Performance Analysis of GNSS Global and Regional Integrity Concepts

Helmut Blomenhofer, Walter Ehret *THALES ATM GmbH*
Eduarda Blomenhofer, *NavPos Systems GmbH*

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 on 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 March 2001 he was the EGNOS Programme Manager at the EADS subsidiary Astrium GmbH located at Friedrichshafen.

From March 2001 to January 2002 he was the CNS/ATM task force manager and co-ordinated the CNS/ATM related Astrium activities in France, UK and Germany.

Since February 2002 he is the GNSS Business Development Director based at Thales ATM, Germany, being responsible for the build-up of the Thales ATM GNSS activities in close co-operation with the overall Thales corporate GNSS activities.

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 and performance assessment of satellite navigation systems in terms of accuracy, availability, integrity and continuity 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. As an scientific engineer at the Institute of Flight Guidance and Control of the TU Braunschweig he was involved in several GPS based application related study projects. His tasks have been H/W and S/W integration of GPS units, Analysis and Core Navigation algorithm adaptation. From 2000 until 2002 he worked at Aerodata Systems GmbH as development engineer for an integrated GPS/INS avionic system. From 2002 on he is 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 are expected to serve as navigation sources for a variety of applications. The most stringent performance requirements are derived from safety critical applications including aviation APV-II respectively CAT-I precision operations.

The Galileo baseline architecture specifies a global integrity concept. This means e.g. that besides the accuracy, availability and continuity the specified integrity performance must be achieved on a global level. However Civil Aviation Authorities outside Europe, might wish due to sovereignty reasons as well as due to performance reasons to determine the System Integrity of Galileo independently. One concept would be to adapt the different Augmentation approaches for GPS (SBAS, GBAS, GRAS) for the Galileo case. However, the Galileo baseline already foresees to include a multi-regional integrity concept where regions can install own integrity determination architecture while Galileo will provide the interfaces from regions to the Galileo satellites for disseminating of the regionally determined integrity. The basic approach of the Galileo integrity concept hereby is the task split of the Galileo integrity monitoring between the System (providing the GNSS Integrity Channel) and

the User (providing Receiver Autonomous Integrity Monitoring techniques).

The system performance has to be achieved in terms of the specified accuracy, availability and continuity figures. In addition the integrity monitoring has to detect Hazardously Misleading Information (HMI) of the navigation system and to alert the users within the specified Time To Alert (TTA). The Galileo System shall provide timely warning if the errors caused by satellite, clock, signal and / or navigation message are larger than predicted via a combination of a Signal In Space Accuracy (SISA) and Integrity Flag (IF). The SISA is a quantitative estimation of the orbit and clock prediction of the Galileo Control Centre which is updated with every clock update - in a fault free case. 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.

The main design driver of the Galileo architecture is the IF performance. This paper compares the Galileo global integrity concepts with a regional approach using different concepts and IF algorithms but also different ground architectures.

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. For Galileo, the user requirements on a Satellite Navigation System have been carefully assessed with respect to technical and economical feasibility.

REQUIREMENTS ANALYSIS AND SIMULATION INPUT PARAMETERS

Performance Requirements

The ICAO Annex 10 (SARPS Radionavigation Aids) lists the definition of the requirements in the current version (Amendment 77) [1] together with the limits for the different phases of flight. ***Figure 1*** compares the Required Navigation Performance (RNP) per phase of flight with the existing or expected GNSS system performance.

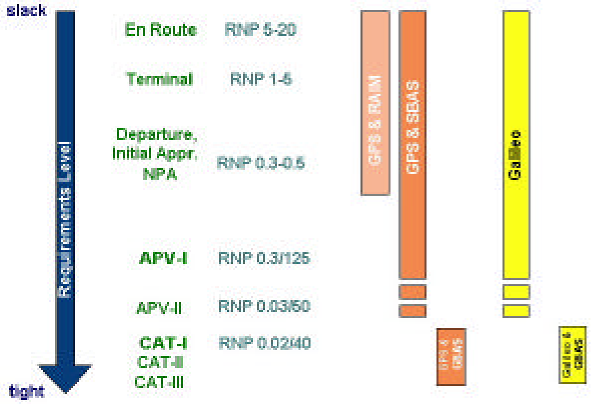


Figure 1 Aviation Phases of Flight versus GNSS Performance

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 only 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.

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.

Table 1 shows the Galileo System 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. The Galileo MRD requirements for horizontal navigation are even more stringent than the ICAO GNSS SARPS requirements for APV-II [1].

