first order partial derivatives, which are the elements of a row of the design matrix, are thereby obtained by the Taylor series expansion of the corresponding nonlinear function yielding the linear algebraic equation, which belongs to this row of the design matrix. It must be noted that the first three components of $\boldsymbol{x}$ are the three components of the user receiver position deviation from the predicted user receiver position. Moreover, the error vector is Gaussian with zero mean vector and with constant positive definite covariance matrix $\boldsymbol{R}$, i.e. $\boldsymbol{\varepsilon}_M \sim \mathbf{N}(\boldsymbol{0}, \boldsymbol{R})$. The $n\times n$ matrix $\boldsymbol{R}$ is specified by $\boldsymbol{R} = (\boldsymbol{W}^T\boldsymbol{W})^{-1}$ with the $n\times n$ diagonal matrix

$$\boldsymbol{W} = \mathrm{diag}(\sigma_1^{-1}, \ldots, \sigma_n^{-1}) \tag{2}$$

where σ_i is the standard deviation of the ith component of the error vector ($\sigma_i > 0 \ \forall \ i \in \{1, ..., n\}$). If the ith component of the error vector belongs to a Galileo satellite measurement, then the variance σ_i^2 of this component of $\boldsymbol{\varepsilon}_M$ is specified as follows [5]:

$$\sigma_i^2 = \sigma_{SISA,i}^2 + \frac{\sigma_{UIVE,i}^2}{1-\left(\dfrac{R_e \cos E_i}{R_e + h_I}\right)^2} + \sigma_{SNR,i}^2 + \frac{\sigma_{m45}^2}{\tan^2 E_i} + \frac{\sigma_{trv}^2}{\sin^2 E_i} \tag{3}$$

with

σ_i	Standard deviation of the ith component of $\boldsymbol{\varepsilon}_M$
$\sigma_{SISA,i}$	Standard deviation of the combined satellite ephemeris and clock error contribution
$\sigma_{UIVE,i}$	Standard deviation of the vertical ionospheric error contribution
R_e	Mean radius of the earth
E_i	Elevation angle of the satellite
h_I	Height of the maximum electron density
$\sigma_{SNR,i}$	Standard deviation of the user receiver noise contribution
σ_{m45}	Standard deviation of the multipath error contribution at 45 degrees
σ_{trv}	Standard deviation of the vertical tropospheric error contribution

Note that the standard deviation $\sigma_{SISA,i}$ of the combined satellite ephemeris and clock error contribution is determined by the Signal In Space Accuracy (SISA), which is provided by Galileo to the users, of the corresponding satellite since the SISA of a satellite is a $k\cdot\sigma$ bound of the corresponding measurement error component, which is caused by the combined ephemeris and clock error of this satellite (i.e. $\sigma_{SISA,i} = \mathrm{SISA}_i/k$ where SISA_i is the Signal In Space Accuracy of the corresponding satellite). In addition to this, the standard deviation $\sigma_{UIVE,i}$ of the vertical ionospheric error contribution is approximately equal to zero when a Galileo user receiver uses two signals with different carrier frequencies for the determination of the navigation solution.

Now, the substitutions $\boldsymbol{y} = \boldsymbol{W}\boldsymbol{y}_\mathrm{M}$, $\boldsymbol{G} = \boldsymbol{W}\boldsymbol{G}_\mathrm{M}$ and $\boldsymbol{\varepsilon} = \boldsymbol{W}\boldsymbol{\varepsilon}_\mathrm{M}$ are used in order to obtain the following system of normalized linear algebraic equations:

$$\boldsymbol{y} = \boldsymbol{G}\boldsymbol{x} + \boldsymbol{\varepsilon} \tag{4}$$

where

$\boldsymbol{y}$	n×1 normalized residual vector
$\boldsymbol{G}$	n×m normalized design matrix
$\boldsymbol{x}$	m×1 vector of the deviations of the unknowns from the predicted values of the unknowns
$\boldsymbol{\varepsilon}$	n×1 normalized error vector

Furthermore, it is additionally assumed that no more than one of the n measurements is incorrect and that an incorrect measurement is represented by the corresponding component, which has a mean that is not equal to zero, of the normalized error vector.

Adapted RAIM Algorithm Availability

The availability of the integrity monitor of a user receiver must be checked in order to decide whether or not the integrity monitoring, which is performed by this user receiver, meets the user performance requirements. The user integrity monitor availability check of the parity method with aligned coordinate systems bases on the QR decomposition $\boldsymbol{G} = \boldsymbol{QR}$ of $\boldsymbol{G}$ where the n×n matrix $\boldsymbol{Q}$ is an orthogonal matrix and the n×m matrix $\boldsymbol{R}$ has zeros in row m+1 to n and an upper triangular m×m matrix $\boldsymbol{R}_x$ in row 1 to m. Moreover, $\boldsymbol{Q} = (\boldsymbol{Q}_x^T, \boldsymbol{Q}_p^T)$ is partitioned into the n×m matrix $\boldsymbol{Q}_x^T$ and the n×(n-m) matrix $\boldsymbol{Q}_p^T$. In addition to this, an orthogonal (n-m)×(n-m) matrix $\boldsymbol{A}_k$ is chosen so that the first element of the kth column of the (n-m)×n matrix $\boldsymbol{P}_k = \boldsymbol{A}_k\boldsymbol{Q}_p$ is p_{1k} and all other elements of the kth column of $\boldsymbol{P}_k$ are zero. Using the complementary error function

$$F_{\text{CEF}}(t) = \frac{1}{\sqrt{2\pi}} \int_t^{\infty} e^{-y^2/2}\, \mathrm{d}y\,, \tag{5}$$

then the threshold is determined by

$$d_T = F_{\text{CEF}}^{-1}(\mathrm{P}_{fa}/2n) \tag{6}$$

with

d_T	Threshold
$F_{\text{CEF}}^{-1}(t)$	Inverse function of the complementary error function
P_{fa}	False alarm probability
n	Number of measurements

