Investigation of the GNSS/Galileo Integrity Performance for Safety of Life Applications

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BIOGRAPHY

Dr. Helmut Blomenhofer

After finishing University he was Research Associate at the Institute of Geodesy and Navigation (IfEN) of the University FAF Munich from 1990 to 1995 and did research and software development in high-precision kinematic Differential-GPS.

From March 1995 to December 1997 he was at Daimler-Chrysler Aerospace AG (Dasa); NFS Navigations- und Flugführungs-Systeme being responsible for the development of an Integrated Navigation and Landing System (INLS) for aircraft precision approaches and automatic landings.

From January 1998 to 2001 he was the EGNOS Programme Manager at the EADS subsidiary Astrium GmbH located at Friedrichshafen.

Since 2002 he is GNSS Business Development Director at Thales ATM, Germany.

Eduarda Blomenhofer is Managing Director of NavPos Systems GmbH, a German SME which specialised in the satellite navigation related systems engineering, software development and consultancy. She owns an Engineer Degree in Surveying/Geodesy from the Porto University, Portugal. She is working in satellite navigation since 1990, with activities on high precision differential GPS algorithms and software for real time applications, data processing and service volume simulation for GPS, Glonass, GBAS, SBAS and Galileo.

Walter Ehret graduated as an Aeronautical and Space Engineer from the Technical University (TU) of Braunschweig, Germany in 1996. Since 1996 he is involved in research and engineering activities related with Satellite Navigation. He is currently working as Systems Engineer at THALES ATM in Langen where he is involved in Galileo related tasks and particularly Integrity related issues.

ABSTRACT

GPS and Galileo will provide navigation signals for a variety of applications. Amongst them, the most stringent system requirements are derived from safety critical applications including aviation precision approach operations.

GPS integrity is determined by RAIM and/or augmentation systems like WAAS and EGNOS. The Galileo baseline architecture specifies a global integrity concept. This means e.g. that the accuracy and integrity performance must be achieved globally keeping the Time-To-Alert thresholds. A major performance measure is additionally the availability of the Accuracy and Integrity figures and the Continuity of Service.

The GPS augmentation systems provide wide area differential corrections and also related residual errors which are used to compute the respective Protection Levels.

The Galileo integrity monitoring concept uses error predictions (caused by satellite, clock, signal and or non-precise navigation message) which are validated in real-time. The predicted component which is transmitted with the navigation message is called SISA (Signal In Space Accuracy) and is an estimation of the orbit and clock prediction of the Galileo Control Centre which is updated with every clock update. If an error occurs in the satellites, clocks, signal, navigation message or in the processing itself, then it has to be detected by the Integrity Processing Facility (IPF) in real-time and a warning flag IF has to be sent to the user within the necessary Time-to-Alert. As the check in the IPF has to be performed nearly instantaneous (fraction of the Time to Alert), there has to be a sufficient number of Sensor Stations to get a statistically significant test, which allows even to identify and to exclude Sensor Stations with local disturbances in the observations.

This paper investigates the expected integrity performance of the Galileo Safety of Life Service. A comparison with combined GPS/Galileo RAIM

performances is included. The investigation was done using advanced Service Volume Simulation (SVS). For the consideration of space segment operational outages the Durand-Caseau model is applied in the RAIM analysis. To account for the Continuity Risk during the approach phase of flight, the critical satellite concept is applied. The simulated Integrity performances are mapped to the aviation performance standards of ICAO. The simulation results in this paper are updated as compared to previous publications [19] and [20] to consider the suggested reference scenarios of [16].

INTRODUCTION

Galileo will be used by a variety of user groups. Each of them generates requirements or standards and there exist various definitions. The user groups for safety critical applications are mostly found in the different modes of transportation which are Road, Rail, Marine and Air. For the analysis presented in this paper, the Galileo requirements are used and compared with the ICAO aviation requirements.

The safety critical application of satellite based 'Global Navigation and Landing' systems in civil aviation in principle allows navigation and guidance of aircraft throughout all phases of flight and weather conditions. The advantages of satellite based navigation systems are obvious. But for safety critical applications, today's safety level of navigation and landing systems at least has to be maintained, and if possible, it has to be improved.

The embedded Integrity function in the Safety of Life Service of the Galileo System is the key for the ability to serve as navigation means in safety critical applications. It represents the major difference compared to the existing US NAVSTAR GPS.

The use of RAIM (Receiver Autonomous Integrity Monitoring) techniques and the development of augmentation systems tried to compensate this gap within GPS. The commonality between these augmentation systems (Space Based, Ground Based, Aircraft Based) is that they are independent from the GPS system operator.

Galileo will be different in this respect as it will be controlled and operated by a civil entity which shall guarantee the services for the various user classes.

REQUIREMENTS ANALYSIS AND SIMULATION INPUT PARAMETERS

Performance Requirements

ICAO Annex 10 (SARPS Radionavigation Aids) defines the requirements for the different phases of flight [1]. ***Figure 1*** compares the Required Navigation Performance (RNP) per phase of flight with the existing or expected GNSS system performance.

The use of GPS together with RAIM fulfills requirements down to the Non-Precision flight phases. However these receivers are to be used as supplemental means of navigation with the exception of Remote En Route (Oceanic and domestic routes) where primary use is allowed. This is mainly due to limitations of the GPS RAIM availability.

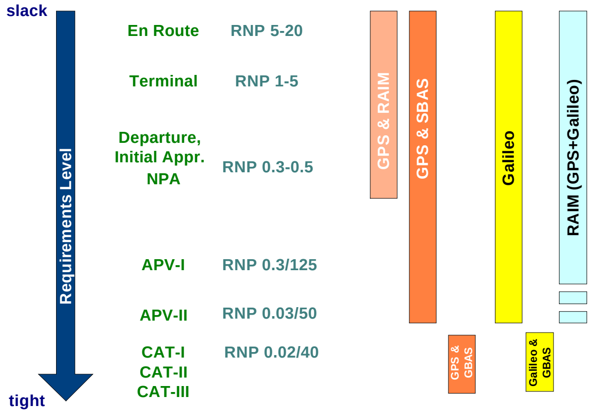

Figure 1: Aviation Phases of Flight versus GNSS Performance

The introduction of Satellite Based Augmentation Systems (SBAS) like WAAS in US, MSAS in Japan and EGNOS in Europe will improve the capability of GPS in terms of accuracy but especially in terms of System Integrity such that GPS/SBAS devices can fulfill at least APV-II requirements. A comparable level of performance is intended for Galileo. The following tables list the ICAO and Galileo requirements.