Accuracy (95%)	horizontal: 4m
	vertical: 8m
Availability	99.5 % of service life time
Continuity Risk	$< 10^{-5}$ / 15s
Integrity	HAL: 12m
	VAL: 20m
	TTA: 6 seconds
	Integrity Risk: $< 3.5\text{x}10^{-7}$ / 150s

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

Accuracy (95%)	horizontal: 16 m
	vertical: 8 m
Availability	99.0% to 99.999%
Continuity Risk	$< 8\text{x}10^{-6}$ / 15s
Integrity	HAL: 40m
	VAL: 20m
	TTA: 6 seconds
	Integrity Risk: $< 2\text{x}10^{-7}$ / approach

Table 2: ICAO APV-II Requirements

UERE – User Equivalent Range Error

A UERE budget (see ***Table 3***) in dependence of the satellite elevation angle was used, which was defined in the Galileo B2C study [3]. The simulation duration was three days to account for the repetition of the Galileo satellite constellation.

Elev.	10	15	20	25	30	40	50	60	90
UERE	1.26	1.13	1.07	1.05	1.03	1.01	1.01	1.00	1.00

Table 3: UERE budgets for E1/E5b Galileo signal for PL calculations (B2C phase)

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 analyze 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. If at the initiation of an approach the decision making will imply an additional decision criteria the availability will be degraded. 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 three different concepts to determine GNSS Integrity.

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

Each of these basic concepts has many derivatives and there exist many approaches to realize them.

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 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.

$$VPL = Slope_{\max}^{vert} \cdot pbias \cdot s_{UERE} \tag{Eq. 1}$$

where $Slope_{\max}^{vert}$ 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 alert limit plane.

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.

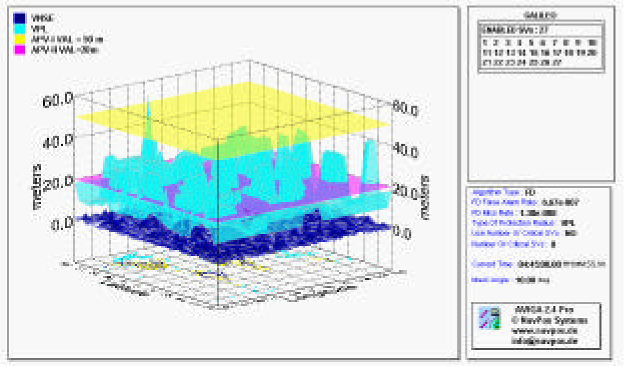
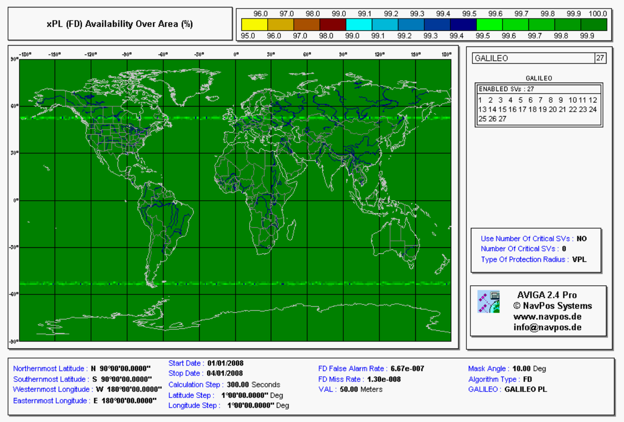


Figure 2: Galileo Protection Level Simulation based on FD RAIM without critical satellites

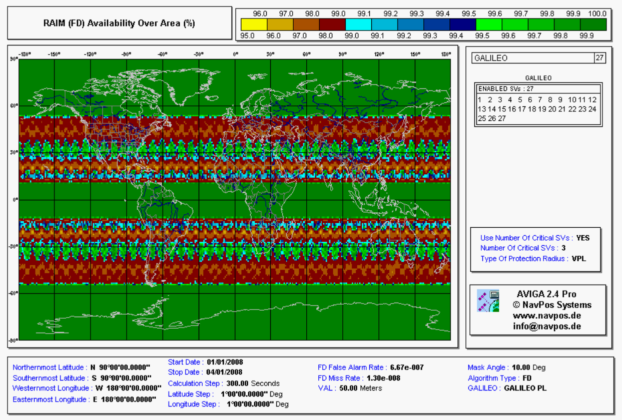


Use Number Of Critical SVs : NO
Number Of Critical SVs : 0
Type Of Protection Radius : VPL

Northernmost Latitude : N 90°00'00.0000"
Southernmost Latitude : S 90°00'00.0000"
Westernmost Longitude : W 180°00'00.0000"
Easternmost Longitude : E 180°00'00.0000"
Start Date : 01/01/2008
Stop Date : 04/01/2008
Calculation Step : 300.00 Seconds
Latitude Step : 1°00'00.0000" Deg
Longitude Step : 1°00'00.0000" Deg
FD False Alarm Rate : 6.67e-007
FD Miss Rate : 1.30e-008
VAL : 50.00 Meters
Mask Angle : 10.00 Deg
Algorithm Type : FD
GALILEO : GALILEO PL