The false alarm probability is thereby specified as follows:

$$\mathrm{P}_{fa} = r_{fa} \cdot t_{CT} \tag{7}$$

where

P_{fa}	False alarm probability
r_{fa}	False alarm rate
t_{CT}	Correlation time of the measurement errors

If the standard deviation of one of the measurement error components of the used sensors and navigation systems is significantly greater than the standard deviations of all other measurement error components of the used sensors and navigation systems, then the correlation time t_{CT} of this measurement error component, which has this greatest standard deviation, is used for the computation of the false alarm probability P_{fa}. Otherwise one of the measurement error components of the used sensors and navigation systems has the greatest standard deviation and this greatest standard deviation is of the same order of magnitude as the standard deviations of some other measurement error components of the used sensors and navigation systems so that the largest correlation time t_{CT} of these measurement error components, which have these greatest standard deviations, is used for the calculation of the false alarm probability P_{fa}.

Thus, if the m×m matrix $\boldsymbol{C}_L$ represents the linear transformation that transforms the three user receiver position deviation components of $\boldsymbol{x}$ to the topocentric local Cartesian coordinate system with its axes along the local north, local east and local vertical down at the user receiver position whereas the remaining components of $\boldsymbol{x}$ are not changed by this linear transformation, then the Horizontal Protection Level (HPL) as well as the Vertical Protection Level (VPL) are given as follows:

$$\text{HPL} = \underset{k=1,\ldots,n}{\text{Max}} \left[\frac{d_T + F_{\text{CEF}}^{-1}(\mathrm{P}_{md})}{|p_{1k}|} \cdot \sqrt{b_{1k}^2 + b_{2k}^2} \right] \tag{8}$$

$$\text{VPL} = \underset{k=1,\ldots,n}{\text{Max}} \left[\frac{d_T + F_{\text{CEF}}^{-1}(\mathrm{P}_{md})}{|p_{1k}|} \cdot |b_{3k}| \right] \tag{9}$$

where

HPL	Horizontal Protection Level
VPL	Vertical Protection Level
d_T	Threshold
$F_{\text{CEF}}^{-1}(t)$	Inverse function of the complementary error function
P_{md}	Missed detection probability
p_{1k}	First element of kth column of $\boldsymbol{P}_k$
b_{1k}	First element of the kth column of the m×n matrix $\boldsymbol{B} = \boldsymbol{C}_L(\boldsymbol{G}^T\boldsymbol{G})^{-1}\boldsymbol{G}^T$
b_{2k}	Second element of the kth column of the m×n matrix $\boldsymbol{B} = \boldsymbol{C}_L(\boldsymbol{G}^T\boldsymbol{G})^{-1}\boldsymbol{G}^T$
b_{3k}	Third element of the kth column of the m×n matrix $\boldsymbol{B} = \boldsymbol{C}_L(\boldsymbol{G}^T\boldsymbol{G})^{-1}\boldsymbol{G}^T$

The missed detection probability is at this defined by

$$\mathrm{P}_{md} = r_{md} \cdot t_{CT} \tag{10}$$

with

P_{md}	Missed detection probability
r_{md}	Missed detection rate
t_{CT}	Correlation time of the measurement errors

This adapted RAIM algorithm is available for horizontal navigation when the HPL is smaller than or equal to the Horizontal Alarm Limit (HAL). Otherwise the HPL is greater than the HAL and this adapted RAIM algorithm is not available for horizontal navigation. In addition to this, if the VPL is smaller than or equal to the Vertical Alarm Limit (VAL), then this adapted RAIM algorithm is available for vertical navigation. Note that this adapted RAIM algorithm is not available for vertical navigation when the VPL is greater than the VAL.

Fault Detection Method

The fault detection algorithm of the parity method with aligned coordinate systems bases on the matrices $\boldsymbol{P}_k$ too. If $\boldsymbol{p}_k^T$ (k = 1, ..., n) are the first rows of these matrices $\boldsymbol{P}_k$, then the test statistics are given as follows:

$$d_k = \boldsymbol{p}_k^T \boldsymbol{y} \tag{11}$$

This adapted RAIM algorithm decides that no incorrect measurement exists when $|d_k| \le d_T$ for all k = 1, ..., n where d_T is the threshold specified by equation (6). Otherwise this adapted RAIM algorithm decides that an incorrect measurement exists.