Accuracy (95%)	horizontal: 4m
	vertical: 8m
Availability	99.8 % of service life time
Continuity Risk	< $8x10^{-6}$ / 15s
Integrity	HAL: 40m
	VAL: 20m
	TTA: 6 seconds
	Integrity Risk: < $2.0x10^{-7}$ / 150s (system contribution)

Table 1: Galileo Performance Requirements for the Safety of Life Service Level A

Accuracy (95%)	horizontal: 16 m
	vertical: 8 m
Availability	99.0% to 99.999%
Continuity Risk	< $8x10^{-6}$ / 15s
Integrity	HAL: 40m
	VAL: 20m
	TTA: 6 seconds
	Integrity Risk: < $2x10^{-7}$ / approach (SIS contribution)

Table 2: ICAO APV-II Requirements

Table 1 shows the Galileo requirements for the Galileo Safety Of Life Service as stated in the Mission Requirements Document [2]. The comparison of ***Table 1*** and ***Table 2*** yields that the Galileo System aims to be used as a certified navigation means for the flight phases Remote/Oceanic En Route down to non precision approach plus the new defined approach categories with vertical guidance APV-I and APV-II without the need for local or regional augmentation.

UERE – User Equivalent Range Error

A UERE budget (see Table 3) in dependence of the satellite elevation angle was used, which is suggested in [16] as a reference scenario. The simulation duration was one to ten days to account for the repetition of the Galileo satellite constellation. The grid resolution is 1°x1° i.e. 65400 virtual user positions. The used time step in the simulation runs was 300s.

Elev.	10	15	20	30	40	50	60	90
UERE	1.31	1.18	1.10	1.04	1.01	1.00	1.00	0.99

Table 3: Galileo L1/E5a Safety of Life (SOL) Service UERE budget for Aeronautical Applications [16]

Operational Outages

The AVIGA tool allows to predict GNSS constellation availabilities. It is also able to take into account outage characteristics like manoeuvres (frequency and duration) and satellite failures in form of

- Short term outages (satellite failure repair)
- Long term outages (satellite replacement)

to evaluate the constellation availability.

Critical Satellites

For the allocation of continuity requirements in the LAAS MASPS [4] the possibility is outlined that the protection level during a 15 seconds period could jump over the specified alarm limit due to loss of signals to one or more satellites (PL>AL risk). For the reduction of the approach continuity risk it is reasonable to analyse the available constellation for the number of so called "critical satellites". These are the satellites which when being removed from the xPL computations would cause the xPL to rise above the limit. Acceptance of one or more of the critical satellites would have an effect on the continuity risk in such a way that it will be reduced if more critical satellites are allowed.

The introduction of the number of critical satellites will have also an effect on the availability of PL< AL. With a low allowed number of critical satellites the availability will be lower but the continuity will be higher.

The consideration of critical satellites is also part of the Galileo baseline. In the frame of this paper simulations have been performed showing the availability of protection levels taking into account a number of allowable critical satellites.

GNSS INTEGRITY CONCEPTS

Basically there are four different concepts to determine GNSS Integrity.

- RAIM
- GBAS - local augmentation
- SBAS - regional augmentation
- Galileo embedded Integrity Concept

Each of these basic concepts has many derivatives and there exist many approaches to realize them. The analysis performed in this document concentrates on the RAIM concept and the New Gailieo Integrity concept.

RAIM - RECEIVER AUTONOMOUS INTEGRITY MONITORING

The natural redundancy of ranging sources in satellite navigation makes RAIM (Receiver Autonomous Integrity Monitoring) an important contributor to the provision of a required integrity level on user side.

One basic method how to use RAIM in a certifiable airborne receiver is given in RTCA Do-208 MOPS for Airborne Supplemental Navigation using the GPS [5]. However, since then, RTCA SC-159 proposed an improved algorithm and associated parameters [6]. This is the reference RAIM algorithm as used in the simulations shown in this paper. The ability to detect anomalies in a pseudorange measurement is highly dependent on the observation geometry. A measure for the sensitivity of the Fault Detection algorithm is the protection level (xPL) either in the horizontal (HPL) or in the vertical (VPL) plane.

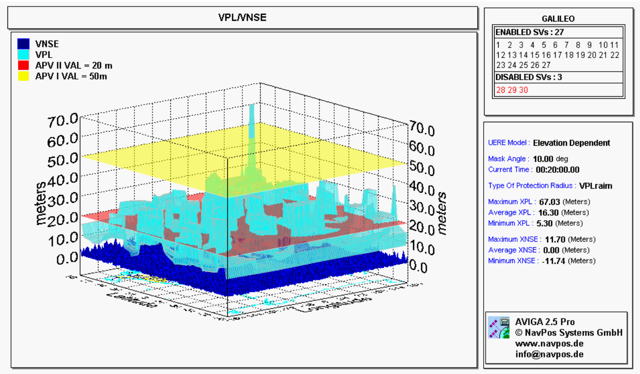

Figure 2: Galileo Protection Level Snapshot based on FD RAIM

Figure 2 presents results of a RAIM VPL computation for the snapshot fault-detection algorithm with fixed False Alarm and Missed Detection rates used as input parameters. The RAIM protection level was computed according [6] and the suggested specification of the UERE for Safety of Life applications (see **Table 3**). The Pfa and Pmd parameters are derived from Precision Approach requirements.

$$VPL = Slope_{\max}^{vert} \cdot pbias \cdot \sigma_{UERE} \qquad \text{(Eq. 1)}$$

where $Slope_{\max}^{vert} \cdot$ is the maximum amplifying coefficient for pseudorange offsets which would cause increase in vertical position error, pbias is a threshold computed off-line and linked to the number of satellites in view. There is low instantaneous RAIM FD availability for APV-II mode in the vertical plane apparently, seen from Figure 2, as many light-blue peaks breach the related alert limit (reddish) plane. The situation is much better for APV-I mode as only few peaks (actually one in the snap-shot) break through the related (yellow) plane.

