GNSS/Galileo Global and Regional Integrity Performance Analysis

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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.

Arian Leonard graduated in 1991 with an MSc. in Aerospace Engineering from the University of Stuttgart. Following his R&D work at German Aerospace and ATM BiD activities in North America, he joined Thales ATM in 1997 as EGNOS Deputy PM. Since 1999 he has been contributing as Galileo Project Manager to various EC and ESA contracts and is currently Galileo Business Development Manager.

ABSTRACT

Augmented 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 precision approach operations.

Where GPS integrity is determined by augmentation systems like WAAS or 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. Further major performance measures are the availability of the Accuracy and Integrity figures and the Continuity of Service.

The GPS augmentation systems provide besides the wide area differential corrections also related residual errors which are used to compute Protection Levels. This is done in near real-time with latency times of maximum 6 seconds (UDRE concept), which grants a timely warning if failures in the GPS system occur.
The Galileo concept uses a combination of predicted errors (caused by satellite, clock, and non-precise navigation message) which are validated in real-time by integrity monitoring taking into consideration the monitoring accuracy. The latter is considered by a new introduced parameter, the SISMA (SIS Monitored Accuracy) The predicted component which is transmitted with the navigation message is called SISA (Signal In Space Accuracy) and is a quantitative estimation of the orbit and clock prediction of the Galileo Control Centre. SISA is updated with every clock correction update in the Navigation Message (Ephemeris Set). The two parameters SISA and SISMA will be used by the user to compute a Protection Level associated to the positioning result. 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 raised. This leads to the exclusion of the related (Faulty) satellite from both, the positioning equations and from Protection level equations.

In the Galileo Global concept there will be a global monitoring network. However Regions will be given the possibility to built up there own regional Monitoring and Integrity Determination Network. Previous assessments and analysis have demonstrated the integrity performance

potential of the Galileo global Integrity concept using simplified Service Volume Simulations (SVS).

This paper shows the results determined by more sophisticated SVS using e.g. inclusion of operational outages as well as the consideration of the critical satellite concept. The SISMA driven performance is analysed for the Global and an exemplary Regional case. The achievable Integrity performance is then mapped to the aviation performance standards as currently discussed by the ICAO. Finally a trade-off will be performed on the basis of previously introduced results for the other Integrity concepts like RAIM for combined GNSS systems or space based augmented GPS.

INTRODUCTION

The provision of integrity is essential to support critical operations in the safety-critical application domain within different modes of transport and in particularly in aviation. Regions/States will have the option of using the Galileo Global Integrity service (Galileo SoL service) which will be offered by the Galileo Operating Company or to implement their own regional concept for the Galileo integrity provision. The two options for implementing Galileo Regional Integrity are the ERIS concept based on broadcasting Regional Integrity through Galileo satellites and the updated SBAS concept, where Galileo Regional Integrity will be broadcast by Geostationary satellites. The decision of a Region/State about it's Regional Integrity provision concept for Galileo, will depend on different criteria (e.g. geopolitical, institutional, technical, industrial policy,…).

In the case of the North-Atlantic and according to IATA**,** North American, Trans-Atlantic and European Air Traffic sums up to a total of 63% of World-wide Air Traffic. Global Navigational Satellite Systems (GNSS), such as GPS and Galileo, are hence independently important elements of the future aeronautical navigation infrastructure. Ensuring these systems are functionally interoperable will further increase their collective value. Although GPS and Galileo must retain their basic authority, mission and operations, comprehensively addressing cross-system interoperability, will eventually provide realization of combined systems' capabilities and a considerable number of benefits as illustrated in the example of the aviation community.

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.

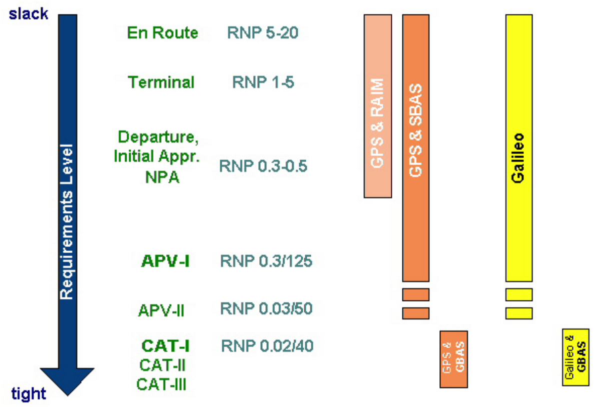

Figure 1 Aviation Phases of Flight versus GNSS Performance

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.