Fault Identification Method

If an incorrect measurement is detected by the fault detection algorithm, then the fault identification algorithm of the parity method with aligned coordinate systems also uses the matrices $\boldsymbol{P}_k$ for the identification of this incorrect measurement. The removal of the first row of a matrix $\boldsymbol{P}_k$ yields the $(n\text{-}m\text{-}1)\times n$ matrix $\boldsymbol{L}_k$. Furthermore, an orthogonal $(n\text{-}m\text{-}1)\times(n\text{-}m\text{-}1)$ matrix $\boldsymbol{F}_{k,q}$ is chosen so that the first element of the qth column of the $(n\text{-}m\text{-}1)\times n$ matrix $\boldsymbol{Z}_{k,q} = \boldsymbol{F}_{k,q}\boldsymbol{L}_k$ is equal to $z_{1q}^{(k)}$ and all other elements of the qth column of $\boldsymbol{Z}_{k,q}$ are equal to zero except for the kth column of $\boldsymbol{Z}_{k,q}$ (i.e. $q \in N \wedge q \neq k$ with $N = \{1, ..., n\}$). If $\boldsymbol{z}_{k,q}^T$ (k = 1, ..., n; q = 1, ..., k-1, k+1, ..., n) are the first rows of the matrices $\boldsymbol{Z}_{k,q}$, then the identification values are given as follows:

$$h_{k,q} = \boldsymbol{z}_{k,q}^T \boldsymbol{y} \tag{12}$$

The threshold d_T, which is specified by equation (6), is used by this fault identification algorithm, too. If no subscript j, which fulfils the condition

$$|h_{k,j}| > d_T \;\forall k \in \left\{k \in N \middle| k \neq j\right\} \wedge |h_{j,q}| \le d_T \;\forall q \in \left\{q \in N \middle| q \neq j\right\}, \tag{13}$$

exists with $j \in N$, then this fault identification algorithm is not available. Otherwise this condition is fulfilled by a subscript j and this fault identification algorithm is available. The measurement, which belongs to this unique subscript j, is identified by this fault identification algorithm as the incorrect measurement in this case.

GIC CONTRIBUTION TO USER INTEGRITY MONITORING

The failure sources, which affect the Galileo satellite measurements of a user receiver, are multifarious where the GIC can only monitor a part of these failure sources. For instance, local failure sources, which only corrupt the measurements of the user receivers located close to these local failure sources, as extreme multipath (e.g., due to satellite signal reflections on the surface of an aircraft, i.e. on the surface of the user itself), extreme ionosphere, poor user/satellite geometry (e.g., due to aircraft banking maneuvers), satellite signal interferences and/or jammer signals are not observable by the GIC. Note that the failure sources of the user receivers cannot be monitored by the GIC, too. Therefore, the GIC cannot check the (full) integrity on user level so that the users have in any case to apply RAIM like techniques. This means that the GIC can only verify the (partial) integrity of the ground control and space segments (i.e. the GIC can only monitor each individual measurement error component, which is caused by the combined ephemeris and clock error of the corresponding Galileo satellite). On the other hand, a user receiver can detect at maximum n-m incorrect measurements among the used measurements so that the integrity of the navigation solution, which is provided by this user receiver, increases when this user receiver utilizes the integrity information provided by the GIC.

The general purpose of the ground-based integrity monitoring, which is performed by the GIC, is the verification of the SISA values, which are provided by Galileo to the users. This SISA verification is performed by checking whether or not the SISA of each individual satellite bounds the corresponding measurement error component, which is caused by the combined ephemeris and clock error of the corresponding satellite, at all user locations, which lie within the Galileo service area, with a specified probability P_{SISA}, which is either derived from the user performance requirements or an appropriate value defined by Galileo. This means that the ground-based integrity monitoring only checks whether or not the condition

$$P_{SISA} \le P(|X_k| < \mathrm{SISA}_k) = F_k(\mathrm{SISA}_k) - F_k(-\mathrm{SISA}_k) \tag{14}$$

holds at the worst user location for each individual SISA_k where SISA_k denotes the SISA of the kth satellite and

$F_k(x_k) = P(X_k < x_k)$ is the actual probability distribution function of the actual measurement error component X_k, which belongs to the kth satellite and which is caused by the combined ephemeris and clock error of the kth satellite, at the worst user location for SISA_k.

The current Galileo baseline specifies the subdivision of the world into regions. In addition to this, the current Galileo baseline also defines the transmission of one global SISA for each individual satellite (i.e. world-wide service area for the SISA of each individual satellite) and of one regional integrity flag for each individual satellite as well as for each individual region, which is the service area for the corresponding integrity flag. Each of these regional integrity flags consists of two bits with the information “Not Monitored”, “Don't Use” or “Usable”. If a Galileo satellite cannot be monitored by the ground-based integrity monitor of a region (e.g., due to the insufficient number of available measurements for this satellite regarding this region), then the corresponding integrity flag is set to “Not Monitored”. Otherwise this satellite can be monitored by the ground-based integrity monitor of this region and the corresponding integrity flag is set to “Usable” when the SISA of this satellite bounds the corresponding measurement error component, which is caused by the combined ephemeris and clock error of this satellite, at all user locations, which lie within this region, with the specified probability P_{SISA}. Moreover, if the ground-based integrity monitor of this region can monitor this satellite and if the measurement error component, which is caused by the combined ephemeris and clock error of this satellite, at the worst user location for the SISA of this satellite regarding this region is not bounded by this SISA with the specified probability P_{SISA}, then the corresponding integrity flag is set to “Don't Use”. It must be noted that a Galileo satellite measurement, which belongs to a satellite with a regional integrity flag set to “Not Monitored” or to “Don't Use”, is not used by a user receiver, which is located within the corresponding region and which applies the integrity information (i.e. the SISA values of the Galileo satellites as well as the regional integrity flags of the Galileo satellites) provided by Galileo.