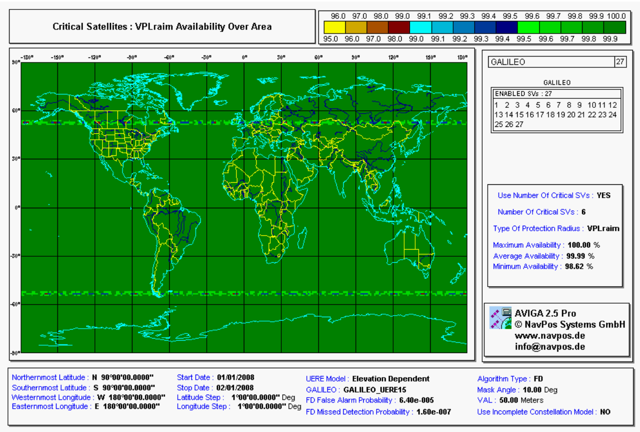

Figure 3: Galileo APV-I Vertical RAIM Availability with 6 critical satellites

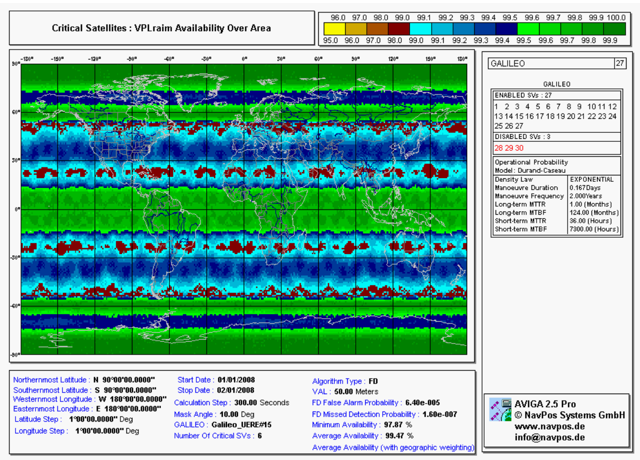

Figure 4: Galileo APV-I Vertical RAIM Availability considering space segment operational outages and 6 critical satellites

The simulation results presented on Figure 3 show the potential of the Galileo system using RAIM alone to provide the required level of integrity and continuity risks for APV-I. This conclusion is justified by tight values of False Alarm and Missed detection applied in the simulation runs.

The RAIM VPL availability interval is in nearly all grid points (1°x1°) worldwide and time steps of 5min better than 99.9 % (see Figure 3). Few spots exist along the 56 degree latitudes with availabilities between 98.6% and 99.0%. Some smaller areas along the 56 degree latitudes show availabilities between 99.0 and 99.9%. The rest of the globe shows availabilities of better than 99.999% (dark green). Compared with the specifications for APV-I approaches this is sufficient to meet the requirements. Up to 6 critical satellites were allowed in the simulation presented in Figure 3.

Based upon GPS observations for satellite manoeuvre frequency and duration, as well as short term and long term satellite outages and assuming that Galileo will at least show similar or better outage performances, the APV-I vertical RAIM Availability was calculated adding the Durand-Caseau Model with the following parameters:

- exponential density law
- manoeuvre duration: 4 hours
- manoeuvre frequency: 2.0 years
- long term MTTR: 1.0 month
- long term MTBF: 124 months
- short term MTTR: 36 hours
- short term MTBF: 7300 hours

The comparison of Figure 3 and Figure 4 shows a small reduction of the vertical RAIM Availability due to operational outages from better 99.9% to 99.5% in average. In some areas the availability drops just beneath the 99.0 value.

RAIM Using Combined GPS and Galileo

For the combined simulations, the GPS II L1/L5 and GPS III L1/L5 UERE error budgets as suggested in the reference scenarios [16] were used which assume dual frequency measurements for both systems.

Elev.	10	15	20	30	40	50	60	90
GPS II L1/L5 UERE	1.86	1.71	1.64	1.59	1.57	1.56	1.56	1.56
GPS III L1/L5 UERE	1.36	1.15	1.04	0.96	0.93	0.92	0.91	0.91

Table 4: UERE budget for GPS III L1/L5 [n]

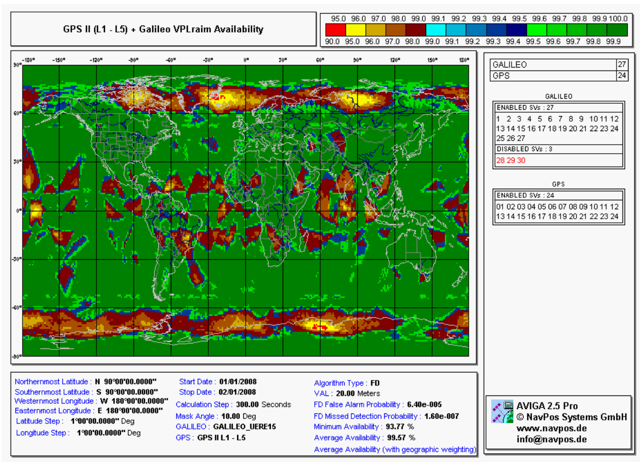

Figure 5: GPS II L1/L5+Galileo APV-II Vertical RAIM Availability (without critical satellites; without space segment operational outages)

The RAIM performance of the combined nominal constellations of GPS and Galileo easily fulfils the APV-I requirements. At the time when Galileo will become fully operational, the GPS constellation is expected to broadcast a SIS UERE according to GPS II L1/L5. APV-II requirements seem to be achievable in most regions of the world. However outages can be seen in some areas even without the consideration of critical satellites and operational outages (see Figure 5). The situation will improve with GPS III. Figure 6 shows the RAIM availability using Galileo in combination with GPSIII. In Figure 7, the simulation according Figure 6 of the combined GPS and Galileo APV II RAIM Availability was repeated, but considering operational outages according to the Durand-Caseau model for both constellations. The results look very promising.