Figure 3 : Galileo APV-I Vertical RAIM Availability (without critical satellites)

Without the consideration of critical satellites, the RAIM VPL over a constellation repetition interval is in nearly all grid points (1°x1°) worldwide and time steps of 5min better than 99.9 % (see Figure 3). Few small areas exist along the 56 degree latitudes with availabilities between 99.2% and 99.9%. Compared with the specifications in [1] for APV-I approaches this can be sufficient to meet the requirements. However, if critical satellites need to be taken into account for APV-I approaches using Galileo, then the RAIM Availability is in the order of 98% and therefore does not fulfil the APV-I Availability requirement 99.0%. Figure 4 shows the RAIM Availability with max. 3 critical satellites being considered.



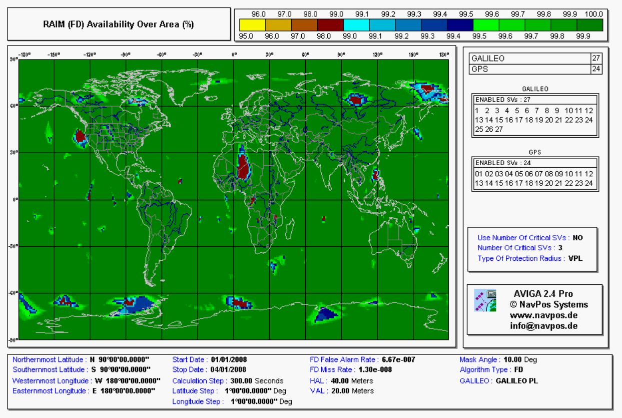
Use Number Of Critical SVs : YES
Number Of Critical SVs : 3
Type Of Protection Radius : VPL

Northernmost Latitude : N 90°00'00.0000"
Southernmost Latitude : S 90°00'00.0000"
Westernmost Longitude : W 180°00'00.0000"
Easternmost Longitude : E 180°00'00.0000"
Start Date : 01/01/2008
Stop Date : 04/01/2008
Calculation Step : 300.00 Seconds
Latitude Step : 1°00'00.0000" Deg
Longitude Step : 1°00'00.0000" Deg
FD False Alarm Rate : 6.67e-007
FD Miss Rate : 1.30e-008
VAL : 50.00 Meters
Mask Angle : 10.00 Deg
Algorithm Type : FD
GALILEO : GALILEO PL

Figure 4: Galileo APV-I Vertical RAIM Availability with max. 3 critical satellites

RAIM Using Combined GPS and Galileo

For the combined simulations the GPS III UERE error budget of 1.5m was used.

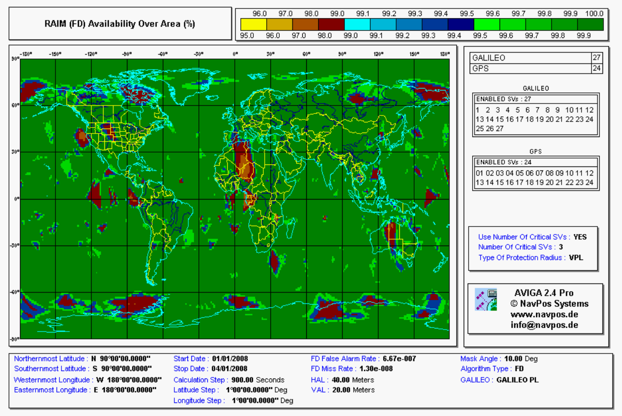


Use Number Of Critical SVs : NO
Number Of Critical SVs : 3
Type Of Protection Radius : VPL

Northernmost Latitude : N 90°00'00.0000"
Southernmost Latitude : S 90°00'00.0000"
Westernmost Longitude : W 180°00'00.0000"
Easternmost Longitude : E 180°00'00.0000"
Start Date : 01/01/2008
Stop Date : 04/01/2008
Calculation Step : 300.00 Seconds
Latitude Step : 1°00'00.0000" Deg
Longitude Step : 1°00'00.0000" Deg
FD False Alarm Rate : 6.67e-007
FD Miss Rate : 1.30e-008
HAL : 40.00 Meters
VAL : 20.00 Meters
Mask Angle : 10.00 Deg
Algorithm Type : FD
GALILEO : GALILEO PL

Figure 5 : GPS+Galileo APV-II Vertical RAIM Availability (without critical satellites)

The RAIM performance of combined GPS and Galileo easily fulfils the APV-I requirements. APV-II requirements seem to be achievable in most regions of the world. However outages can be seen in some areas even without critical satellites (see ***Figure 5***). The worst RAIM availability result was in the order of 97% (see ***Figure 6***) considering up to 3 critical satellites.



