GALILEO
Integrity Performance Assessment Results And Recommendations

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BIOGRAPHIES

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ABSTRACT

Within the frame of the European Space Agency (ESA) project Galileo integrity performance assessment (GIPA, ESA contract no. 15393/01/NL/DS), integrity performance of the Galileo system has been analysed in detail. The opinions expressed in this paper are those of the authors and do not necessarily reflect the official views or policy of ESA.

Both, ground integrity channel (GIC) as well as user level performances have been investigated. Several critical issues related to Galileo system integrity performance have been identified and a set of ten use cases has been defined with each of the ten use cases tackling a different issue. Within these use cases not only the baseline Galileo integrity architecture but also alternative approaches have been considered. The main focus has been laid on algorithmic issues. Operational aspects like communication network or up-link issues have not been considered within this project.

Among the critical issues are the signal-in-space-accuracy (SISA) representation (scalar versus vector SISA), the SISA refresh rate, SISA checking margin assumption, integrity flag (IF) spatial concept, integrity monitoring station (IMS) network, IMS measurement quality, navigation signal, satellite orbit and clock and IMS clock error feared events as well as elevation masks at user and IMS level. The sensitivity of the integrity performance to these critical issues has been investigated partially by Monte-Carlo simulation, near end-to-end simulation, or analysis. Results with respect to false-alarm rate and missed-detection probabilities at GIC and user level as well as availability at user level have been obtained for the use cases.

The first part of the paper gives a brief introduction to integrity and integrity performance at GIC level

and user level. The basic situation is visualised and the functionality and performance of the Galileo integrity ground segment, the safe detection and isolation of satellite clock and orbit errors on the basis of the measurements taken at IMS, are characterised.

In the second part of the paper, the use cases and underlying assumptions are described. A user-equivalent-range-error (UERE) budget was adopted from Galileo phase B1. Orbit and clock errors were modelled according to the latest available early trials study results. A priori fault probabilities have been set to obtain statistical significant results in an efficient way and with not too high computational effort.

Results of the individual use cases are given in the third part of the paper together with a discussion and conclusions that could be drawn from the results.

In the last part of the paper recommendations are given with regard to different integrity architecture options. The main conclusion that could be derived is that under the environmental conditions that have been assumed in the simulations the current Galileo baseline integrity architecture seems to be well in line with current integrity performance expectations.

Among the main recommendations are:

- Use a scalar SISA value for broadcast. A vector SISA approach is only marginally better (in case of global integrity approach), but computational effort and transmission bandwidth are higher.
- The SISA refresh rate is not critical to the integrity checking performance at GIC level as far as a safe checking margin is provided on top of the real errors. However, there is a severe impact on receiver autonomous integrity monitoring (RAIM) availability at user level.
- As a spatial concept use a global integrity approach. The achievable performance will depend mainly on the density of monitoring stations in a certain region and the quality of the pre-processed measurements.
- Implement a depth-of-coverage (DOC) 4 network. While a DOC 3 network provides too less redundancy, the benefit of a DOC 5 network at ground segment level is only small, when systematic effects on measurements are low (not considering monitoring station faults).
- Choose an IMS elevation mask of 15°. A too low elevation mask will introduce too much systematic effects, while a too high elevation mask significantly reduces the number of available measurements.
- Choose a user elevation mask of 10°. For the user it is most important to have as much measurements as possible.

Finally, a note on caution is given as every simulation – as well as any experimenting with real data – has its limitations that have to be kept in mind to understand or extrapolate the results and conclusions. These limitations are briefly presented.

SCOPE OF THE STUDY

The main goal of the GIPA project is the analysis of the integrity architecture, performance and drivers from an algorithmic point of view. Operational aspects of the system, like integrity up-link issues or network failures are not considered here.

The results of the GIPA study are performance figures under special environmental conditions that have been chosen as a basis for the use case simulations. The performance figures are at ground segment integrity channel level (mainly probabilities of missed-detection and false-alarm) and at user level (availability as well as probabilities of missed-detection and false-alarm).

It must be noted that the performance figures cannot be directly compared with system and/or user level integrity requirements. The following figure shows the role of the GIPA project within the integrity performance determination.