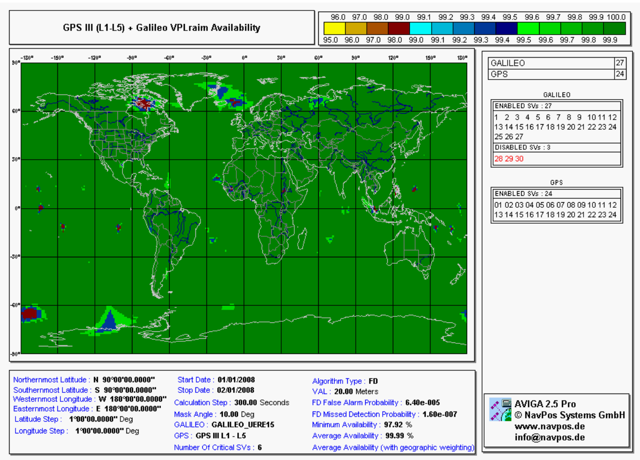

Figure 6: GPS III+Galileo APV-II Vertical RAIM Availability (without critical satellites; without space segment operational outages)

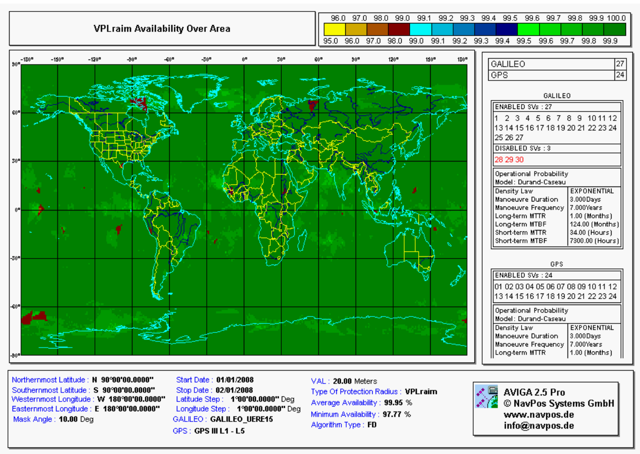

Figure 7: GPS+Galileo APV-II Vertical RAIM Availability considering space segment operational outages (to be updated)

THE GALILEO SISA/SISMA/IF CONCEPT

The Galileo system will provide several user services. One of these services is the Safety of Life service. This service will incorporate the provision of integrity information in its message structure. For the user-xPL (protection level) computation the Galileo System will provide the Signal In Space quality in terms of a parameter called Signal In Space Accuracy (SISA). The SISA shall bound the true errors SISE with a certain confidence to be allocated by the performance allocation process. Physically the SISA will have the dimension meters and be a statistical parameter comparable to a standard deviation. The SISA is an outcome of the OD&TS and is as the Ephemeris and Clock update parameters a prediction. These predictions are determined in a batch process updating the parameters each 10 minutes. However an uplink of the most actual set of parameters including SISA for broadcasting may take up to 100 minutes. Studies as [7] and GSTB-V1 experimentation seem to show that this maximum update interval is sufficient regarding the Galileo Mission Requirements. Since SISA is a prediction of the orbit and clock errors at least 100 min in advance, the dependence of it is strongly connected to the modeling quality. The SISA is expected to bound the errors under so called "nominal conditions" that means that all on board of the satellites and on ground segment will work in the specified frame for at least the next 100 minutes.

In case of a system failure, the user has to be alerted within a 6 seconds Time To Alert (TTA). Therefore an independent check of the SISA versus the SISE is foreseen in the Galileo Integrity concept each second. The indicator is the Integrity Flag (IF) which warns the user of the alert condition. Additionally the IF can be flagged preventatively whenever the system operator detects anomalies in the ground segment or the space vehicle. There is an additional parameter introduced, the SISMA (SIS Monitoring Accuracy) which describes the SISE determination quality based on the GSS observation geometry of a satellite. SISMA will be broadcast in a shorter time interval of 30 seconds nominally. It also contains the value of IF if needed. In case of an alarm an update of the SISMA/IF tables is sent between the nominal update interval.

The general overview over the concept is given in Figure 8. Without description of the total Galileo architecture the integrity most relevant facilities are shown in brief.

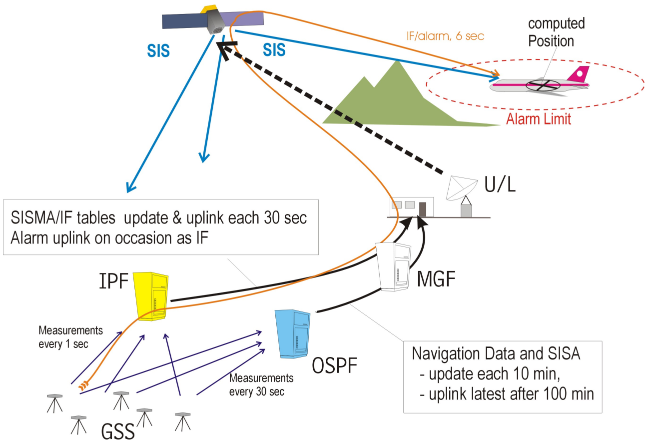

Figure 8: SISA/IF signal loops

The Galileo Sensor Stations (GSS) are distributed globally to cover the worldwide service performance requirements. The total number and site locations are still in discussion, since the constraining factors are not fixed yet. The latest baseline foresees 30 GSS sites. The following variables have to be considered:

- Elevation Masks of the GSS
- Performance of SISA and SISE determination
- redundancy schemes
- required Depth Of Coverage (DOC, i.e minimum number of GSS seen by each Galileo satellite)

Figure 9 shows the Galileo Ground Segment Depth of Coverage as seen from the suggested 30 Galileo Sensor Stations (GSS). An elevation mask of 10 degrees per GSS has been used. Using this GSS network a minimum visibility of 7 GSS per satellite can be achieved. This means if the minimum number of GSS per satellite is 6 there is sufficient redundancy for one GSS outage.

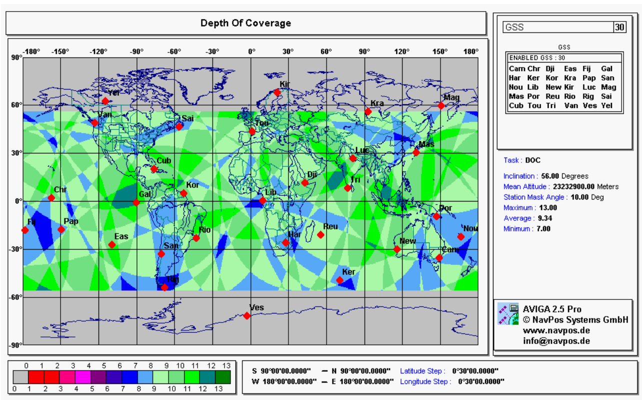

Figure 9: Galileo Ground Segment to Satellite Depth of Coverage

Each GSS is equipped with several Galileo Receivers which observables are fed into two different communication channels one leading to the Orbit Synchronisation Processing Facility (OSPF) and the other to the Integrity Processing Facility (IPF). So two independent chains are installed, the Navigation chain and the Integrity chain.

The OSPF and IPF are part of the Galileo Control Center (GCC). The OSPF receives in 30 second intervals observables from all the GSS and is such computing the navigation message content with the SISA incorporated.