Assuming that each satellite failure results in a position solution error, which exceeds the alarm limit, of a user receiver with a probability, which is equal to one, as well as that the probabilities of available and within the specified accuracy operating integrity monitoring functions (i.e. GIC as well as user integrity monitor) are also equal to one, then the probability of at least one undetected failure (i.e. the integrity risk) with respect to a user receiver and the probability of loss-of-function (i.e. the continuity risk) regarding this user receiver are given as follows:

$$\begin{aligned} \mathrm{P}_{uf} &= 1-(1-\mathrm{P}_F \cdot \mathrm{P}_{md,G} \cdot \mathrm{P}_{md,U})^n \\ \mathrm{P}_{uf} &\approx n \cdot \mathrm{P}_F \cdot \mathrm{P}_{md,G} \cdot \mathrm{P}_{md,U} \end{aligned} \tag{15}$$

$$\begin{aligned} \mathrm{P}_{lof} &= \mathrm{P}_{fa,U} + (1-\mathrm{P}_{fa,U}) \sum_{i=n-m+1}^{n} \binom{n}{i} \mathrm{P}_{fa,G}^{i} (1-\mathrm{P}_{fa,G})^{n-i} \\ \mathrm{P}_{lof} &\approx \mathrm{P}_{fa,U} \end{aligned} \tag{16}$$

where

P_{uf}	Probability of at least one undetected failure (i.e. integrity risk) at user
P_F	Probability of a Galileo satellite failure
$\mathrm{P}_{md,G}$	Conditional probability of missed detection for the GIC on the condition that a Galileo satellite has failed
$\mathrm{P}_{md,U}$	Conditional probability of missed detection for the user on the condition that a Galileo satellite has failed and that this faulty satellite has not been detected by the GIC
P_{lof}	Probability of loss-of-function (i.e. continuity risk) at user
$\mathrm{P}_{fa,U}$	Probability of false alarm for the user
$\mathrm{P}_{fa,G}$	Probability of false alarm for the GIC
n	Number of user measurements
m	Number of unknowns at user

It must be noted that P_F is the reliability figure (failure probability) of Galileo.

GALILEO HYBRIDIZATION WITH OTHER NAVIGATION SYSTEMS AND/OR SENSORS

Several methods can be used for the navigation solution integrity monitoring at user level where RAIM like techniques are applicable for the integrity monitoring, which is performed by the user receiver, when Galileo is hybridized with other navigation systems, e.g. with GPS and/or with LORAN-C, and/or with further sensors, e.g. with an Inertial Navigation System (INS) and/or with a barometric altimeter. The addition of the measurements from further navigation systems and/or from other sensors to the Galileo satellite measurements generally increases the user integrity monitoring availability since the number of available measurements at the user receiver significantly increases. Note that the adapted RAIM algorithm, which is briefly described above and which is obtained by the modification of the RAIM method proposed by Brenner [1], can also be used by a user integrity monitor when Galileo is hybridized with other navigation systems (e.g. GPS, LORAN-C, etc.) and/or with further sensors (e.g. INS, barometric altimeter, etc.).

If a user receiver uses measurements from further navigation systems as GPS and/or LORAN-C in addition to the Galileo satellite measurements, then the unknowns are the three user receiver position coordinates and the user receiver clock offsets with respect to the Galileo network time as well as to the network times of these other navigation systems. Thus, the first three components of the $m\times 1$ vector $\boldsymbol{x}$, which is specified by equations (1) and (4), are the three components of the user receiver position deviation from the predicted user receiver position and the remaining components of this vector $\boldsymbol{x}$ are the user receiver clock offset deviations from the predicted user receiver clock offsets. For instance, the number of unknowns is equal to five and the design matrix $\boldsymbol{G}_M$, which is defined by equation (1), is of the form

$$\boldsymbol{G}_M = \begin{bmatrix} \bar{g}_{1,1} & \bar{g}_{1,2} & \bar{g}_{1,3} & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \bar{g}_{n_1,1} & \bar{g}_{n_1,2} & \bar{g}_{n_1,3} & 1 & 0 \\ \tilde{g}_{n_1+1,1} & \tilde{g}_{n_1+1,2} & \tilde{g}_{n_1+1,3} & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \tilde{g}_{n_1+n_2,1} & \tilde{g}_{n_1+n_2,2} & \tilde{g}_{n_1+n_2,3} & 0 & 1 \end{bmatrix} \qquad (17)$$

when Galileo is only hybridized with GPS and when the number of Galileo satellite measurements is equal to n_1 with $n_1 > 0$ as well as when the number of GPS satellite measurements is equal to n_2 with $n_2 = n - n_1 > 0$. The first three elements $\bar{g}_{i,j}$ ($i = 1, ..., n_1$; $j = 1, 2, 3$) of the ith row of $\boldsymbol{G}_M$ are the components of the 3×1 unit vector pointing from the corresponding Galileo satellite position to the predicted user receiver position and the first three elements $\tilde{g}_{k,j}$ ($k = n_1+1, ..., n_1+n_2$; $j = 1, 2, 3$) of the kth row of $\boldsymbol{G}_M$ are the components of the 3×1 unit vector pointing from the corresponding GPS satellite position to the predicted user receiver position in this case.

On the other hand, if Galileo is hybridized with a barometric altimeter, then only one additional measurement is available at the user receiver where the unknowns are the three user receiver position coordinates and the user receiver clock offset with respect to the Galileo network time (i.e. the number of unknowns is equal to four). The third element of the row, which belongs to this barometric altimeter measurement, of the design matrix specified by equation (1) is equal to one and all other elements of this row are equal to zero.