GALILEO	27
GPS	24

GALILEO
ENABLED SVs : 27
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27

GPS
ENABLED SVs : 24
01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Use Number Of Critical SVs : YES
Number Of Critical SVs : 3
Type Of Protection Radius : VPL

Northernmost Latitude : N 90°00'00.0000"
Southernmost Latitude : S 90°00'00.0000"
Westernmost Longitude : W 180°00'00.0000"
Easternmost Longitude : E 180°00'00.0000"
Start Date : 01/01/2008
Stop Date : 04/01/2008
Calculation Step : 900.00 Seconds
Latitude Step : 1°00'00.0000" Deg
Longitude Step : 1°00'00.0000" Deg
FD False Alarm Rate : 6.67e-007
FD Miss Rate : 1.30e-008
HAL : 40.00 Meters
VAL : 20.00 Meters
Mask Angle : 10.00 Deg
Algorithm Type : FD
GALILEO : GALILEO PL

Figure 6: GPS+Galileo APV-II Vertical RAIM Availability with max. 3 critical satellites

THE GALILEO SISA/IF GLOBAL CONCEPT

The Galileo system will provide various service levels for the users. 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 is foreseen only each 100 minutes. Studies as [7] seem to show that this 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 1 second epochs. 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.

The general overview over the concept is given in ***Figure 7***. Without description of the total Galileo architecture the integrity facilities are shown in brief.

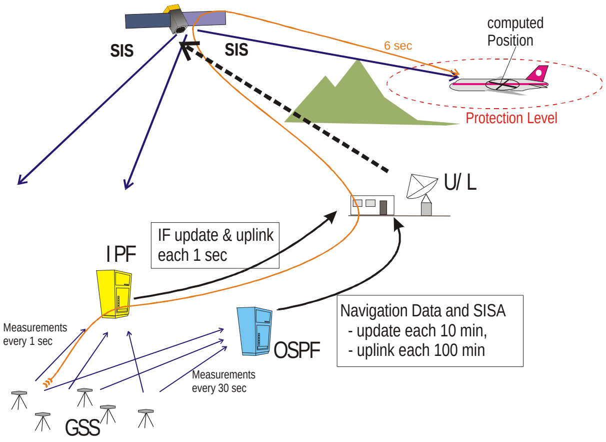


Figure 7: SISA/IF signal loops

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 IF determination
- redundancy schemes
- required Depth Of Coverage (DOC, i.e minimum number of GSS seen by each Galileo satellite)

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 or three frequencies, L1, E5A and E5B

SISA is a bound for the SIS contribution to the User Equivalent Range Error in the so called "fault free" or "nominal" case. It will be broadcasted to the users together with the Ephemeris data. So each Galileo satellite broadcasts its own SISA. The SIS contribution is so far the Ephemeris error and Satellite Clock error contribution. SISA, as a scalar value, is computed for the Worst User Location in a satellite footprint. This is a conservative approach for the rest of the area. SISA is a prediction of the SIS Errors and its update rate is the same as the Ephemeris (together with the clock parameters). Therefore a much more frequent check has to be implemented checking whether the SISA represents the true SIS error situation (e.g due to an Feared Event leading to an abnormal Signal degradation). This will be done by an independent online process which compares the predicted SIS accuracy (SISA) with the actual SIS error (SISE). If SISA does not represent the true error a warning flag (IF) is set. Therefore the update rate of the IF (or "Don't Use") flags will be on a second by second basis. There will be a subset of Galileo satellites which transmit IF for all satellites (IF tables).

SISE/IF/XPL COMPUTATIONAL 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 xPL 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].

Several 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

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

The following main inputs are used for SISE/IF computations in IPF:

Fast Changing Variables: dR_i^j is **preprocessed pseudo-range residuals for j-th satellite** and i-th GSS station assumed to contain ephemeris and clock error for j- th[1] satellite, the other kinds of errors have to be removed in preprocessing; $\vec{R}^j$ is a **ECEF position vector of j-th satellite** calculated from the broadcast ephemeris.

Slow Varying Parameters: SISA in one of forms described above.

Configuration Parameters: $\vec{R}_i$ is a precisely known ECEF position vector of i-th GSS station.

System Integrity Requirements: The required probability of false alarm Pfa and the required probability of missed detection Pmd related with IFs.

For simplicity, the satellite index j is omitted hereafter.

SISE ALGORITHMS

At the first step 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 = $A \cdot x + B \cdot y + C \Leftrightarrow$

$$dR_i^j = A \cdot x_i + B \cdot y_i + C \qquad \text{(Eq. 2)}$$

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, $i = 1,...n$;

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

SISE Upside-down algorithms

In this case an 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:

$$[(H_E{}^T H_E)_{11}^{-1} x^2 + (H_E{}^T H_E)_{22}^{-1} y^2 + (H_E{}^T H_E)_{33}^{-1}] * s^2 \qquad \text{(Eq. 3)}$$

and

$$(e_u^T (H^T H)^{-1} e_u) s^2 \qquad \text{(Eq. 4)}$$

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 s is a UERE standard deviation of GSS station.