The IPF receives each second a measurement set of each GSS and is estimating for each Galileo satellite its current SISE which is then compared with the latest transmitted SISA in the Navigation message.

Regarding the transmission strategy the following baseline has been chosen so far:

The Safety Of Life service incorporates the transmission on two frequencies, L1 and E5A/E5B.

SISA is updated at least with the Clock parameters in the Ephemeris message. The update rate is 100 minutes or shorter. Each satellite transmits SISA for itself only.

SISMA will be broadcast on at least 2 satellites per user, containing SISMA values for several satellites in view. The update rate is nominally 30 seconds. If an alarm has to be raised, then a new SISMA table is broadcast as an alarm message.

SISMA/SISE/IF ALGORITHMS

Though SISA is estimated by the OD&TS loop independently of the integrity determination processes, its representation and statistical characteristics play the basic role for provision of the overall Integrity. The SISA representation impacts directly on the SISE/IF computational algorithms and its statistical characteristics define a portion of integrity risk related with SISA, and hence, the sum of integrity risks associated with SISE/IF and P_hmi algorithms. At present several suggestions are made for the SISA definition:

An estimation of the bound of the SISE error with a certain confidence level [8].

A prediction of the minimum standard deviation (1-sigma) of the unbiased Gaussian distribution, which over-bounds the SISE predictable distribution for all possible locations within the satellite coverage area [9].

SISE is the satellite-to-user error due to satellite navigation message clock and ephemeris errors, which is a function of time and user location [9].

The following SISA representations have been investigated:

a) **Four dimensional vector SISA** representation uses a vector $(\Delta\vec{R}_{eph}, \Delta clk)$ where $\Delta\vec{R}_{eph} = (\Delta x, \Delta y, \Delta z)$, Δclk are ephemeris and clock errors respectively. The ephemeris errors can be presented either in the ECEF frame or in the orbital frame. In case of ECEF frame the equivalent ranging error along the user-satellite line-of-sight (LOS), SISAu includes two terms. One is the projection of $\Delta\vec{R}_{eph}$ onto the user-satellite LOS and the other is the clock error Δclk.

b) Three dimensional vector SISA representation is described by a vector: $(\Delta AlongTrck,\ \Delta CrossTrck,\ \Delta Rad + \Delta clk)$ where $\Delta AlongTrck,\ \Delta CrossTrck,\ \Delta Rad$ are ephemeris errors $\Delta x, \Delta y, \Delta z$ expressed in the orbital frame.

c) Scalar representation of SISA is the maximum of the ranging error SISAu reached at the Worst User Location (WUL)

d) Matrix representation of SISA is described by the covariance matrix

$$E(XX^T),\ \text{with}\ X = (\Delta x, \Delta y, \Delta z, \Delta clk)$$

SISMA COMPUTATION

SISMA (or sigma-check) is a parameter, which shows at what accuracy level the Integrity Processing Facility (IPF) is capable to determine a satellite's SISE error comprised of ephemeris and clock errors. An IPF module was implemented in AVIGA to perform the simulations based on the Galileo Integrity concept.

The i-th satellite ephemeris and clock error in ECEF frame can be presented as

$$\Delta\vec{x}_i = (\Delta X_i \quad \Delta Y_i \quad \Delta Z_i \quad c\Delta T_i)^T$$

for four parameters estimation task (4P) and

$$\Delta\vec{x}_i = (\Delta X_i' \quad \Delta Y_i' \quad \Delta Z_i' \quad)^T$$

for three parameters estimation task (3P).

The three parameters task can be considered if instead of ephemeris error components there are taken their sums with projections of the clock error $c\Delta T_i$ onto ECEF axes.

The GSS measurement errors are introduced as by the noise vector $B = (b_1 \quad \ldots \quad b_j \ldots \quad b_n)^T$, where n is the number of GSS stations tracking i-th satellite and b_j is a Gaussian error with standard deviation

$$\sigma_j = \sqrt{SIG0^2 + SIG1^2 / \tan^2(El_{ji})}\,. \quad \text{Eq. 2}$$

$$Z = A \cdot X + B \qquad \text{Eq. 3}$$

where

Z is the vector of residuals errors of GSSs;
A is a (n x 4) matrix of directional cosines between GSSs and satellite i;
X = $\Delta\vec{x}_i$.

For the system of linear equations (Eq. 3), the weighted least square solution and its covariance error matrix can be found.

$$X_{est} = (A^T \cdot COV(B)^{-1} A)^{-1} A^T \cdot COV(B)^{-1} Z \quad \text{Eq. 4}$$

$$COV_{X_{est}} = (A^T \cdot COV(B)^{-1} A)^{-1}$$

The solution X_{est} is just an ECEF vector of ephemeris and clock errors whereas an actual value of error experienced by the user is the projection of this vector onto the user –satellite Line-of-Sight (LOS), the vector $a_{uS} = (e_{uX} \quad e_{uY} \quad e_{uZ} \quad 1)^T$. Then the estimation error for the user a_{uS} can be written as

$$\sigma^2_{SISE_{est}} = a^T_{uS} COV_{Xest} a_{uS}\,. \qquad \text{Eq. 5}$$

The maximum value of $\sigma^2_{SISE_{est}}$ searched over the satellite i footprint is called sigma-check or SISMA. The granularity of this search is specified by the Longitude/Latitude Worst User Location (WUL) Search Steps (see Figure 10).

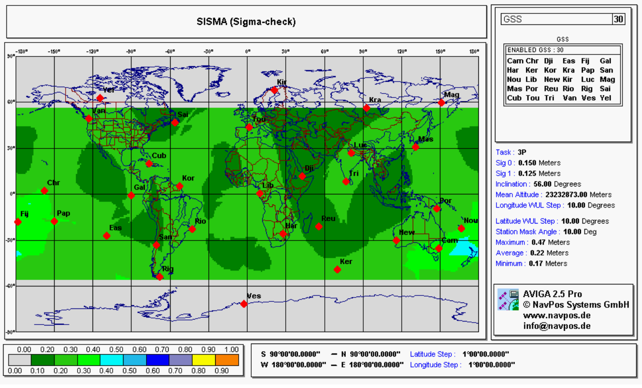

Figure 10: SISMA using 3-Parameter Estimation

IF or SISMA is set to a four bit value which is formed as follows:

Set to 0 = "Not OK" if the required probability of false alarm Pfa is not satisfied.