ADAPTED RAIM ALGORITHM AVAILABILITY SIMULATION

A first preliminary qualitative assessment of the integrity monitoring level, which can be achieved at user level, was performed by an adapted RAIM algorithm availability simulation. The adapted RAIM algorithm, which is briefly described above and which results from the modification of the RAIM method proposed by Brenner [1], was thereby used for this simulation.

Simulation Assumptions

Table 1 shows the Galileo constellation parameters used for the adapted RAIM algorithm availability simulation.

Table 1. Galileo Satellite Constellation Parameters [2]

Parameter	Simulation Assumption
Walker Constellation	30/3/0
Altitude	23322.371 km
Inclination	54°
Eccentricity	0

Moreover, the Optimized 24 GPS Constellation, which is specified by the RTCA Special Committee 159 document RTCA/DO-229B [6], was used for this simulation. Instead of using the ephemeris reference epoch of the Galileo satellite constellation specified by the Performance Budget File [2] and the ephemeris reference epoch of the Optimized 24 GPS Constellation defined by the RTCA Special Committee 159 document RTCA/DO-229B [6] for this simulation, the ephemeris reference epoch of the Galileo satellite constellation and the ephemeris reference epoch of the Optimized 24 GPS Constellation were set to the 4th of June 2000 (2000, 6, 4, 00:00:00) for the adapted RAIM algorithm availability simulation. In addition to this, the LORAN-C stations specified by the Loran-C Chain Information document [4] were used for this simulation too. Furthermore, the adapted RAIM algorithm availability simulation was performed world-wide for the 9th of June 2000 over 24 hours with a sampling time of 600 s as well as with a grid spacing of 1°.

The CAT I user performance requirements, which were used for the adapted RAIM algorithm availability simulation, are shown in the following table.

Table 2. CAT I User Performance Requirements [3]

Parameter	Simulation Assumption
Continuity Risk	10^{-5} per Approach
Integrity Risk	$4 \cdot 10^{-8}$ per Approach
Vertical Alarm Limit (VAL)	10 m
Time To Alarm (TTA)	6 s

For the adapted RAIM algorithm availability simulation, it was additionally assumed that the HAL is equal to 10 m, that the elevation mask angle is equal to 5°, that the correlation time t_{CT} of the measurement errors is equal to 360 s, that the standard deviation of the GPS measurement errors (without selective availability) is equal to 8 m, that the standard deviation of the barometric altimeter measurement errors is equal to 50 m, that the nominal standard deviation of the LORAN-C measurement errors is equal to 61.5 m as well as that the standard deviation of the measurement errors of accurate LORAN-C measurements is equal to 4 m. Moreover, instead of using the Galileo measurement error standard deviation specified by equation (3) for the adapted RAIM algorithm availability simulation, an elevation dependent standard deviation (1.1 m - 4.3 m) of the Galileo measurement errors was used for this simulation. It was also assumed regarding this simulation that the duration of a CAT I approach is equal to 150 s and that only one user, which conducts a CAT I approach, is affected by a satellite

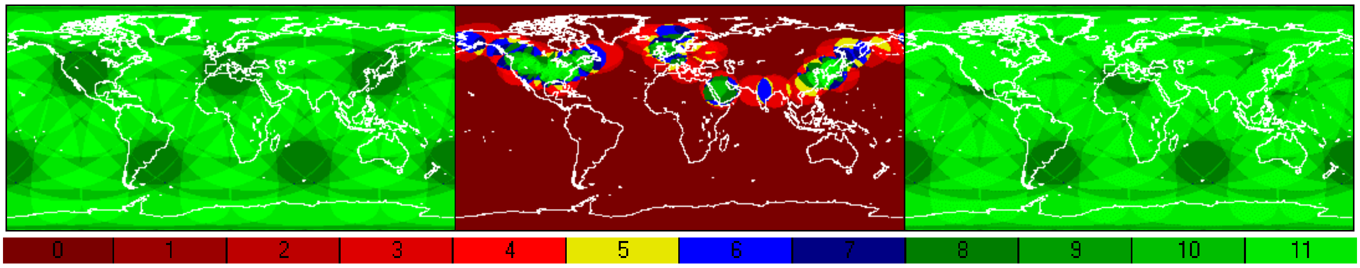

Figure 1. Galileo Satellite and/or LORAN-C Station Visibility at 9th of June 2000, 01:00:00 (Left: Galileo Satellite Visibility; Center: LORAN-C Station Visibility; Right: Combined Galileo Satellite and LORAN-C Station Visibility)

failure, which is not detected by the GIC, at a time. Therefore, the CAT I continuity risk rate r_{CR}, which is equal to $6.67 \cdot 10^{-8}$/s, and the CAT I integrity risk rate r_{IR}, which is equal to $2.67 \cdot 10^{-10}$/s, were used for the adapted RAIM algorithm availability simulation so that the probability of at least one undetected failure (P_{uf}) regarding a user receiver is given by $P_{uf} = r_{IR} \cdot t_{CT} = 9.6 \cdot 10^{-8}$ and the probability of loss-of-function (P_{lof}) with respect to this user receiver is determined by $P_{lof} = r_{CR} \cdot t_{CT} = 2.4 \cdot 10^{-5}$.