Minimum –norm algorithms

This type of algorithms handles a case when the number of unknowns in the measurement equations is more than the number of equations that could take place in a regional integrity case. It could also be beneficial during the In-Orbit Validation phase, when only a subset of monitoring stations is available. Its optimal Least Squares solution for SISE looks differently as compared to the above Global Integrity cases:

$$SISE = H^T (HH^T)^{-1} z \qquad \text{(Eq. 5)}$$

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. The solid ternary IF approach which was adopted as a baseline in the initial phase of the Galileo project tends to be transforming into a more flexible methods of SISA monitoring. Two such approaches have been suggested:

IF Minimum Detectable Bias (MDB) Approach

Figure 8 illustrated this approach in which two cases are considered

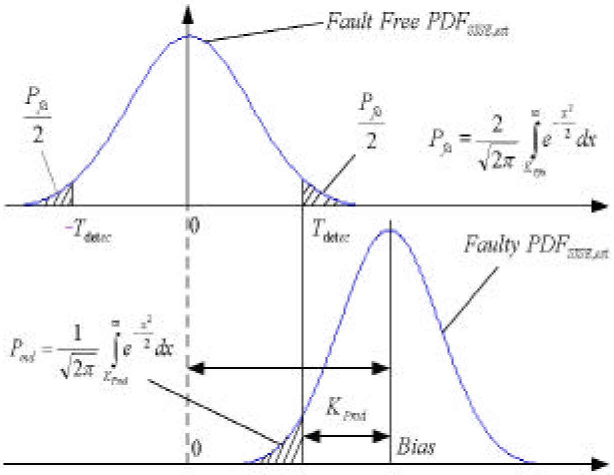


Figure 8: Minimum Detectable Bias

Fault – free case :

In this case an actual $SISE_{act}$ is assumed to have Gaussian distribution $N(0, s_{SISA}^2)$ with the standard deviation s_{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 $N(0, s_{CHECK}^2)$, where the so-called “sigma-check” s_{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 8***. The IPF SISE algorithm has to detect this bias when estimating the actual SISE.

$$MDB = K_{Pfa} \cdot s_{SISE_{est}} + K_{Pmd} \cdot s_{CHECK} \quad \text{(Eq. 6)}$$

where $K_{Pmd} = \dfrac{Bias - T_{\det ec}}{s_{CHECK}}$.

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

IF Sigma Check Approach

In this case the IF 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 (see ***Figure 8***) 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 s_{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 sigma check s_{CHECK}. The latter should improve the integrity availability for different classes of users.

COMPUTATION OF PROTECTION LEVEL

Galileo can use the following protection levels:

- SBAS EGNOS/WAAS like xPL
- RAIM xPL
- xPL specific to Galileo Integrity Concept

xPL mechanism can be viewed on as a final integrity barrier performing screening out of the failed satellites from the navigation solution.

Herein after we will consider xPL computation approach for Galileo Sigma Check Integrity concept. Likewise GBAS system the current Galileo approach considers two cases:

Case 1: No faulty satellites.

In this case xPL0 is calculated according to EGNOS like procedure

xPL0 = Func{ User-Sat j geometry, $s^{j}_{uere}, K^{User}_{Pfa}$ } (Eq. 7)

where $s^{j}_{uere} = \sqrt{s^{2}_{SISA,j} + s^{2}_{User-j,Rx,MP,trop...}}$.

Case 2: One satellite is faulty

xPL1 = $\max\limits_{j}\{xPL1_j\}$, (Eq. 8)

where $xPL1_j =$ Func{ User-Sat j geometry, s^{j}_{uere}, $s_{SISA,j}$, $s_{User-j,Rx,MP,trop...}$, s_{CHECK}, K^{User}_{Pmd} }

Finally, xPL = max(xPL0, xPL1).

Note: $s_{SISA,j}$, s_{CHECK} are broadcast in the Galileo navigation data, and K^{User}_{Pfa}, K^{User}_{Pmd} are scaling probabilities of false alarm and missed detection Pfa and Pmd provided by the user xPL algorithm.

The xPL also plays the role of decision triggers about availability of the service [12], the service is declared available if:

xPL < XAL, assuming xPL and PVT are available. This condition ensures the specified integrity risk allocated to xPL computation.

Less than 3 satellites are critical to meet the protection level condition, this means that there are no more than 3 satellites for which excluding one satellite at a time causes XPL for (n-1) satellites exceed XAL.