The GIPA project goal is a sensitivity analysis of the ground segment (and user level) integrity algorithms with respect to certain critical key parameters. This goal should not be confused with a full reliability availability maintainability and safety (RAMS) analysis. This is the main reason, why no formal statement with regard to a system/user level integrity performance requirement can be given.

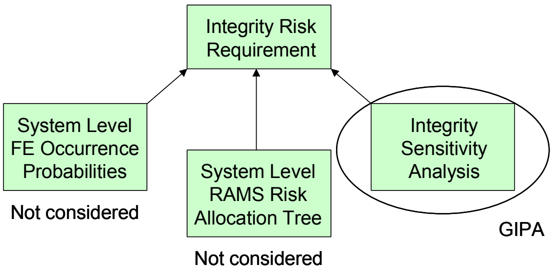

Figure 1: Scope of GIPA

A full list of feared events together with a priori probabilities of occurrence and a RAMS risk

Identifier	Description	Simulation Type
GUC-01-0	SISA Representation (Scalar or Vector)	Monte-Carlo
GUC-02-0	SISA Refresh Rate	Monte-Carlo
GUC-03-0	SISA Margin Assumption	Monte-Carlo
GUC-04-0	IF Spatial Concept (Global, Regional)	Monte-Carlo
GUC-05-0	IMS Network (Number/Location)	Monte-Carlo
GUC-06-0	IMS Measurement Quality	Monte-Carlo
GUC-07-0	Navigation Signal	Low-Level
GUC-08-0	Feared Events	Near End-To-End
GUC-09-0	Elevation Masking Angle at User	Monte-Carlo
GUC-10-0	Elevation Masking Angle at IMS	Monte-Carlo

Table 1: List of GIPA Use Cases

allocation tree were necessary to complete the full integrity performance picture. This, however, was out of scope of this project. The main focus of the project has been set on the integrity performance assessment. Model definition and tool development were only minor tasks in the project.

USE CASES

From earlier studies a set of critical integrity issues has been identified. This set of critical issues led to a set of ten use cases that are addressed within the GIPA project and is given in Table 1.

Each of the use cases contained several sub-cases, in which different aspects of the issue have been analysed. The sub-cases are not listed here.

The approach that is used within GIPA is to assess integrity algorithm sensitivity via simulations and analysis. No real data have been used. Three different types of approaches have been used: Monte-Carlo simulations, low-level simulations and near end-to-end simulations. The Monte-Carlo simulations were based on measurement errors assumed to be present on already pre-processed measurements, while in the near end-to-end simulations a full pre-processing chain has been implemented. Low-level simulations refer to receiver tracking-loop level simulations that realistically modelled the full signal structure.

The used RAIM parameters have been derived from the Galileo system requirements, which are specified in the GALILEO System Requirements Document (see GALILEO SRD (2001)), with respect to the safety-of-life services. In addition to this, the following baseline characteristics and environmental conditions have been used for the simulations:

- The used satellite constellation is a 27/3/1 Walker constellation with a circular orbit of radius 29993707.0 m and 56° inclination.
- A DOC4 ground station network has been used.
- In the fault-free case, the satellite orbit errors are modelled as white Gaussian noise, set to 0.08 m (one sigma) in each of the coordinate axes directions (x, y, z), and the model for the satellite clock errors is also white Gaussian noise, set to 0.24 ns (one sigma). Moreover, several use cases have been run with a satellite clock error of 2.0 ns (one sigma) and/or satellite orbit errors modelled differently in radial, along-track and cross-track directions (one sigma values: radial 0.14 m, along-track 0.5 m, cross-track 0.3 m).
- For the fault case (probability 10% in Monte-Carlo simulations), a white Gaussian orbit error of 10 m (one sigma) is applied to each of the position coordinates and/or a white Gaussian clock error of 10 m (= 0.00000003 s one sigma) is applied to the satellite clock.
- The SISA has been set to a fixed value of 0.93 m (one sigma) regarding the scalar broadcast SISA representation.
- A IMS elevation mask of 15° and a user elevation mask of 10° have been used.
- The used Galileo UERE budget is given in Table 2.