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: $< 3.5 \times 10^{-7}$ / 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	$< 8 \times 10^{-6}$ / 15s
Integrity	HAL: 40m
	VAL: 20m
	TTA: 6 seconds
	Integrity Risk: $< 2 \times 10^{-7}$ / approach

Table 2: ICAO 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].

BENEFITS OF COMBINED GPS/GALILEO USE

Performance Benefits of Interoperability :

Due to the improved availability of integrity for the combination of SBAS/GPS+Galileo it is expected to achieve the navigation performance required for CAT-I during all phases of flight. Here preliminary simulations have been shown, whereby the Vertical Navigation System Error VNSE and the Vertical Protection Level VPL to stay well below the APV-II vertical alert limit.

Safety Benefits of Interoperability :

One of the most promising benefits of GPS and Galileo Interoperability to the Aviation Community could be that the level of navigation performance usually reserved to larger airports only, could be made available continuously for unequipped ground locations as well as throughout the entire airspace at all flight levels and during all phases of flight. This would significantly increase the overall aviation safety in regions that are not covered by on ground system and in parts of the world where currently there is less ATC infrastructure available. Further, at less developed airports, safety could be improved by enabling vertically guided approaches to all runway ends. Search and rescue operations could be supported with improved accuracy and integrity of the navigation equipment. (e.g. rescue helicopter approaches to the home base under poor meteorological conditions). The exact position determination capability in conjunction with ADS-B could enhance situation awareness (surveillance) and thereby further improve safety.

Robustness Benefits of Interoperability :

It is expected that a two frequency Galileo (E1 & E5a, E5b) and a two frequency SBAS will be operational by 2010, followed by a two frequency GPS III (L1 & L5) in 2015. Regarding the interoperability of GPS and Galileo a number of mid-term scenarios with single frequency GPS (L1) and long-term scenarios with two frequency GPS (L1 & L5) can be considered. In the latter significant levels of operational redundancy at the CAT-I level are expected for the combination of Galileo(L1/E5) + GPS(L1/L5) + SBAS(L1/L5). This combination provides a very robust architecture which should be capable of providing the required navigation performance even in degraded modes of the GNSS services.

Benefits according to ICAO ref. GNSS P/4-WP/5 :

"The increasing number of GNSS signals and constellations offer significant benefits to civil aviation in terms of GNSS ground architecture simplification and alleviation of institutional concerns."… ", the introduction of new constellation and additional signals will facilitate the transition to GNSS as a global system for all phases of flight." Further in this regard, the FAA and Eurocontrol are in the unique position as leaders of US and European airspace systems to affect global ATM solutions and are key to achieving the benefits of GPS and Galileo Interoperability for the aviation community.

Benefits to Airports :

The combination of SBAS/GPS + Galileo could provide all weather CAT-I precision approach guidance to virtually every runway in the US and Europe as early as 2010, when both L1 and E5 signals become available via Galileo and at a later stage via GPS III. By achieving primary means navigation at core high-density areas, at regional airfields, and at remote regions the service areas could be extended. Usually, CAT-I precision approach capability is reserved to larger airports. GNSS (GPS and Galileo) Interoperability will also support less developed regional airports, which cannot afford conventional ILS and MLS systems. With the help of GNSS, regional airports will become fully usable and competitive, allowing the same level of service to be established at relatively low investment costs. Additionally, due to the enhanced availability of accuracy throughout the entire airspace and at all flight altitudes, aircraft separations could be optimised thereby enabling improved use of airspace capacity in the terminal area. Separation can be further reduced with the introduction of ADS-B techniques/equipment once adapted by a majority of airspace users. In conjunction with new operational procedures for all users, enabling closely spaced parallel approaches, converging approaches in marginal visual meteorological conditions (VMC), curved approached based on Precision Area Navigation (P-RNAV) as well as guided missed approaches, system capability and capacity can be significantly improved. Finally, follow-on operational enhancements could be enabled including: trajectory planning and management, thereby extending the daily window as well as the take-off and landing frequency, precision gate-to-gate operations, and achieving seamlessness of air navigation through standardisation between the US and European airspace systems. By means of these measures, based ultimately upon the improved capabilities of interoperable systems, many of today's ATC limitations could be overcome and the consequential financial losses could be mitigated.