If the satellite is monitored and the required probability of false alarm Pfa is satisfied then IF is the integer from 1 to 14 coding SISMA (σ_{CHECK}) obtained by the SISE algorithm.

IF = 15 means "Not monitored" status of the IF.

Thus, this approach provides the user with IF satisfying the required Pfa and broadcasting the coded value of SISMA (in the following designated as σ_{CHECK}). The latter should improve the integrity availability for different classes of users.

SISE ALGORITHMS

As the first step the IPF has to evaluate SISE. There have been considered several algorithms to compute SISE. They can be split into two groups [10], [11].

SISE EGNOS type algorithms

Based on the assumption that for a certain area of earth, SISE can be a scalar value approximated by the plane surface that is SISE = $A \cdot x + B \cdot y + C \Leftrightarrow$

$$\delta R_i^j = A \cdot x_i + B \cdot y_i + C \qquad \text{(Eq. 6)}$$

where x,y are latitude and longitude arguments;

A, B, C are unknown coefficients;

(x_i, y_i) are coordinates of GSS stations tracking j-th satellite, $i = 1, \ldots n$;

n is the number of GSS stations tracking j-th satellite.

SISE Upside-down or inverse algorithms

In this case the approach is the same as in the basic navigation equations used for positioning with exception that unknowns ($\Delta \vec{R}_{eph}^{j}, \Delta clk^{j}$) are satellite ephemeris and clock errors expressed in ECEF frame whereas the role of satellites is played by the ground GSS stations.

Accuracy of SISE Estimation

Under some simplifying assumptions, the accuracy of SISE estimation achieved by these algorithms can be presented by two scalars:

$$[(H_E{}^T H_E)_{11}^{-1} x^2 + (H_E{}^T H_E)_{22}^{-1} y^2 + (H_E{}^T H_E)_{33}^{-1}] * \sigma^2 \qquad \text{(Eq. 7)}$$

and

$$(e_u^T (H^T H)^{-1} e_u) \sigma^2 \qquad \text{(Eq. 8)}$$

where H_E is the design matrix dependent on the user's coordinates x, y and monitoring stations' positions. The matrix H is upside-down navigation matrix of the j-th satellite and GSS stations monitoring this satellite, e_u is a unit satellite-user vector, and σ is a UERE standard deviation of GSS station.

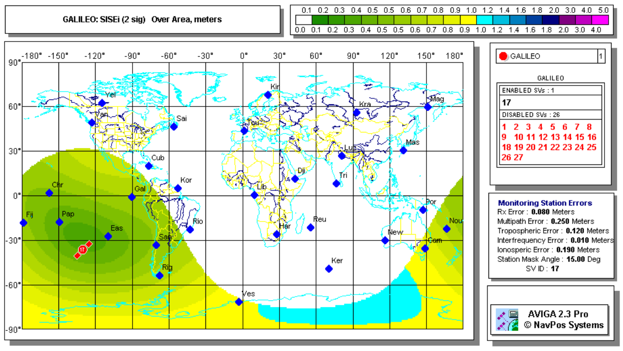

Figure 11: SISE Estimation for one Galileo Satellite as Function of Sensor Stations (to be updated)

For the provision of Galileo integrity, the main role is assigned to the integrity flags which are generated in the Integrity Processing Facility. The generation of integrity flags is based on the determination of SISE in real time. The value of SISE depends on the number ground sensor stations (GSS) and the satellite to GSS errors. Figure 11 shows snap-shot SISE values for a single satellite. The scalar SISE is dependent on the user location and visibility of the satellite. Near the Nadir position of the satellite SISE is as low as 10-20 cm. While at the border of the footprint SISE can raise up to 1.2 meters. However it should be mentioned this is a 2-sigma value.

INTEGRITY FLAG (IF) GENERATION

The goal of these algorithms that have to generate the IF is to satisfy given probabilities of Pfa and Pmd yet not jeopardizing the availability of integrity for users with different required levels of integrity risk.

IF Minimum Detectable Bias (MDB) Approach

Figure 12 illustrated this approach in which two cases are considered

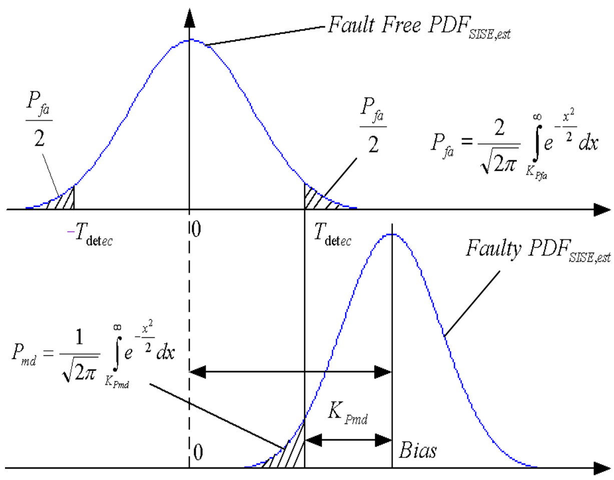

Figure 12: Minimum Detectable Bias

Fault – free case :

In this case an actual $SISE_{act}$ is assumed to have Gaussian distribution $N(0,\sigma^2_{SISA})$ with the standard deviation σ_{SISA} being a broadcast parameter. The IPF estimate of $SISE_{act}$ is $SISE_{act} + \Delta SISE_{est}$, where $\Delta SISE_{est}$ is an estimation error of the SISE computation algorithm which is calculated at the IPF. It is assumed that $\Delta SISE_{est}$ follows $N(0,\sigma^2_{CHECK})$, where the so-called "sigma-check" σ_{CHECK} characterizes the accuracy of the SISE estimation

Faulty Case

In this case an actual SISE is assumed equal to a bias value as shown on Figure 12. The IPF SISE algorithm has to detect this bias when estimating the actual SISE.

$$MDB = K_{Pfa} \cdot \sigma_{SISE_{est}} + K_{Pmd} \cdot \sigma_{CHECK} \quad \text{(Eq. 9)}$$

where $K_{Pmd} = \dfrac{Bias - T_{detec}}{\sigma_{CHECK}}$.

The MDB method generates the ternary IF and guarantees a specified Minimum Detectable Bias and probabilities of missed detection and false alarm related with the IF generated for a given satellite.

