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Galileo Integrity Concept and its Applications to the Maritime Sector

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ABSTRACT: Galileo is the European Global Navigation Satellite System, under civilian control. Galileo will provide their users with highly accurate global positioning services and their associated integrity information. The main objective of this article is to explain the basis of the Galileo integrity concept, which is fundamental for safety-critical applications such as maritime navigation. A review of the expected performance that will be achieved has been also included.

1 INTRODUCTION

Galileo is the European Global Navigation Satellite System, under civilian control. Galileo will provide to their users highly accurate global positioning services and their associated integrity information. The element within the Galileo Ground Mission Segment (GMS) in charge of the computation of Galileo integrity information is the IPF (Integrity Processing Facility), being developed by GMV (Grupo Mecanica del Vuelo).

The integrity algorithms of the GMS are responsible of providing a real-time monitoring of the satellite status with timely alarm messages in case of failures. The accuracy of the integrity monitoring system is characterized by the SISMA (Signal In Space Monitoring Accuracy), which is broadcast to the users through the integrity message together with the satellite integrity flags (OK, Not Monitored, Do Not Use)

Galileo is currently in its detailed design and development phase. The design and development phase for the IPF started in May 2005. The Critical Design Review (CDR) of the system has been successfully at the beginning of 2008, while the Factory Qualification Review (FQR) is expected for 2009. The SW prototypes of the integrity algorithms have already been implemented and the assessment of the critical performance figures has already been performed with outstanding results.

The main objective of this paper is therefore to explain the basis of the Galileo integrity concept, which is fundamental for safety-critical applications such as maritime navigation. It will include the mathematical formulation that shall be present at receiver level together with the details that are required to understand it from the maritime user point of view. A review of the potential level of performance based on the preliminary results available from the development phase will be also provided.

Additionally, information is provided related to the potential evolutions of the Galileo integrity concept, which is currently being defined in the frame of the GNSS evolution program led by ESA and in the 7th Framework Program of the European Commission led by the GSA, in which GMV takes an active role. In this environment, requirements from the maritime user community are being considered.

2 THE GALILEO INTEGRITY CONCEPT

2.1 *Overview*

Integrity can be defined as a measure of the trust that can be placed in the correctness of the information supplied by the system. Integrity includes the ability of the navigation system to provide users with timely and valid warnings (alerts) when the system must not be used for the intended operation (ICAO, 2006). In the current Galileo baseline the integrity aspects concerning the SIS errors will be achieved by means of two parameters: Signal-In-Space Accuracy (SISA) and the Integrity Flag (IF). Together with a new satellite ephemeris and clock models broadcast to the users, it is also sent the SISA, which is a prediction of the associated errors with a certain confidence level for the whole coverage area and valid for the applicability time of the models. The computation of this parameter is performed in another element of the GMS named OSPF (Orbitography and Synchronization Processing Facility) based on off-line data processing. Additionally, in order to meet the stringent integrity requirements such as the maximum Time To Alert (TTA), it is broadcast in real time the Integrity flags, which inform the users if SISA is properly bounding or not the SIS errors in that moment.

The Signal-In-Space Accuracy (SISA) plays an important role in the Galileo integrity concept, as it should cope with the navigation message errors in fault-free conditions. The description of the algorithms in charge of the SISA computation is out of the scope of this paper, which is devoted to the real-time integrity monitoring system of Galileo allocated to the IPF.

2.2 *High-Level Description*

In order to validate the navigation message being broadcast by the satellites, an independent estimation of the Signal-In-Space Error (SISE) is performed in real-time. This estimation, which is also modeled as a random process with an associated uncertainty, allows the verification of the overbounding of the true SISE distribution by the broadcast SISA. The assumption made in this case is that the difference between the true SISE projected at Worst User Location (WUL) and the estimated one can be overbounded by a Gaussian distribution with the standard deviation equal to SISMA. In this context, the SISMA can be considered as a quality measure of the integrity check within the IPF. Additional information on the Galileo integrity concept can be found in (Oehler, 2005). From the operational point of view, the IPF design does not consider any real-time human intervention, so key factors are the algorithms' robustness and reliability, directly derived from the stringent integrity and continuity requirements.

Before entering more deeply in the explanation of the Galileo user integrity concept and its potential applications for the maritime community the Galileo overbounding concept should be clarified. As stated in (Hernández, 2008), it can be defined in the following way:

Table 1. Galileo Overbounding definition.