SISA PROTECTION LEVEL SIMULATIONS USING SBAS LIKE XPL

According to the Protection Level Integrity concept the Safety Of Life user can apply the Galileo Signal-in-Space when the calculated XPL is less than the corresponding alert limit XAL. It is assumed that the current value of XPL overbounds positioning errors with a considerable level of confidence.

The broadcast SISA is an upper bound for clock and ephemeris errors, and therefore can be directly utilized in derivation of SBAS protection level as follows

$$XPL = Kx\sqrt{\sum_{i=1}^{N} s^{2}_{n,i} s^{2}_{UERE,i}} \quad \text{(Eq. 9)}$$

where

$s^{2}_{UERE,i} = s^{2}_{SISA,i} + s^{2}_{iono,i} + s^{2}_{tropo,i} + s^{2}_{mp+noise,i}$ is the UERE variance of i-th satellite;

$s^{2}_{n,i}$ is the entry of the weighted projection matrix reflecting satellite-user geometry given, for example in RTCA DO-229() [13];

Kx is a constant that sets confidence level related with XPL.

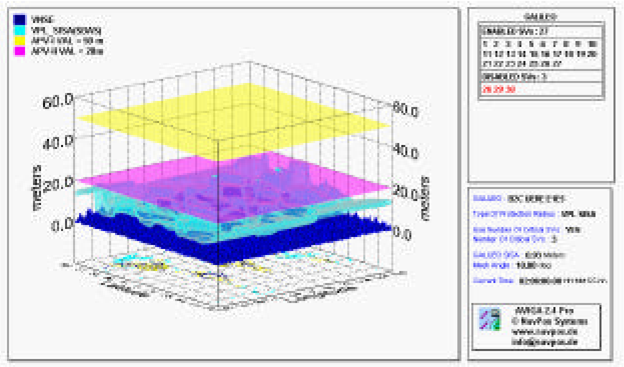
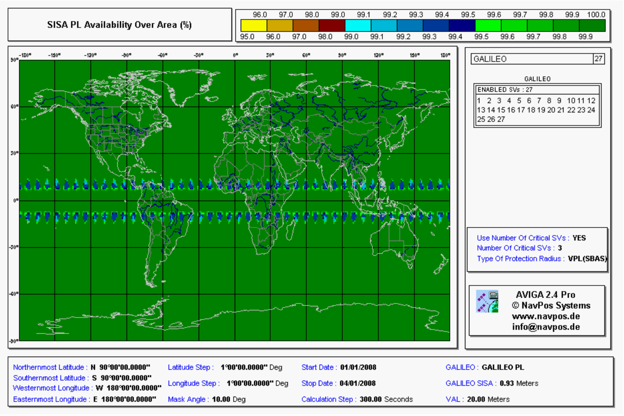


Figure 9: SISA Protection Level Snapshot

The graph on ***Figure 9*** shows the simulation results of VPL in accordance with Eq. 9, the light blue surface presents the computed values over the world grid carried out for baseline Galileo constellation 27/3/1 with SISA=0.93m and the UERE components as specified in ***Table 3***. Up to 3 critical satellites were considered in the simulation.



ENABLED SVs : 27
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27

Use Number Of Critical SVs : YES
Number Of Critical SVs : 3
Type Of Protection Radius : VPL(SBAS)

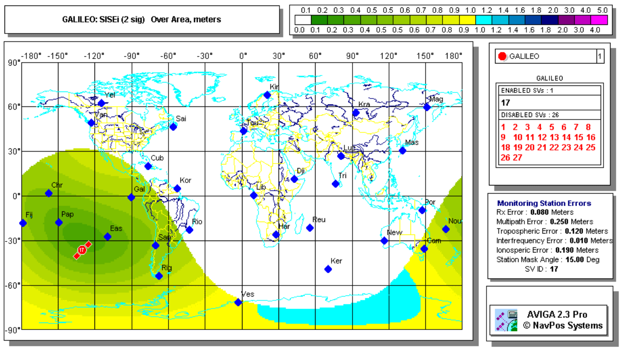
Northernmost Latitude : N 90°00'00.0000"
Southernmost Latitude : S 90°00'00.0000"
Westernmost Longitude : W 180°00'00.0000"
Easternmost Longitude : E 180°00'00.0000"
Latitude Step : 1°00'00.0000" Deg
Longitude Step : 1°00'00.0000" Deg
Mask Angle : 10.00 Deg
Start Date : 01/01/2008
Stop Date : 04/01/2008
Calculation Step : 300.00 Seconds
GALILEO : GALILEO PL
GALILEO SISA : 0.93 Meters
VAL : 20.00 Meters

Figure 10: Galileo SISA PL Availability for APV-II

The dark blue surface lying mainly beneath the VPL surface shows the user's vertical positioning errors over the same world grid. The two planes in ***Figure 9*** are Alert Limits for APVII and APVI modes. It is interesting to note that there can be seen some apparent cases of instantaneous unavailability of VPL integrity on the APVII Alert Limit plane where the light-blue surface penetrates the plane. This is caused by the exclusion of critical satellites in the simulation.