Benefits to Airlines :

An improved navigation performance, possibly in combination with ADS-B techniques, is a further step towards Precision Area Navigation (P-RNAV). Hence, the resulting efficiency and relaxation of air traffic congestions would be considerable. As a consequence of the increased traffic throughput delay times could be drastically reduced, achieving substantial cost savings for both airlines and passengers. Additionally, the reduction of the number of different equipment for navigation, in airspace and on ground and for landing as well as the provision of a single human machine interface for all flight phases, allows cost reduction in terms of both equipment and pilot training. An easy to use navigation equipment is also more favorable to the pilot. The future multimode receiver MMR could be based upon multiple and independent navigation sources like GPS, Galileo, Inertials, etc., thus providing enhanced redundancy, safety and integrity on board the aircraft. To make the cost saving accessible to the airlines industry a certified equipment would be necessary which could be used for all phases of flight. It is expected that certification of the combined on-board equipment would benefit from the similarity of the GPS and Galileo systems. In addition, airlines could operate more frequently form regional airports and benefit from reduced airport taxes that result from navigation infrastructure cost reduction. This would enable commercial GA and business/company flights to achieve significant growth rates and commercial benefits.

Interoperability Benefits at No Extra Cost
A further improvement of the combined performance and robustness can be achieved at no extra cost. Preliminary simulation results have shown that the angle that separates the Galileo and GPS planes, i.e. the phase angle between the two independent constellations has an impact on the combined performance. Optimisation of this parameter known as the Right Ascension of Ascending Node RAAN for both constellations will improve the combined GNSS performance. A further advantage is the increase of robustness in case of GPS and/or Galileo satellite failures allowing continuity of operation in degraded modes. It must be noted that this kind of harmonisation is purely a planning issue (function of the launch date) and that any relative RAAN angle can be achieved for Galileo and GPS III without any impact on individual system designs or costs. Within the remaining window of opportunity until Systems Requirements are frozen for Galileo (~2005) and in future for GPS III, this parameter could still be determined for maximum interoperability.

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 one to three 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	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)

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.

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.

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

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.

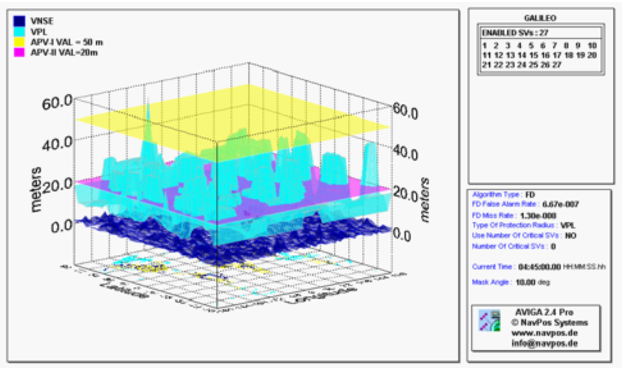

Figure 2: Galileo Protection Level Snapshot based on FD RAIM

RAIM Using Combined GPS and Galileo

For the combined simulations the GPS III UERE error budget of 1.5m was used which assumes dual frequency measurements.

The RAIM performance of the combined nominal constellations of 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 the consideration of critical satellites and operational outages (see Figure 3). In Figure 4 the combined GPS and Galileo APV II RAIM Availability was calculated considering operational outages for both constellations according to the Durand-Caseau model.

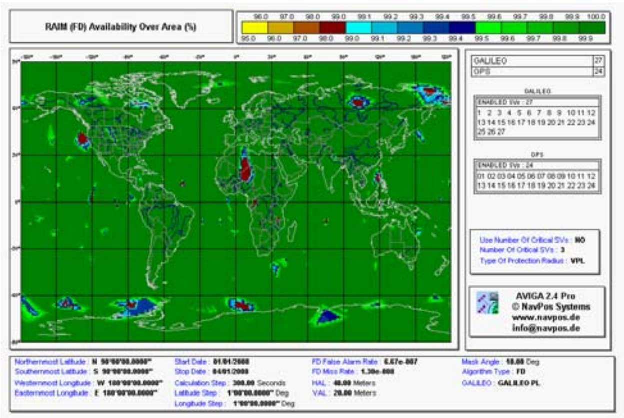

Figure 3 : GPS+Galileo APV-II Vertical RAIM Availability (without critical satellites)