The distribution of a random variable A is over-bounded by a distribution of a random variable B, if for all L≥0:
P(|A|≥L) ≤ P(|B|≥L) for all L≥0

This definition of the Galileo overbounding concept is quite similar to the CDF (Cumulative Density Function) overbounding definition stated by (DeCleene, 2000), although there are some differences as explained in (Hernández, 2008).

The objective of the IPF is to validate the navigation message of the satellites. The validation is based on IPF estimation of the SISE and its comparison with the broadcast SISA and the internally computed SISMA. According to the assumptions mentioned earlier, the IPF will assume that the estimated SISE is overbounded by a Gaussian unbiased distribution:

- True SISE overbounded by $N(0, SISA)$;
- SISE estimation error (True SISE minus Estimated SISE) overbounded by $N(0, SISMA)$;
- Estimated SISE overbounded by $N\left(0, \sqrt{SISA^2 + SISMA^2}\right)$;

Under these assumptions, the user considers that the threshold applied at IPF level in order to decide if a navigation message is valid or not is given by the variance of the distribution characterizing the estimated SISE, together with the required false alarm probability:

$$T = k_{pfa,u} \cdot \sqrt{SISA^2 + SISMA^2} \quad (1)$$

$$If \quad (Estimated\ SISE > T) \quad \Rightarrow \quad IF = Do\ not\ use \quad (2)$$

being $k_{pfa,u}$ the point of the normal distribution that leaves in the tails (two-tail problem) a probability equal to the specified false alarm rate. Thus, if the estimated SISE projected to the worst user location is higher than the allowed threshold, the satellite is flagged as "DO NOT USE" in order to indicate the user that its navigation message is not valid and the satellite should not be used for positioning.

The current specification of the IPF element envisages a maximum false alarm probability in the order of 10^{-7} in 15 seconds, which gives a $k_{pfa,u}$ factor approximately of 5.212. Considering that the required values for SISA and SISMA are 0.85 and 0.7 meters, respectively, in case no more barriers were implemented, the minimum detectable errors by the IPF would be in the order of 6 meters.

2.3 *User Integrity Risk Computation*

Galileo users will compute the Integrity Risk (IR), which is the probability of having Hazard Misleading Information (HMI). This will come out as a result of a combination of the horizontal and vertical errors, considering both the fault-free situation (FF) and the one where there is one failing satellite (1F). The case of multiple satellite failures is excluded from the user integrity risk computation since they are covered by other mechanisms established in the Galileo system Fault Tree Analysis (FTA). It is important to note that satellites with an IF set to "DO NOT USE" will be excluded from the user position and integrity computation.

The basic underlying assumptions allowing the user to determine the integrity risk of his position solution at any global location are:

– In a "Fault-Free-Mode" the true SISE for a satellite is overbounded by a zero-mean Gaussian distribution with a standard deviation equal to SISA;
– In general, the IPF will detect the faulty satellites and they will be flagged as "don't use";
– One satellite of those flagged as "OK" is considered to be faulty but not detected ("Failure Mode"). For this satellite the true SISE is overbounded by a Gaussian distribution whose mean is the "IPF rejection threshold" (T) and the standard deviation is equal to SISMA, $N(T, SISMA)$;
– The probability that more than one satellite at each instance in time is faulty but not detected is negligible for the user equation.

Therefore the computation of the integrity risk is as follows:

Table 2. Galileo Integrity Risk Computation.

IR =	Vertical_IR + Horizontal_IR = Vertical_IR_FF + Vertical_IR_1F + Horizontal_IR_FF + Horizontal_IR_1F

$$P_{HMI}\left(Error_v, Error_h\right) = P_{IntRisk,V} + P_{IntRisk,H} =$$
$$1 - erf\left(\frac{Error_v}{\sqrt{2}\cdot\sigma_{u,V,FF}}\right) + \exp\left(-\frac{Error_h^2}{2\cdot\xi_{FF}^2}\right) +$$
$$\frac{1}{2}\cdot\sum_{j=1}^{N} P_{fail,sat=j}\cdot\left(\left(1 - erf\left(\frac{Error_v + \mu_{u,V}}{\sqrt{2}\cdot\sigma_{u,V,FM}}\right)\right) + \left(1 - erf\left(\frac{Error_v - \mu_{u,V}}{\sqrt{2}\cdot\sigma_{u,V,FM}}\right)\right)\right) + \quad (3)$$
$$\sum_{j=1}^{N} P_{fail,sat=j}\cdot\left(1 - \chi^2_{2,\delta u,H}cdf\left(\frac{Error_h^2}{\xi_{FM}^2}\right)\right)$$

3 EXPECTED PERFORMANCE

The Galileo system will provide different services: the Open Service (OS) providing positioning and timing, the Commercial Service (CS) that will disseminate additional ranging information on a fee-based scheme, the Public Regulated Service (PRS) providing positioning, timing and integrity for restricted-access signals and the Safety of Life (SoL), which will provide integrity messages for the navigation data included in the OS signals.