Elevation Angle [°]	UERE [m]
5.0	4.58
10.0	2.61
15.0	1.93
20.0	1.59
30.0	1.36
40.0	1.24
50.0	1.16
60.0	1.11
90.0	1.08

Table 2: Galileo UERE Budget

The feared events, which have been analysed in use case GUC-08-0, comprise specific satellite position errors, specific satellite clock errors and specific IMS clock errors. Each of these feared events has

Sub-Use-Case Identifier	Feared Event (Ramp-Type)
GUC-08-A	Satellite position error (radial; 5.0m/s)
GUC-08-B	Satellite position error (along-track; 5.0m/s)
GUC-08-C	Satellite position error (cross-track; 5.0m/s)
GUC-08-D-1	Satellite clock error (5.0 m/s)
GUC-08-D-2	Satellite clock error (1.0 m/s)
GUC-08-D-3	Satellite clock error (0.5 m/s)
GUC-08-D-4	Satellite clock error (0.1 m/s)
GUC-08-D-5	Satellite clock error (1.0 m/s; halved times: quiet time 25 s, ramp time 50 s, FE period 300 s)
GUC-08-D-6	Satellite clock error (1.0 m/s; DOC5 ground station network)
GUC-08-E-1	Ground station clock error (5.0 m/s)
GUC-08-E-2	Ground station clock error (0.5 m/s)

Table 3: GUC-08-0 sub-cases and feared events

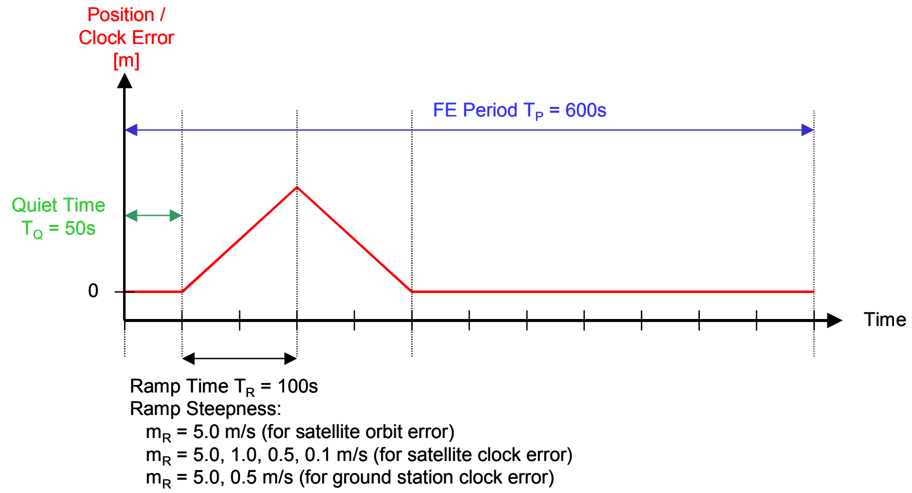

Figure 2: Feared event characteristics used in use case GUC-08-0

been investigated in a separate sub-case of use case GUC-08-0 as shown in Table 3 where these specific errors are modelled as linear functions of the time (i.e. as ramp functions with specified slopes). The characteristics of these feared event (FE) ramps are given in Figure 2.

INTEGRITY MODELS

The task of the ground segment integrity system is to validate the correctness of the signal-in-space-accuracy (SISA) value transmitted for each satellite. The SISA is a value that should cover the satellite orbit and clock errors that are experienced by the users. Figure 3 shows the basic situation.

The ground segment integrity algorithms are based on the measurements taken by a integrity monitoring station (IMS) network. The approach chosen here is similar to the approach chosen for the European Geostationary Navigation Overlay Service (EGNOS) Independent Check Set. The residual orbit and clock error bias curve is approximated and estimated as a first order surface (plane).

Ground segment integrity check algorithms have been developed for:

- Regional integrity check (latitude/longitude plane estimation)
- Regional integrity check (tangential plane estimation)
- Global integrity check (tangential plane estimation)
- Scalar and vector SISA algorithms (based on OSPF orbit and clock covariance matrix)

The regional integrity check algorithm (based on latitude/longitude plane estimation) has its roots in the EGNOS Check Set algorithm development. In its application for Galileo, the boundaries of the algorithm have been made variable. This way, the algorithm can be applied to different service regions.