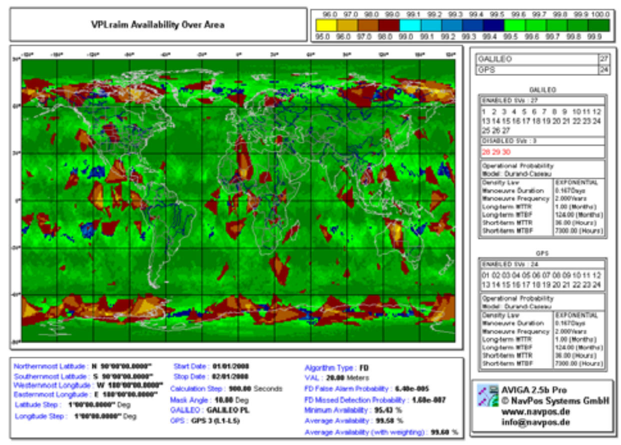

Figure 4: GPS+Galileo APV-II Vertical RAIM Availability considering space segment operational outages

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 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 5. Without description of the total Galileo architecture the integrity facilities are shown in brief.

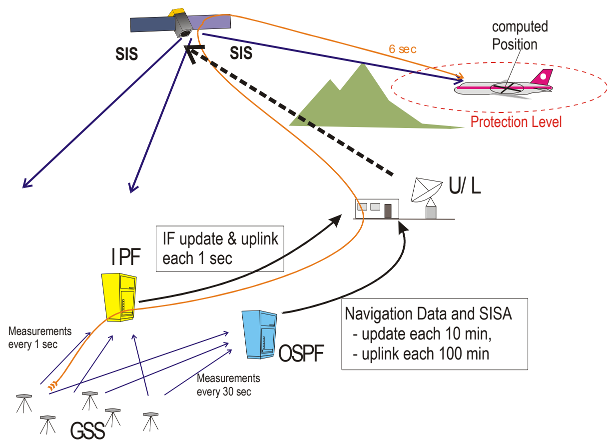

Figure 5: SISA/IF signal loops

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)

Figure 6 shows the Galileo Ground Segment Depth of Coverage as seen from the suggested 30 Galileo Sensor

Stations (GSS). Using this GSS network a minimum visibility of 7 GSS per satellite can be achieved.

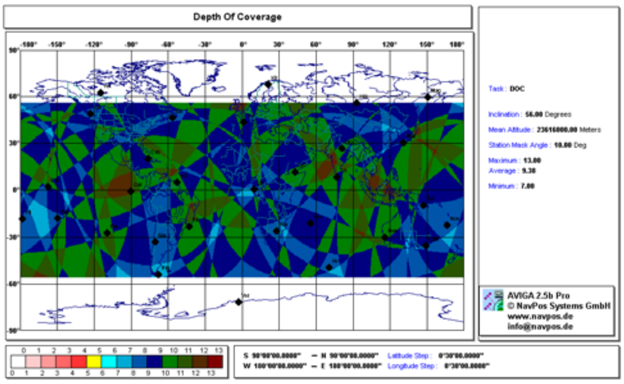

Figure 6 : Galileo Ground Segment to Satellite Depth of Coverage

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 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 broadcast 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 a 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. Galileo satellites will transmit IF for all satellites (IF tables).

SISMA/SISE/IF/XPL 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].

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 with a search granularity specified by the Longitude/Latitude Worst User Location (WUL) Search Steps (see Figure 7).

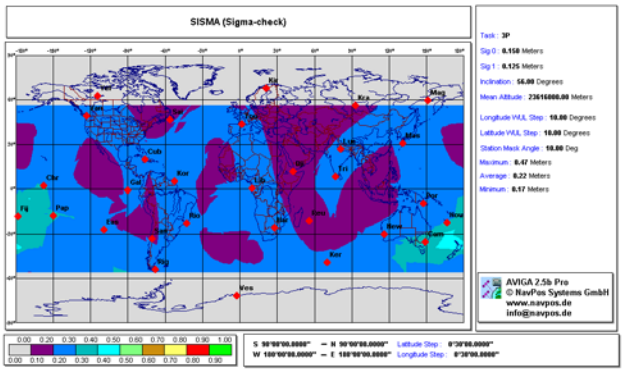

Figure 7 : SISMA using 3-Parameter Estimation

SISE COMPUTATION

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]. 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 8 shows snap-shot SISE values for a single satellite.