As any other navigation system providing integrity, the SoL requirements can be expressed in terms of accuracy, availability, continuity and integrity. The following table summarises the main Galileo system requirements.

Table 3. Galileo OS/SoL system performance requirements (without considering the receiver contribution).

Parameter	Performance
Positioning accuracy (95%)	4 m horizontal; 8 m vertical
Integrity Risk	≤ 2.0e-7 in any 150 s
Continuity Risk	≤ 8.0e-6 in any 15 s
Availability of Service	100% nominal 99.5% degraded at WUL
Time To Alert	≤ 5.2 seconds
Horizontal Alert Limit (HAL)	12 m
Vertical Alert Limit (VAL)	20 m
Coverage	Worldwide

In order to be compliant with the currently specified requirements, the design of the Galileo system must take into account several critical aspects, which are usually called performance drivers. First of all, it needs to be clarified that the expected performance are similar to those of EGNOS, but with a global coverage instead of a regional one. Therefore the design of Galileo has been conditioned to a large extent for the compliance to the requested performance. Moreover, performance averaging over time or geographical location is not allowed, which brings additional constraints.

The performance allocation to the different components of the system has been a very complicated process (Oehler 2008). Extensive simulations and computations were requested to derive the current figures. The most relevant ones are presented hereafter.

Table 4. Galileo OS/SoL system performance allocation.

Parameter	Performance
Navigation Message ranging accuracy (67%)	65 cm
SISA (67%)	85 cm
SISMA	70 cm Nominal GSS network 130 cm Degraded GSS network
GSS network	40 sensor stations

In order to meet the availability and continuity requirements, it was required to consider not only the nominal configuration of the system but those degraded ones in which elements of the system were missing, giving degraded performance. This is the reason why the SISMA performance is specified with the nominal and degraded GSS networks.

After the detailed performance analysis and algorithm design, most of the performance figures are expected to be accomplished, although some areas need further work. For example, the ionospheric scintillations have been found to be one of the major threats affecting the performance, since they may imply a signal quality degradation and even signal loss, resulting in visibility gaps for certain satellites. This is also present at user level, and it can not be mitigated or compensated at system level, affecting also to DGNSS and SBAS. This threat is nevertheless location-dependent, since it affects the equatorial and high-latitude regions and they are sufficiently frequent so as to be considered as an intrinsic part of the environment, even in years of low solar activity. (Schlarmann, 2008) shows that the current assessment of the expected level of performance is in line with the requirements except for the conditions in which scintillations are present.

Another performance driver is the quality of the raw data provided by the Galileo Sensor Stations (GSS). Both the pseudorange and carrier phase measurements are requested by the algorithms in charge of computing the SISA and SISMA. Advanced filtering and data processing techniques are being used; however the level of multipath at sensor station level will be a critical factor for the achievement of the performance

4 POTENTIAL EVOLUTION AND APPLICABILITY TO MARINE NAVIGATION

In principle, there is an important aspect in the Galileo Integrity Concept compared with the operational user requirements established by IMO in its resolution for future Global Navigation Satellite System (IMO, 2001). IMO established the requirements for integrity based on the concepts of alert limits and integrity risk. While in principle they are the same concepts as those specified for Galileo, the implementation at system level is different from the one done in SBAS systems such as EGNOS and WAAS (RTCA, 2006). In SBAS, the user computes a Protection Level, defined as the region for which the missed alert probability requirement (or integrity risk) can be met, and compares it with the Alert Limit. In Galileo, the design is in the other way round, the user computes the integrity risk corresponding to the Alert limit and then compared with the maximum affordable limit. IMO's resolution does not preclude one implementation or the other, although it seems to follow a common approach with ICAO (International Civil Aviation Organisation), which introduced the concept of Protection Level in its SARPS (Standard And Recommended Practices for GNSS).