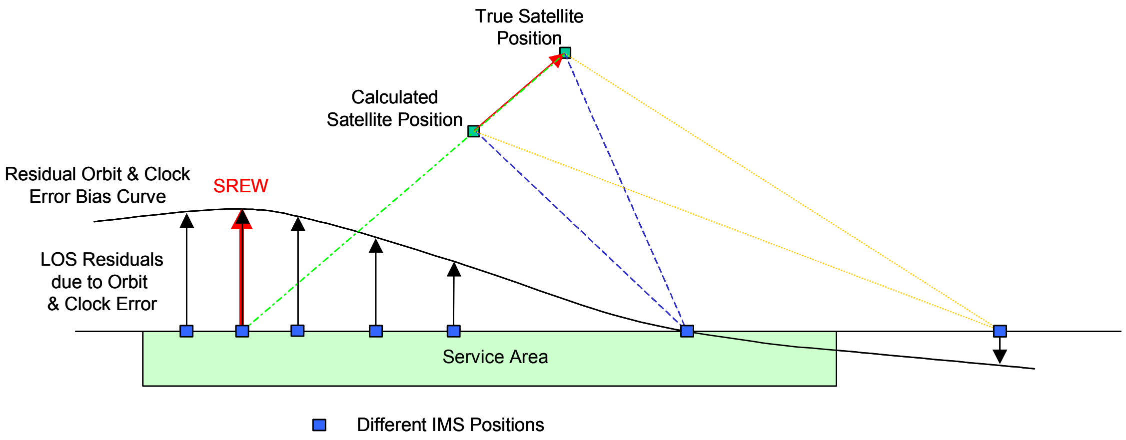

Figure 3: Satellite clock and orbit error as experienced by the user

A generalisation of the regional integrity check algorithm (latitude/longitude) has been developed, that is independent of latitude/longitude coordinates. In this approach a tangential plane in the satellite foot-point is defined and the bias plane is estimated above this basis.

The same generalised algorithm that is used in case of regional integrity can also be used in the global integrity case. As there are no regional boundaries, a slightly different approach in the evaluation of the estimated bias plane is taken in case of a scalar SISA. The detailed algorithm can be found e.g. in Werner et al. (2001).

In case of a scalar broadcast SISA, the signal in space error at the worst user location (SREW) is computed and compared against the broadcast SISA value. In the vector SISA case, the orbitography and synchronisation processing facility (OSPF) transmits the satellite orbit and clock covariance matrix to the user. The broadcast SISA is then dependent on the user location. In this case, the service area is sampled and the estimated signal-in-space-error at each location is compared to the SISA valid at the same location.

At user level, the RAIM algorithm of Brenner (1990) has been used.

SCALAR VS. VECTOR SISA - WORST USER LOCATIONS

During analysis of the vector SISA case, the classical worst-user location appeared in a new light.

Up to now, in the scalar SISA case, there was one worst-user location and this was related to the worst-case SISE (called SREW, satellite residual error at worst-user location). This location was the location, where the estimated SISE was worst, and in addition, where the highest integrity risk was present.

Considering the vector SISA case, things are different. Again, there is a worst-user location, which still resembles the user with worst SISE. However, due to the spatial dependency of the broadcast SISA, the user at the worst-user location could be very well protected by the broadcast SISA, whereas another user, e.g. a user with much lower SISE, could be unprotected by the broadcast SISA. An illustration of the situation is given in Figure 4a, b.

This lead to a re-definition of the worst-user terminus, because we now have two different worst-user situations. We call these two now the *accuracy worst-user location* and the *integrity worst-user location*:

1. *Accuracy worst-user location:* We call the user with the highest SISE the accuracy worst-user. The accuracy worst user is the same in both scalar and vector SISA cases, because the SISE (or the estimated SISE) is independent of the broadcast SISA.

2. *Integrity worst-user location:* This worst-user location has been defined anew. It is the location, where the test statistic (which is the difference of the estimated SISE and the k-factored SISA) is worst. Note, that this means, that this is the user location, with the highest integrity/continuity risk. Note also, that an alarm could be raised by the vector SISA integrity module because of a detected underbound of the SISA in a certain area, although there might be no need for raising an alarm in the accuracy worst-user location.