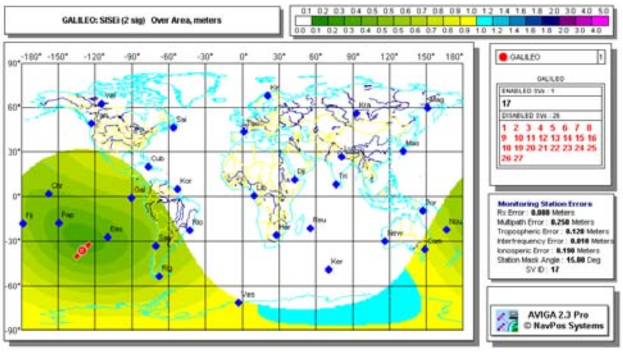

Figure 8: SISE Estimation for one Galileo Satellite as Function of Sensor Stations

INTEGRITY FLAG (IF) GENERATION

The goal of these algorithms that have to generate the IF is to satisfy given probabilities of the probability of false alarm Pfa and the probability of missed detection 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:

DIRECT COMPUTATION OF INTEGRITY RISK PROBABILITY

As a further evolution in the determination of the Galileo Integrity Performance, a more direct computation has been established. Compared to the conventional approach using protection levels vs. alert limits the representation in the figure below directly provides the integrity risk probability values as logarithms distributed as a function of the global geographical location. Further, here the reference plane drawn horizontally at the 3.5 x 10^{-7} value directly bounds the Integrity Risk requirement shown in Table 1, i.e. representing the APV II performance requirement for Galileo Safety of Life Service. The simulations were conducted based on a 1° x 1° geographical grid resolution using step time intervals of 5 minutes. A conservative approach was taken [17] and further fine-tuning will be necessary to eliminate few remaining breaching peaks.

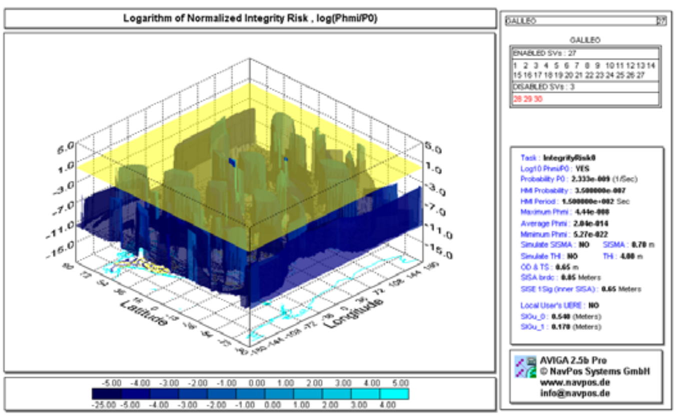

Figure 9: Snapshot view of the Galileo Integrity Risk Probability

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 build a worldwide network. The Galileo baseline foresees 30 GSS. This network is assumed to allow to determine SIS errors for each Galileo satellite with sufficient reliability and availability to meet the SoL service requirements as stated in [2].

However, the ICAO regions are structured differently. 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.

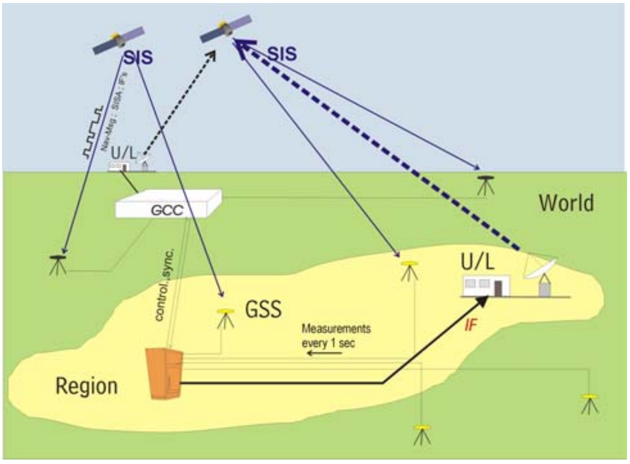

Figure 10: SISE estimation for one Galileo satellite

The Galileo Multi-Regional Integrity Monitoring Concept

The Galileo Multi-Regional Integrity Monitoring Concept suggests to deploy an own Integrity Determination network consistent of several GSS and a regional IPF and possibly U/L on its territory. There would be a dedicated integrity monitoring chain, which is independent from the Galileo System integrity chain. 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.