The ***Figure 10*** presents the VPL availability results averaged over a 3 days simulation period at the time step of 5 Minutes. In most parts of the world it fulfils the Galileo Availability requirement of 99.5%. Only near the equator the availability is between 99.0% and 99.5% which still fulfils the APV-II requirement.

The results presented in ***Figure 9*** and ***Figure 10*** are strongly dependent on the validity of the UERE definition.



ENABLED SVs : 1
17
DISABLED SVs : 26
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 18 19 20 21 22 23 24 25 26 27

Monitoring Station Errors
Rx Error : 0.080 Meters
Multipath Error : 0.250 Meters
Tropospheric Error : 0.120 Meters
Interfrequency Error : 0.010 Meters
Ionosperic Error : 0.190 Meters
Station Mask Angle : 15.00 Deg
SV ID : 17

Figure 11: SISE Estimation for one Galileo Satellite as Function of Sensor Stations

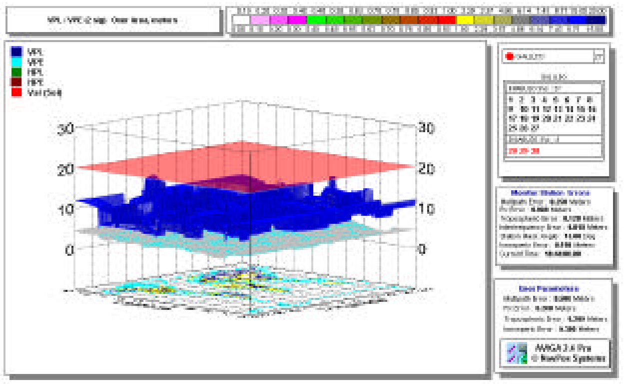


Figure 12: VPE / VPL Simulation based on SISE estimation as Function of Sensor Stations

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. In ***Figure 12*** the Vertical Position Error (VPE) and the Vertical Protection Level (VPL) were simulated using error models instead of a static UERE table (see ***Figure 9***). The SISA was approximated by the SISE values computed at the time of simulation. The SISE itself was processed for all satellites as function of the simulated sensor station observations under consideration of error models for troposphere, ionosphere, multipath, receiver noise at the Galileo Sensor Stations and at the User Positions (1°x1° grid).

DISCUSSION OF (MULTI-) REGIONAL INTEGRITY CONCEPTS FOR GALILEO

The above described Galileo Integrity concept is a global concept, i.e. the Ground Segment deployed Galileo Sensor Stations as a worldwide network. The current baseline foresees 30 GSS. This network is assumed to allow to determine SIS errors for each Galileo satellite with a high enough precision and availability to meet the SoL service requirements as stated in [2].

However, the ICAO regions are structured differently to the preliminary suggested Galileo regions. The countries are responsible for the provision of a navigation and ATS (Air Traffic Service). Therefore for countries or associations of countries (regions) the Galileo system baseline foresees a possibility to determine Galileo Integrity autonomously.

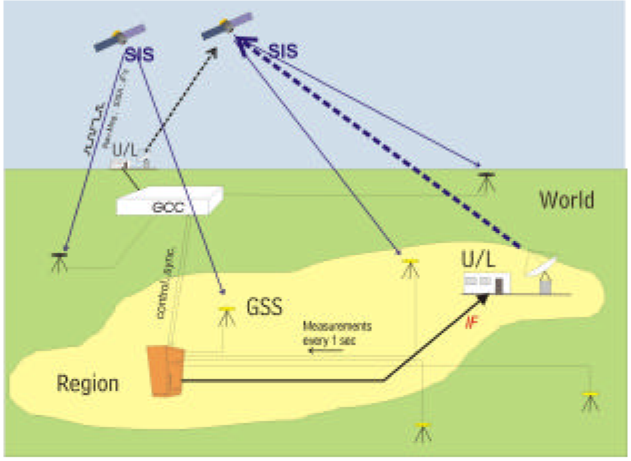


Figure 13: SISE estimation for one Galileo satellite

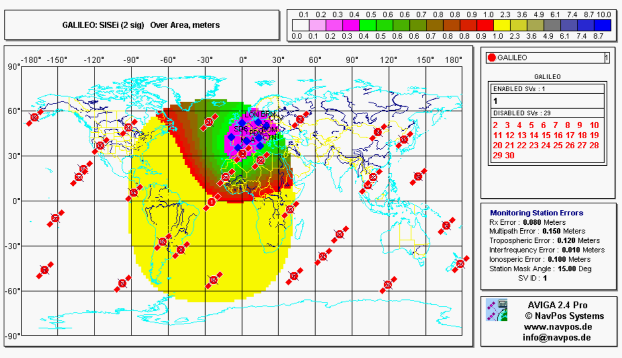
The Galileo Multi-Regional Integrity Monitoring Concept