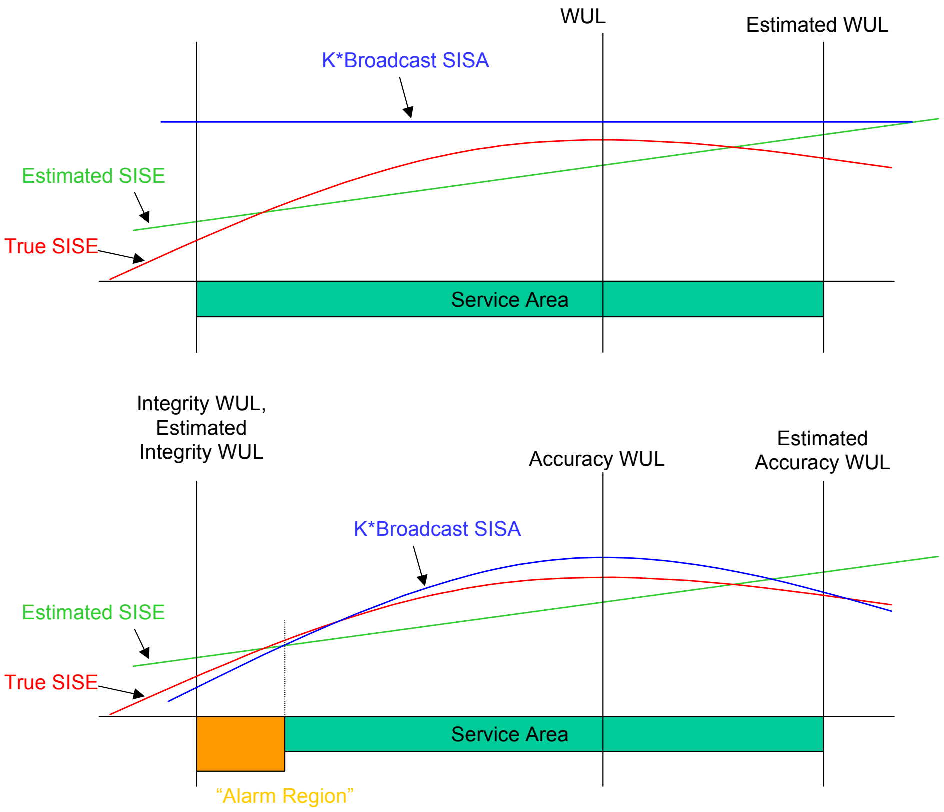

Figure 4a, b: Scalar SISA case: one worst-user location (top), Vector SISA case: two worst-user locations (bottom)

In case of scalar SISA the integrity worst-user location is identical to the accuracy worst-user location. A difference in both locations can appear only in the case that spatial varying SISA values are broadcast. This will, e.g., also be the case for message type 27 (service regions message) in EGNOS (see e.g. RTCA (1999)).

SOFTWARE TOOL DEVELOPMENT

The GIPA tool is a modular tool that allows flexible linking of different algorithmic models. Its architecture is shown in Figure 5.

The GIPA kernel is the heart of the simulator. Its task is to provide a hosting structure for the algorithmic models. Each module has a certain module syntax, describing its input and output data.