Another important difference is the definition of the Signal-In-Space in terms of the broadcast integrity information. SBAS systems rely on the UDRE (User Differential Range Error) for satellite differential correction residual errors, which is similar to the parameter with the same name introduced in DGNSS (IALA, 2004). However, in the case of Galileo the concept of differential correction no longer applies and the predicted accuracy of the broadcast navigation message is disseminated as the SISA, while the accuracy of the integrity monitoring system is also broadcast as the SISMA. SISA and SISMA (including the integrity alerts) play a similar role to the UDRE.

Although IMO has established operational requirements independently of the implementation of the integrity concept, at the end it will be forced to define a standard for the signal definition for future GNSS in the frame of the maritime policy as it did in the past with DGNSS. The situation is the same as for ICAO and the use of Galileo SoL (Safety of Life) service in the frame of the civil aviation community. Because of these reasons, an effort is currently being done in order to support the harmonisation of the Galileo integrity concept and the existing standards that may envisage some evolutions on this respect in the future.

However, a very important aspect of Galileo as a navigation system providing integrity is its worldwide coverage. With an accuracy in the same order of magnitude as DGNSS and SBAS, the advantage of providing seamless integrity performance over the world may bring a huge benefit in terms of a reduction in the investment in the implementation and maintenance of coastal DGNSS networks. Similarly the future plans for the third generation of GPS satellites include the provision of integrity. On this respect, an assessment done by IMO establishes that Galileo could be considered in the future for Oceanic, Coastal, Port approach and restricted water operations (IMO 2003).

Because of the importance of the provision of integrity in the future, both the European Space Agency (ESA) and GSA (GNSS Supervisory Authority) have launched several projects to analyse the potential evolution of the Galileo Integrity concept. A key factor in this process is the interoperability of Galileo at the level of integrity with other existing system, including SBAS. Some preliminary results on the application of the concept of "transparency" to Galileo can be found in (Catalán, 2008). Additionally, the conception of GNSS as a "system of systems" will probably have a significant role in the evolution of Galileo and its integrity concept. In 10 to 20 years, the most probable situation is that users will have at least four GNSS with open dual frequency signals, GPS, Galileo, GLONASS and COMPASS and more than 20 satellites always in view. With such level of redundancy, the level of performance that could be achieved by RAIM (Receiver Autonomous Integrity Monitoring) algorithms in terms of availability could be fully comparable to those already provided by SBAS or in the future by a standalone use of Galileo. Moreover, it has the clear advantage that includes FDE (Fault Detection and Exclusion) due to local effects (interference, multipath, etc.) that is neither present in DGNSS, SBAS or Galileo, combined with a Time To Alert (TTA) of just 1 second. This RAIM applied to the all the systems together could be even enhanced by the use of the integrity information broadcast by each system. Other options alternative to RAIM are also being investigated, such as the RANCO (Range Consensus) algorithm, see (Schroth 2008), in which several groups of 4 satellites are define in order to evaluate the pseudorange of the satellites that did not enter into the position solution. Based on the information coming from the different solutions some satellites are rejected. As it can be seen, there is a consensus that in the case of multiconstellation GNSS the hypothesis that the probability of a multiple satellite failure is negligible is no longer valid.

Therefore the situation would be that each individual system could work in a standalone mode, providing a certain service level in terms of integrity performance, but their combination would yield a better service level. For this, an effort in the satellite navigation community should be required to standardise the requirements for the different satellite navigation systems in terms of interoperability at the level of integrity.

5 CONCLUSIONS

The Galileo Integrity Concept has been presented, as it has been defined and including the required processing at user level. The major difference with respect to SBAS system specification is the substitution of the Protection Level by the Integrity Risk as the variable to be computed at user level. Because of the introduction of terms corresponding to a potential failure in one satellite, the concept can not be directly reversed into a Protection Level to be compared with an Alarm Limit. This implies a change at implementation level, which represents a deviation from the standard defined by ICAO for civil aviation and, in principle, could be adopted also by IMO. However, the system can be compliant with the high-level system requirements, providing a similar level of performance to those of SBAS and perhaps slightly worse to those of DGNSS, but with the great advantage of a global coverage and therefore no investment at local level.

Additionally, the integrity concept of GNSS will still evolve in the incoming years motivated by the appearance of new satellite navigation systems and the upgrade of the existing ones. GNSS will be conceived as a "System of Systems", each one providing service in a standalone mode and with improved performance when all combined together.

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