A visibility simulation for the used Galileo satellite constellation, for the used LORAN-C stations and for the hybridization of Galileo with LORAN-C showed that the number of visible Galileo satellites is, on average, equal to 10 at user level, i.e. $n = 10$ for Galileo (see Figure 1). Thus, the adapted RAIM algorithm availability simulation was performed for the following two cases where it was also taken into account that $P_{md,U}$ (i.e. the conditional probability of missed detection for the user on the condition that a Galileo satellite has failed and that this faulty satellite has not been detected by the GIC) is determined by equation (15).

(i) **Worst case:** $P_F = 10^{-1}$, $P_{md,G} = 1$ (i.e. low Galileo reliability, no ground-based integrity monitoring by the GIC) $\Rightarrow$ $P_{md,U} = 9.6 \cdot 10^{-8}$

(ii) **Good case:** $P_F = 10^{-4}$, $P_{md,G} = 9.6 \cdot 10^{-2}$ (i.e. higher Galileo reliability, ground-based integrity monitoring by the GIC) $\Rightarrow$ $P_{md,U} = 10^{-3}$

Simulation Results

The following figures show the HPL, the VPL as well as the adapted RAIM algorithm availability with respect to horizontal/vertical navigation at the grid points of a world-wide grid for the worst case and for the good case where it is also considered that a user receiver uses either only Galileo measurements or Galileo measurements in combination with GPS, LORAN-C and/or barometric altimeter measurements.

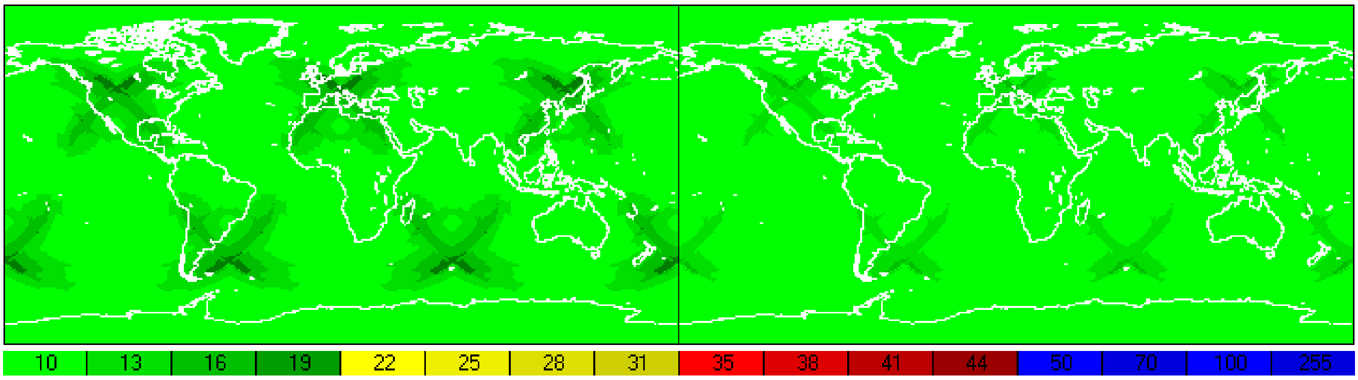

Figure 2. Horizontal Protection Level [m] for Galileo at 9th of June 2000, 01:00:00 (Left: Worst Case; Right: Good Case)

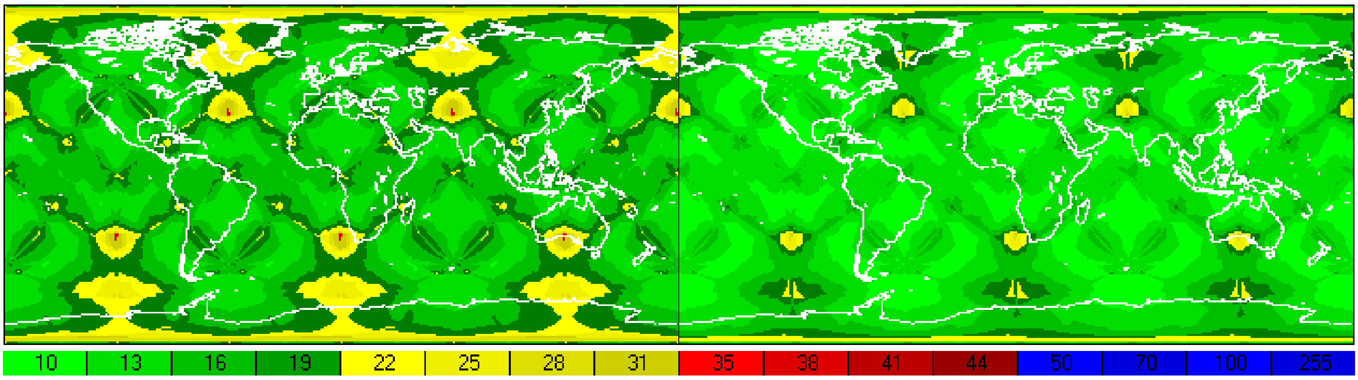

Figure 3. Vertical Protection Level [m] for Galileo at 9th of June 2000, 01:00:00 (Left: Worst Case; Right: Good Case)