For an example area, the regional performance was simulated with arbitrarily selected 9 GSS sites within and additionally 6 sites outside the region. Figure 11 shows the regional Depth of Coverage using regional sensor stations. Figure 12 shows the respective regional SISMA results. In Figure 13 a snapshot of the SISE is presented for one satellite using these regional sensor stations. Figure 14 shows the Regional VPL availability as determined using the example of the 9 plus 6 GSS network.

A significant performance improvement as compared to the Galileo global integrity performance will only be achievable with a rather high number of regional sensor stations inside and outside the region.

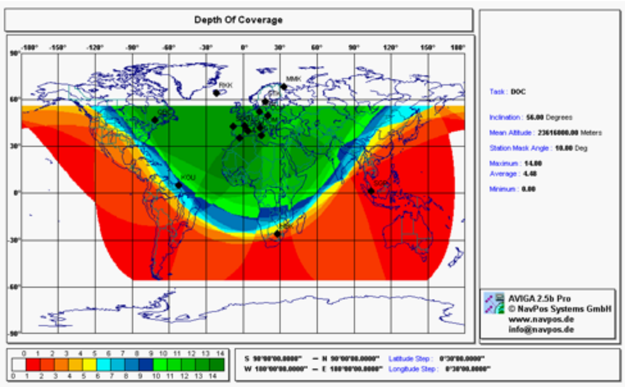

Figure 11: Regional Depth of Coverage Example

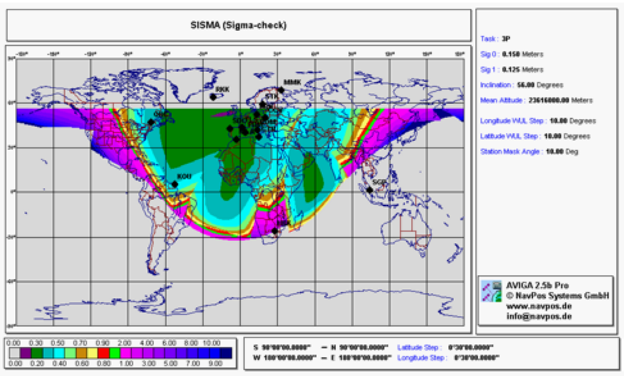

Figure 12: Regional SISMA Example

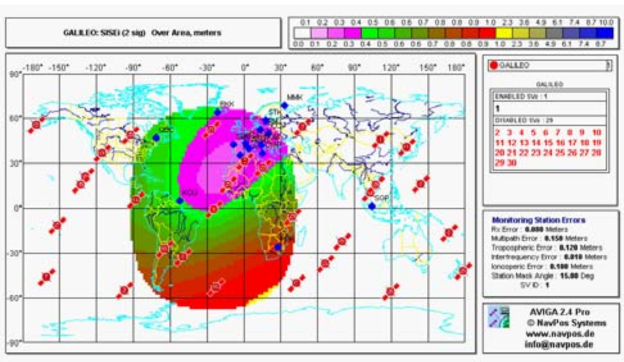

Figure 13: SISE with 9 GSS within ECAC and 6 outside (snapshot)