GALILEO INTEGRITY RISK (USER CONCEPT)

According to approach [17], [18], the user receives direct information about the estimated performance of each satellite (SISA, SISMA, IF) . Processing this information per satellite in the navigation solution the user can evaluate the integrity risk and decide whether it is possible to start the operation or not. The overall or combined user integrity risk is defined from the equation [17]:

$$P_{HMI} = \overbrace{(1 - erf(\frac{VAL}{\sqrt{2}\cdot\sigma_{u,v}})}^{term\_1} + \overbrace{\sum_{io=1}^{n} p_{fail}\cdot\frac{1}{2}\cdot(1 - erf(\frac{VAL - \left|M_u[3,i_0]\cdot B_{0,i_0}\right|}{\sqrt{2}\cdot\sigma'_{u,v}(i_0)})}^{term\_2\_0}$$

$$+ \overbrace{\sum_{io=1}^{n} p_{fail}\cdot\frac{1}{2}\cdot(1 - erf(\frac{VAL + \left|M_u[3,i_0]\cdot B_{0,i_0}\right|}{\sqrt{2}\cdot\sigma'_{u,v}(i_0)})}^{term\_2\_1} +$$

$$+ \overbrace{\chi^2_{f=2}(\frac{HAL^2}{\xi^2})}^{term\_3} + \overbrace{\sum_{i_0=1}^{n} p_{fail}\cdot\chi^2_{nc,f=2}\Big((\frac{HAL^2}{(\xi'(i_0))^2}),(\frac{(M_u[1,i_0]\cdot B_{0,i_0})^2 + (M_u[2,i_0]\cdot B_{0,i_0})^2}{(\xi'(i_0))^2}) \Big)}^{term\_4}$$

(Eq. 10)

where [17]:

- VAL is the specified Vertical Alert Limit
- HAL is the specified Horizontal Alert Limit
- $\sigma_{u,v}$ is the standard deviation of the model CDF that overbounds the vertical position error in fault free state. defined in [17]
- $\chi^2_{f=2}(*)$ is the central chi-squared distribution with 2 degree of freedom (DOF), for DOF = 2 simple exponent
- ξ^2 is the variance of the model CDF that overbounds the fault free position uncertainty along the semi-major axis of the error ellipse in the xy plane
- n is the number of valid measurements
- i_0 denotes the index of a satellite with failed signal
- Pfail is the probability in any 150 s that one and only one of the received signals is outside the specification and flagged by the IF as "OK"
- $\sigma_{u,v}'(i_0)$ is the standard deviation of the model CDF that overbounds the vertical position error, when the satellite i_0 is failed
- B_0,i_0 is the (undetected) bias error affecting signal i_0
- $\chi^2_{nc,f=2}(*,p)$ is the non-central chi-squared distribution with DOF = 2 and parameter p
- $(\xi'(i_0))^2$ is the variance of the model CDF that overbounds the position uncertainty (for signal i_0) along the semi-major axis of the error ellipse in the xy plane when the signal i_0 is failed

Figure 13 shows the simulated Galileo Integrity Risk according Equation 10. The simulation was performed on a worldwide 1°x1° grid with 5 minute steps over the full 10 day Galileo repetition cycle. Figure 13 shows the maximum Galileo Integrity Risk. The yellow plane represents the Fault-free or Single SIS HMI Probability of 1.7e-7 as suggested in the High Level Integrity Allocation of [17]. The Galileo Integrity Risk is well below the requirement in most areas of the world. However, near the equator, there can be seen some peaks which breach the alert limit.

Since the data range in Figure 13 is very large, the AVIGA tool offers to normalize the result and to represent the Galileo Integrity Risk output in a logarithmic form. Figure 14 shows a snapshot of the Galileo Integrity Risk.

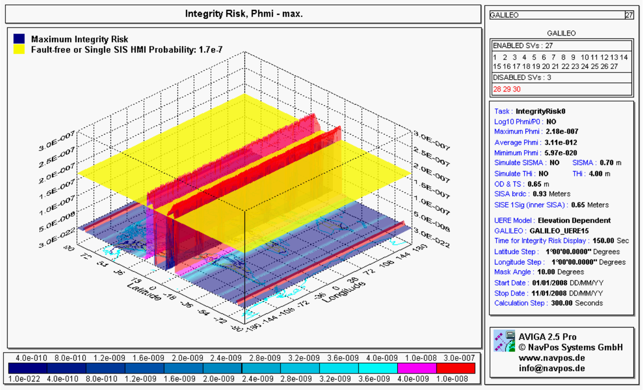

Figure 13: Maximum Galileo Integrity Risk (10day Repeat Cycle)

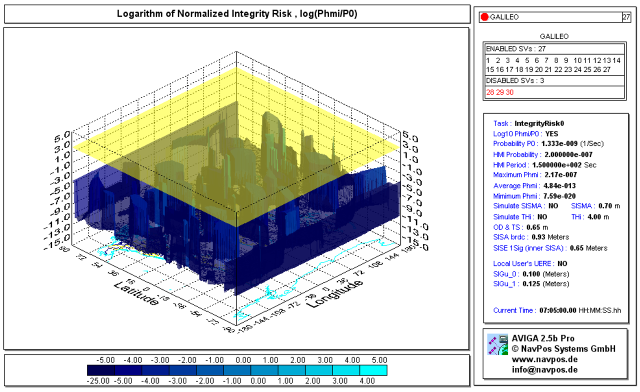

Figure 14: Snapshot view of the Galileo Integrity Risk Probability in a normalised and logarithmic form

The integrity risk PHMI calculated using Eq. 10 can be presented as the sum of the following terms :

term_1 is the probability of occurrence that the vertical position error will exceed VAL in the fault-free case when there is no bias pseudorange measurement on any of n satellite (this corresponds to SBAS).

(term_2_0 +term_2_1) is the probability that one of n satellite is failed i.e. has a bias B_{0,i_0} and the vertical position error associated with this bias is not detected by the IPF algorithms.

term_3 is the probability of occurrence that a horizontal position error will exceed HAL in the fault-free case when there is no bias pseudorange measurement on any of n satellite (this corresponds to SBAS).

term_4 is the probability that one of n satellites is failed i.e. has a bias B_{0,i_0} and the horizontal position error associated with this bias is not detected by the IPF algorithms.