The Galileo Multi-Regional Integrity Monitoring Concept suggests to deploy an own Integrity Determination network consistent of GSS and an regional IPF and possibly U/L on its territory. There would be a dedicated integrity chain, which is independent from the Galileo System integrity chain. However some dependence on Galileo still remains in terms of availability. The regions are given the possibility to generate own Integrity Flags in 1s intervals and such assure warnings if the broadcast SISA does not bound the regionally determined estimate of the true SIS Error SISE. Such a regionally determined IF is dependent on a globally determined SISA.

The advantage of this concept is that the Galileo satellites broadcast the regionally determined IF. It is planned that Galileo will provide a direct satellite U/L access to the regions to broadcast regional IF sets.

Regional SISE Simulations

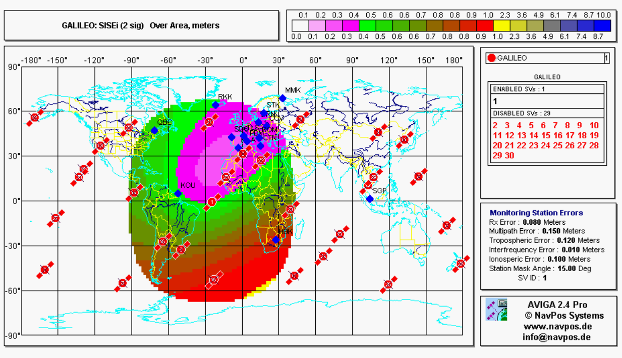
One question within this concept is whether the regional sensor stations will only be deployed within the region or if there are additional sensor stations outside the region. There is a significant difference in the quality of the SISE estimation which can be seen ***Figure 14*** and ***Figure 15***.



ENABLED SVs : 1
1
DISABLED SVs : 29
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

Monitoring Station Errors
Rx Error : 0.080 Meters
Multipath Error : 0.150 Meters
Tropospheric Error : 0.120 Meters
Interfrequency Error : 0.010 Meters
Ionosperic Error : 0.100 Meters
Station Mask Angle : 15.00 Deg
SV ID : 1

Figure 14: SISE with 8 GSS within ECAC (Snapshot)



ENABLED SVs : 1
1
DISABLED SVs : 29
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

Monitoring Station Errors
Rx Error : 0.080 Meters
Multipath Error : 0.150 Meters
Tropospheric Error : 0.120 Meters
Interfrequency Error : 0.010 Meters
Ionosperic Error : 0.100 Meters
Station Mask Angle : 15.00 Deg
SV ID : 1

Figure 15: SISE with 8 GSS within ECAC and 6 outside (snapshot)

The SBAS Concept for Galileo

The SBAS concept will be used to augment US NAVSTAR GPS. Currently there are three SBAS systems under development, which are the US WAAS, the Japanese MSAS and the European EGNOS to augment GPS and potentially Glonass. The SBAS concept uses additional geostationary satellites to broadcast the integrity information and the regional ground segment is setup independent of the satellite navigation system.

The SBAS regional augmentation approach is independent in terms of Integrity determination and dissemination. Similar to the augmentation of GPS, the existing SBAS systems could be modified to add Galileo integrity information. This would include the deployment of a separate monitor station network. For Galileo, the regional monitor station network needs not to be as dense as for today's WAAS or EGNOS networks, because Galileo SoL receivers are expected to use dual frequency measurements to correct the ionospheric errors. In addition to the Galileo global integrity monitoring, the regional SBAS integrity monitoring based on UDRE measurements would further improve the reliability in the use of Galileo for safety critical applications.

A disadvantage of this concept is that the integrity information is broadcast through geostationary satellites only. The GEO SIS can not be received well at high latitudes.

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 flight phase APV II can be expected to be globally achievable with the SISA Protection Level Concept. 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.

Both, the Galileo (Multi-) Regional Integrity Concept and also the independent regional augmentation (SBAS/EGNOS like) concept can increase the Galileo technical performance at the user. The major difference between the two concepts is the level of integration. In the Galileo (Multi-) Regional Integrity Concept the regional integrity information is broadcast with the Galileo Signal-in-Space. Also the additional regional sensor stations are embedded into the overall Galileo ground segment architecture. The SBAS/EGNOS concept uses additional geostationary satellites to broadcast the integrity information and the regional ground segment is setup independent of the Galileo system. There are pros and cons for both approaches.

The next steps are the sensitivity analysis of the Galileo Site Selection on global and regional basis including operational characteristics and also the analysis and comparison of different Integrity Flag algorithms.

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