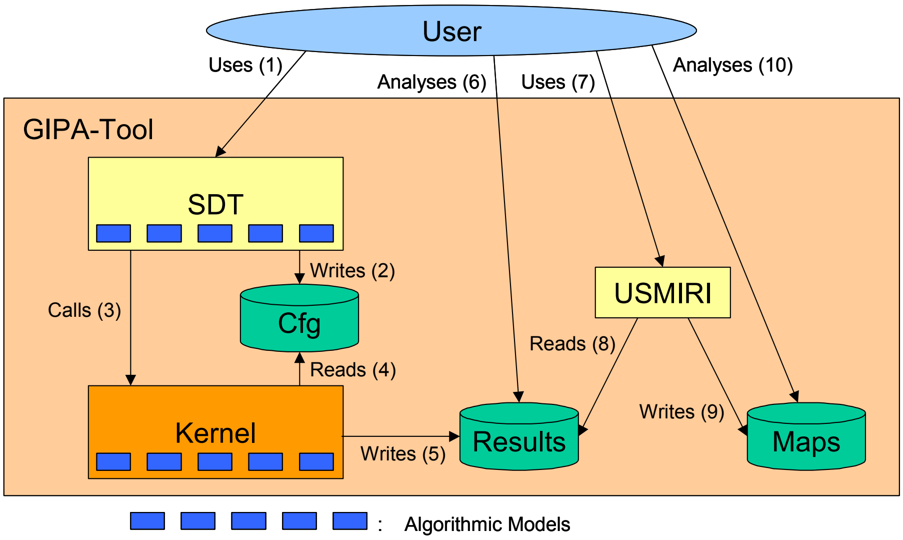

Figure 5: GIPA Tool Architecture

For this reason, a set of standard data types is available specifically dedicated to satellite navigation purposes. The algorithmic models are generated and linked according to the given configuration and scheduled accordingly. The kernel is implemented platform-independently and can be run in batch mode.

The GIPA scenario definition tool (SDT) is a graphical user interface (currently implemented under Windows NT/2000), allowing to configure the GIPA kernel quickly. Algorithmic models can be linked together simply by a few mouse-clicks. The created scenario can be stored as a special "sdt"-file and can easily be exported to a configuration file that is readable by the kernel.

The GIPA user segment module integrity results illustrator (USMIRI) allows generating maps from the data that have been produced by the kernel. The tool is dedicated to illustrating user level performance data such as availability, probabilities of missed-detection and false alarm. The tool is implemented in C++ under Windows 2000.

INTEGRITY PERFORMANCE ASSESSMENT

All of the ten use cases have been executed and the performance results evaluated. In Figure 6 some results at GIC level regarding use cases GUC-05-0 and GUC-06-0 are presented as an example. This figure shows the evolution of the probability figures over a 24 h simulation. The impact of the noise of the pre-processed measurements can be seen clearly.

The accuracy of the SREW estimation has also been analyzed. The estimated SREW values have been compared to the true SREW values and histograms have been plotted over the differences for a DOC3, DOC4, DOC5 and DOCX ground station network (17, 21, 25 and 363 stations, respectively). The results can be seen in Figure 7.