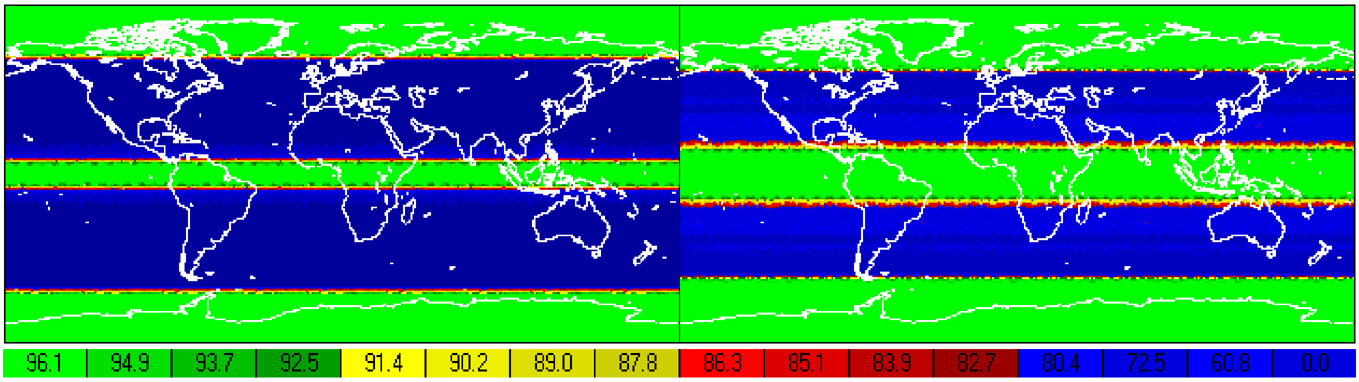

Figure 4. Adapted RAIM Algorithm Availability [%] for Galileo regarding Horizontal Navigation (Left: Worst Case; Right: Good Case)

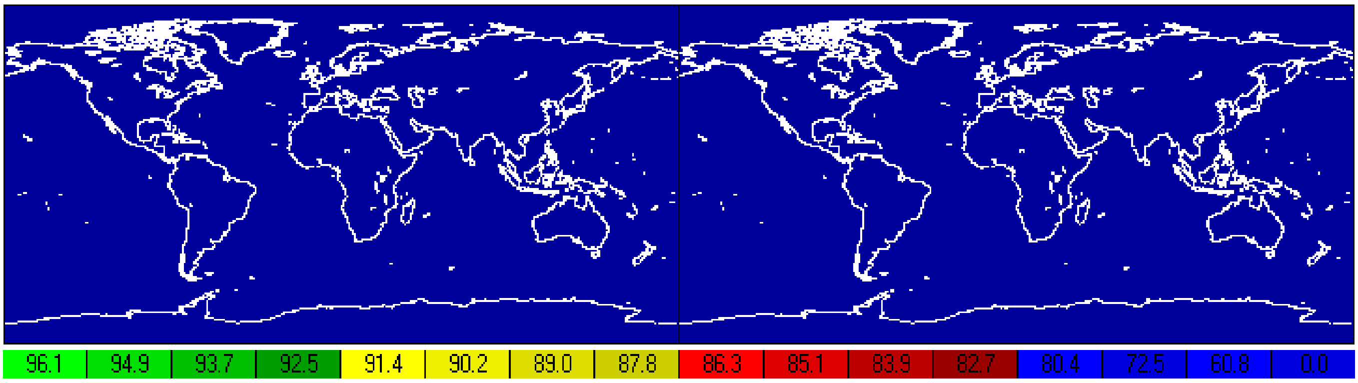

Figure 5. Adapted RAIM Algorithm Availability [%] for Galileo regarding Vertical Navigation (Left: Worst Case; Right: Good Case)

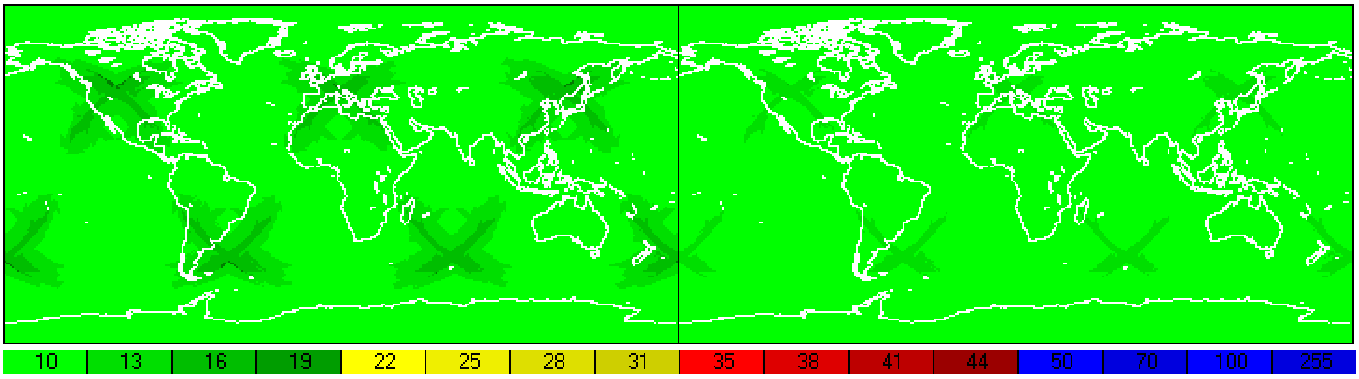

Figure 6. Horizontal Protection Level [m] for Galileo hybridized with GPS at 9th of June 2000, 01:00:00 (Left: Worst Case; Right: Good Case)