Thus, P_{HMI} can be presented as sum of integrity risks in the horizontal and vertical planes

$$P_{HMI} = P_{HMI}^{Vert} + P_{HMI}^{Hor},$$

where

$$P_{HMI}^{VERT} = term\_1 + term\_2\_0 + term\_2\_1$$

$$P_{HMI}^{HOR} = term\_3 + term\_4 \qquad \text{(Eq. 11)}$$

Considering the left side terms in Eq. 11 as independent system parameters, it is still possible to treat the integrity equation Eq. 10 in a more traditional fashion. In this case the risks P_{HMI}^{VERT} and P_{HMI}^{HOR} are known and the user can solve Eq 10, 11 relative to HAL and VAL which can be thought of now as protection levels that is HPL and VPL. The results of the xPL availability computations based on this backward solution for Eq. 10 are presented below.

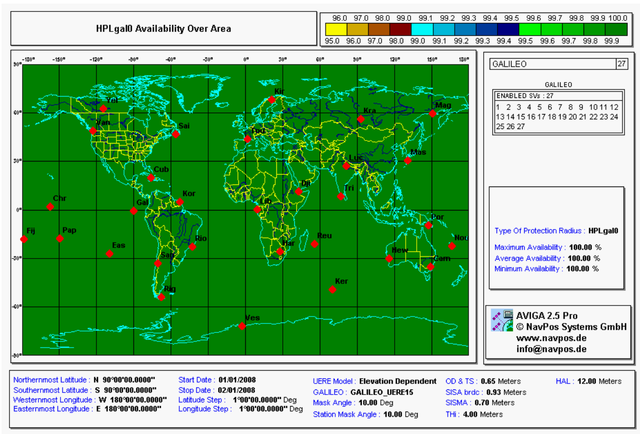

Figure 15: Galileo HPL Availability

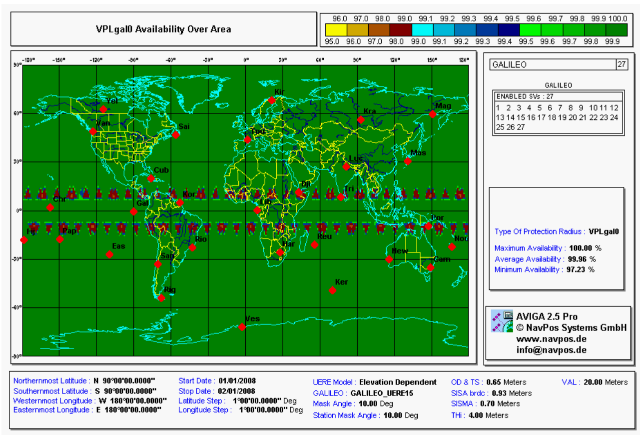

Figure 16: Galileo VPL Availability

The nominal Galileo constellation 27/3/1 with SISA=0.93m and the UERE components as specified in Table 3 were used in the simulation shown in Figure 15 and Figure 16. It presents the VPL availability results averaged over a 1 day simulation period at time steps of 5 Minutes. The geographic grid spacing was 1° which represents 65340 user positions. In most parts of the world it fulfils the Galileo Availability requirement of 99.5%. Only near the equator the availability drops to 97.92%. The average VPL availability is estimated with 99.97%.

As is seen from Figure 13 and Figure 16, the computation of xPL availability based on the backward solution is similar to outputs obtained with the latest Galileo Integrity concept [19, 20] for APV-II. It also can be seen that the small remaining availability problems are in the vertical position domain. Figure 15 shows 100% availability in horizontal plane whilst there are seen availability outages on Figure 16 near the equator.

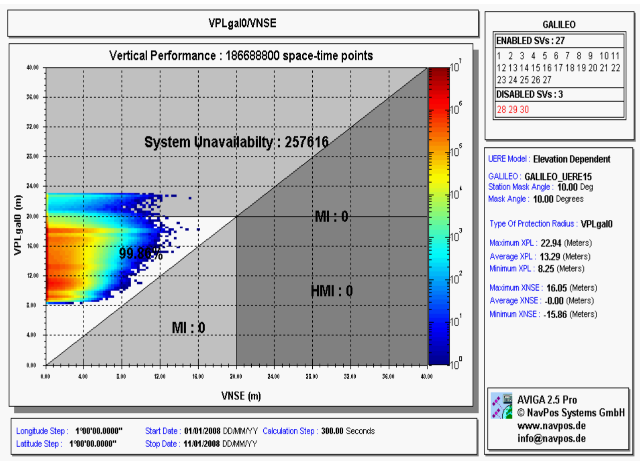

Figure 17: VNSE/VPL Availability over 1°x1° grid in 5 minute steps over the 10day Galileo repeat cycle

The AVIGA tool also offers to use the presentation form of the Stanford Graph for over area simulations. Usually the Stanford Plot is used to show the xNSE/xPL Availability at a given location i.e. one single position. In Figure 17 the presentation form of the Stanford Plot was used to show the simulation results for a worldwide 1°x1° grid (65340 positions) with 300s time steps over the full 10 day Galileo repetition cycle i.e. 2881 epochs. This amounts to more than 186 Million space-time points which were simulated in one run. The result is a vertical availability of 99.86%.

The presented results are strongly dependent on the validity of the UERE definition.

The Galileo Integrity Concept is currently under consolidation. Above simulations are based on the specification as given in [16]. Further conceptual refinements are being developed and are currently in the process of getting implemented.

CONCLUSIONS

The Galileo Safety of Life Service is a major advantage of Galileo compared to GPS. Therefore the Integrity function within Galileo is one of the major challenges in the system development. The layout (number and distribution) of the Galileo sensor station network and also the underlying Integrity concept is crucial for fulfilling the Galileo Integrity requirements.

Without a dedicated Integrity Function in Galileo, it is expected that RAIM techniques allow the use of Galileo for the less critical flight phases down to APV-I. The flight phase APV-II is not expected to be achievable with Galileo RAIM techniques alone. However, the combination of GPS and Galileo is expected to improve the RAIM performance significantly. The Service Volume Simulations look promising, but if APV II can really be achieved is to be verified with the real future GPS III and Galileo constellations. The results of the analysis considering operational outages in the Space Segment and inclusion of the Critical Satellite criteria are very promising.

The Galileo Integrity concept well achieves the APV-II requirements in most areas of the world. Just near the aequator there occur some outages which may need further tuning - for example of the Ground Segment sensor station network.

However, it is to be mentioned that all this analysis is based on the assumption that the Galileo UERE specification for Safety of Life applications is achieved. With the launch of the first Galileo satellites (GSTB-V2) the UERE budget can be validated.

To analyse the situation in depth additional extended simulations should be performed using different error budget assumptions and involving Space and Ground segment outage schemes similar to the ones used for the RAIM availability computations.

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