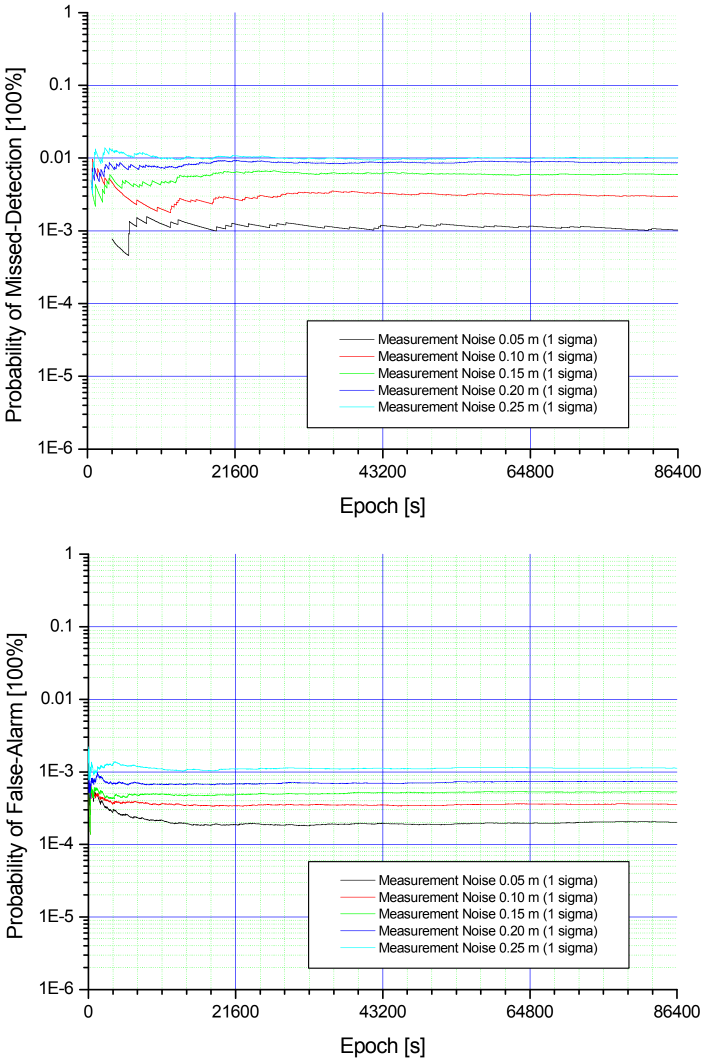

Figure 6: Ground segment performance in terms of missed-detection (top) and false-alarm (bottom) for a DOC4 IMS network

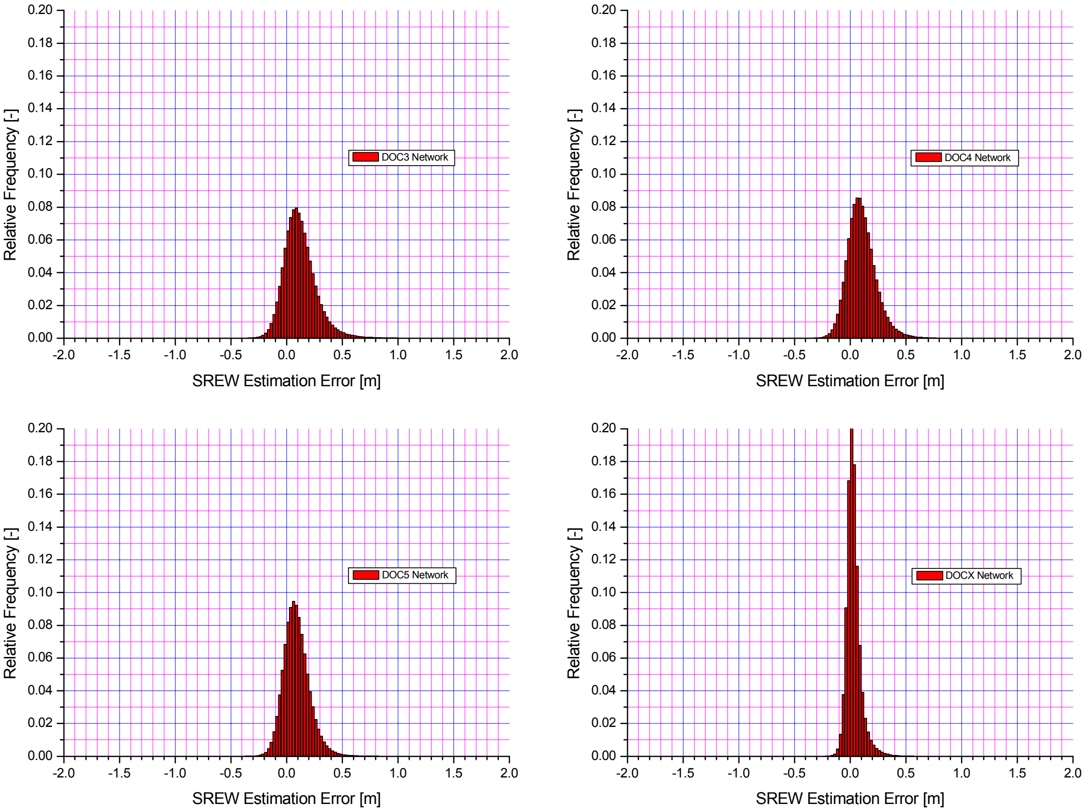

Figure 7: Accuracy of SREW estimation for a DOC3 (top left), DOC4 (top right), DOC5 (bottom left) and DOCX (bottom right) IMS network