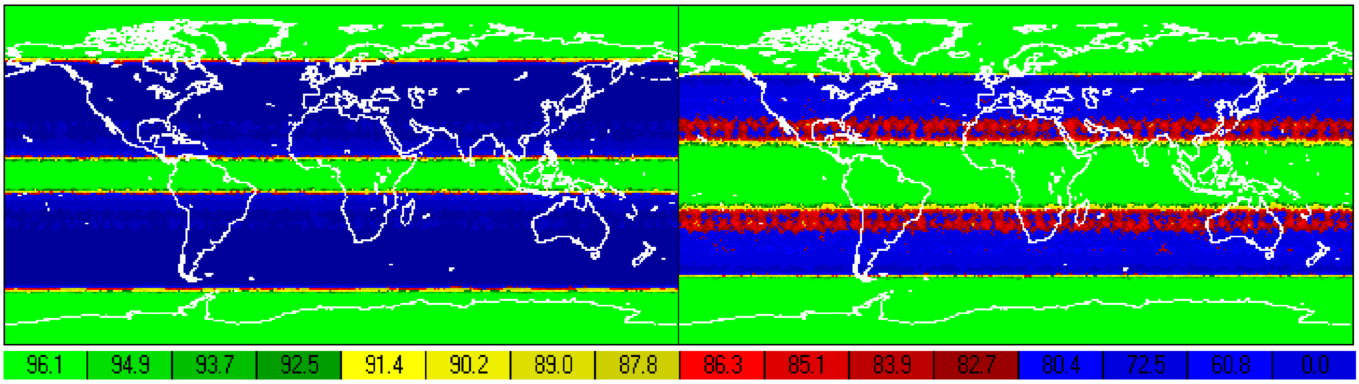

Figure 7. Adapted RAIM Algorithm Availability [%] for Galileo hybridized with GPS regarding Horizontal Navigation (Left: Worst Case; Right: Good Case)

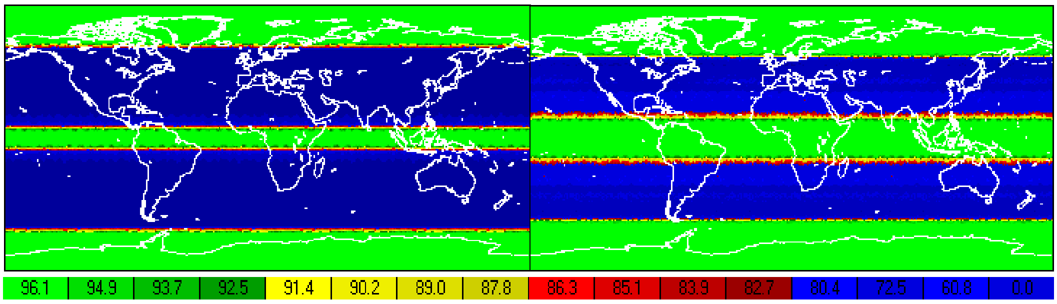

Figure 8. Adapted RAIM Algorithm Availability [%] for Galileo hybridized with LORAN-C and with Barometric Altimeter regarding Horizontal Navigation ($\sigma_{\mathrm{LORAN\text{-}C}}$ = 61.5 m; Left: Worst Case; Right: Good Case)

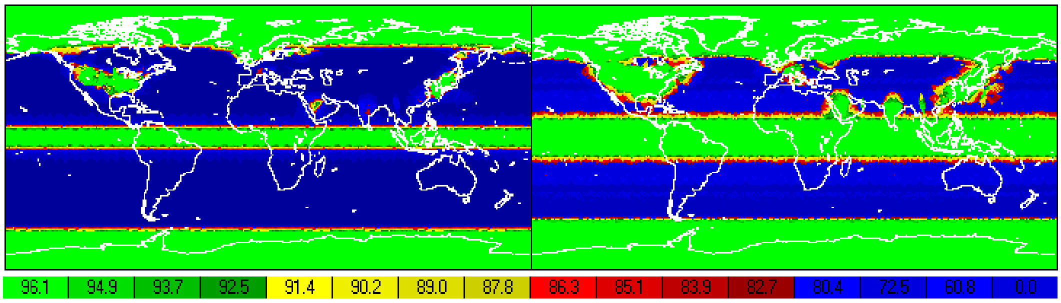

Figure 9. Adapted RAIM Algorithm Availability [%] for Galileo hybridized with LORAN-C and with Barometric Altimeter regarding Horizontal Navigation ($\sigma_{\mathrm{LORAN\text{-}C}}$ = 4 m; Left: Worst Case; Right: Good Case)

CONCLUSIONS

The current Galileo baseline satellite constellation causes two stripes (world-wide) of poor user integrity monitoring availability with respect to horizontal navigation due to six dynamic areas with “degraded” Galileo satellite visibility, i.e. with only 8 visible Galileo satellites, at user level (see Figure 1 and Figure 4). Moreover, the figures above also show that the CAT I user performance requirements, in particular for vertical navigation, cannot be met world-wide and all the time.

If the GIC contributes to the check of the (partial) integrity of the ground control and space segments by performing ground-based integrity monitoring, then the user integrity monitoring availability regarding horizontal navigation increases as can be seen from Figure 4. Furthermore, the hybridization of Galileo with GPS enhances the user integrity monitoring availability with respect to horizontal navigation too (see Figure 4 and Figure 7). On the other hand, the hybridization of Galileo with LORAN-C and with a barometric altimeter only significantly increases the user integrity monitoring availability with regard to horizontal navigation when a user receiver uses accurate LORAN-C measurements, i.e. when $\sigma_{\mathrm{LORAN\text{-}C}}$ = 4 m as can be seen from Figure 4, Figure 8 and Figure 9.

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