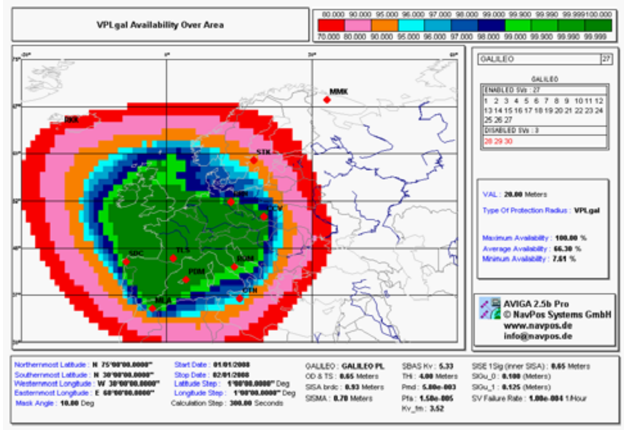

Figure 14: Regional Galileo VPL Availability Example

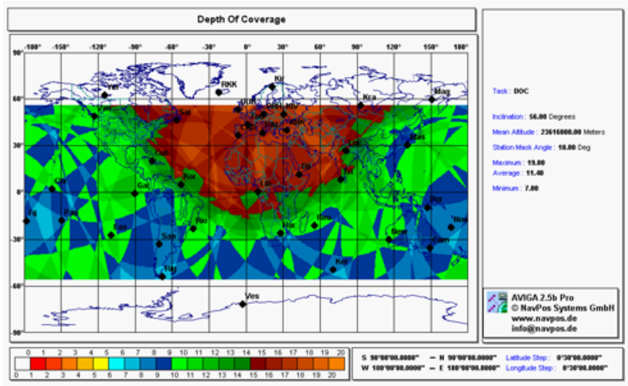

Figure 15: 30 Galileo GSS plus 7 Regional GSS Regional Depth of Coverage Example

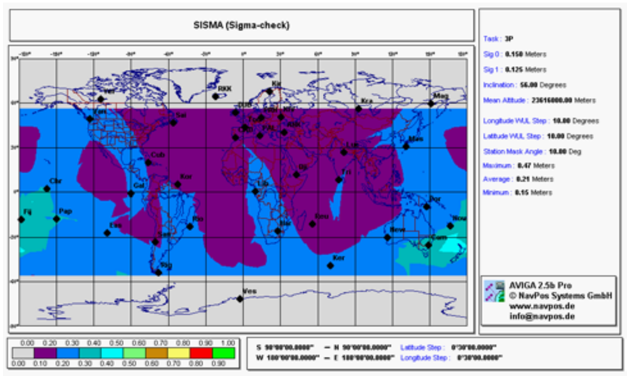

Figure 16: 30 Galileo GSS plus 7 Regional GSS Regional SISMA Example

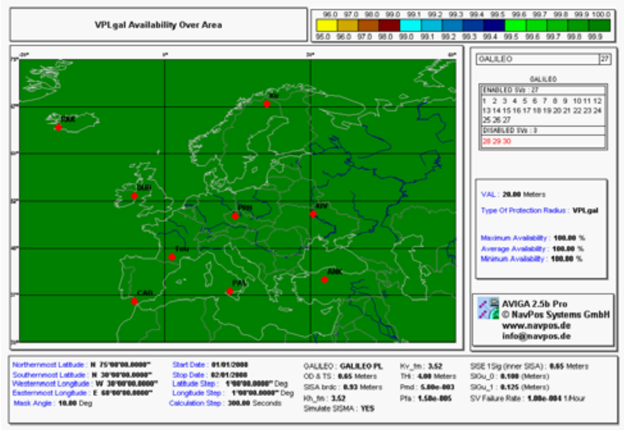

Figure 17: 30 Galileo GSS plus 7 Regional GSS Regional VPL Availability Example

A significant regional improvement in terms of robustness and performance could be achieved, if the regions had access to the Galileo sensor station data. Figure 15, Figure 16 and Figure 17 show an example of the regional Depth of Coverage, SISMA and VPL Availability using the 30 Galileo GSS plus 7 regional GSS.

Comparison with the SBAS Concept

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

Hence, a prerequisite for providing continued safe growth of global air traffic is Trans-Atlantic Cooperation to achieve GPS and Galileo interoperability. 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 could be used together with the 30 GSS of the overall Galileo Ground Segment architecture to improve the overall performance.

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.

Finally, due to the significance of the provision of integrity for safety of life applications, some Regions/States would prefer to have direct control over integrity for sovereignty/independence reasons. However, in view of the numerous advantages that the combined use of GPS and Galileo has to offer, e.g. in the example of aviation, it seems that Trans-Atlantic Cooperation is a prerequisite for managing the future demand for continued safe growth of transport, where in particularly in the aviation field, joint solutions need to be found to meet the pressing problems of safety, security, capacity and delay.

In this regard, ability to bring both industry and governments together in a structured environment could provide a mechanism for consensus building. Provided this is achieved, a set of globally applicable interoperability requirements for the design of future GNSS infrastructures could be determined, to ensure maximum benefit of the combined systems' capabilities for the end users.

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