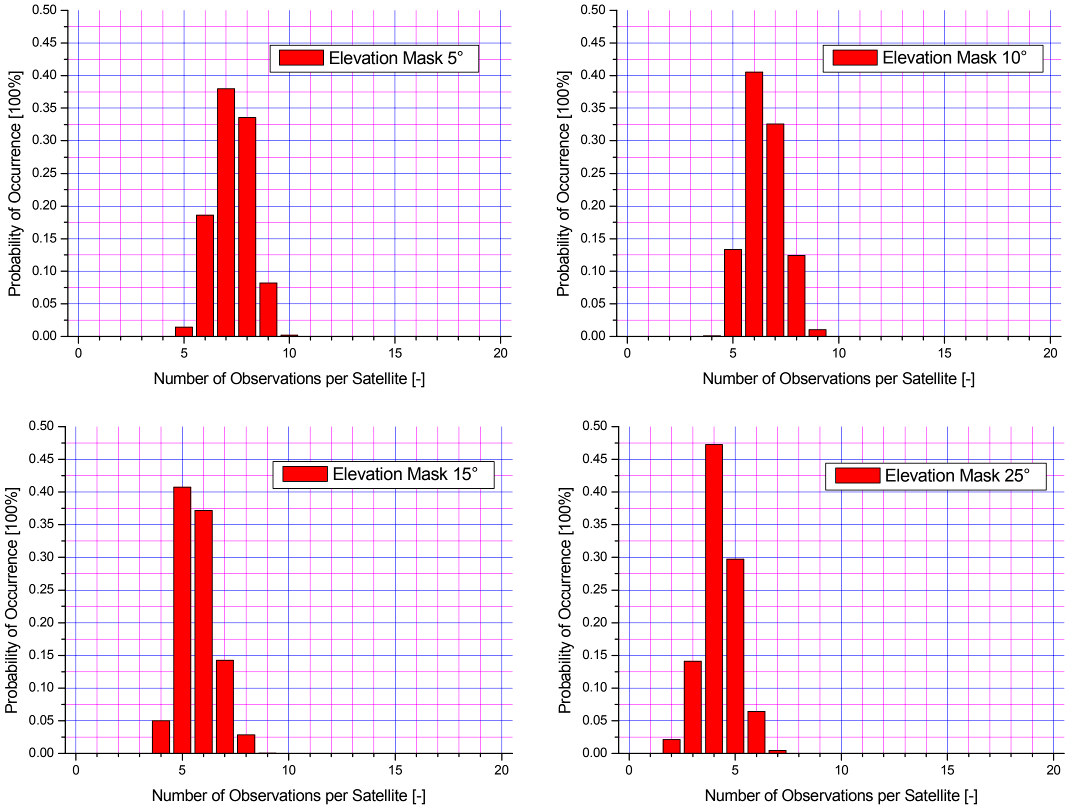

Figure 8: DOC for a DOC4 IMS network regarding different IMS elevation masks

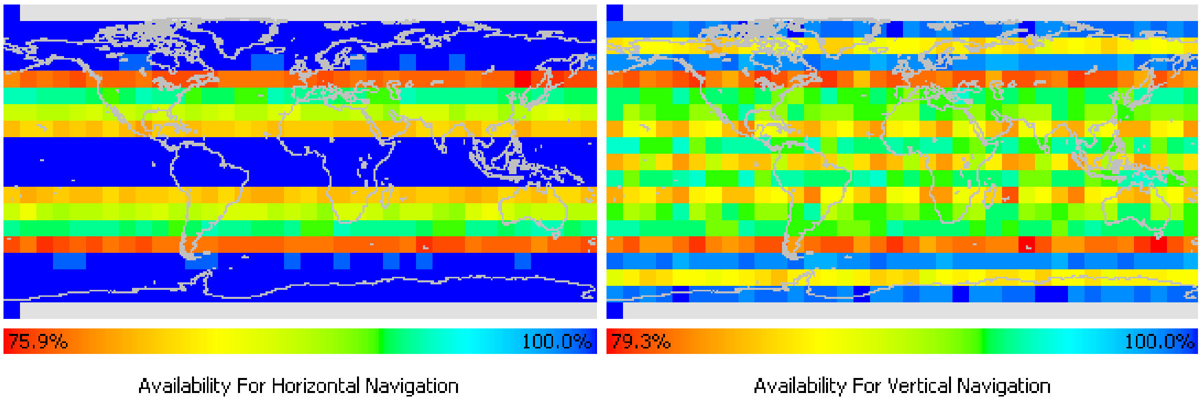

Figure 9: Nominal RAIM availability at user level; fault-free case; application of GIC integrity flags by users

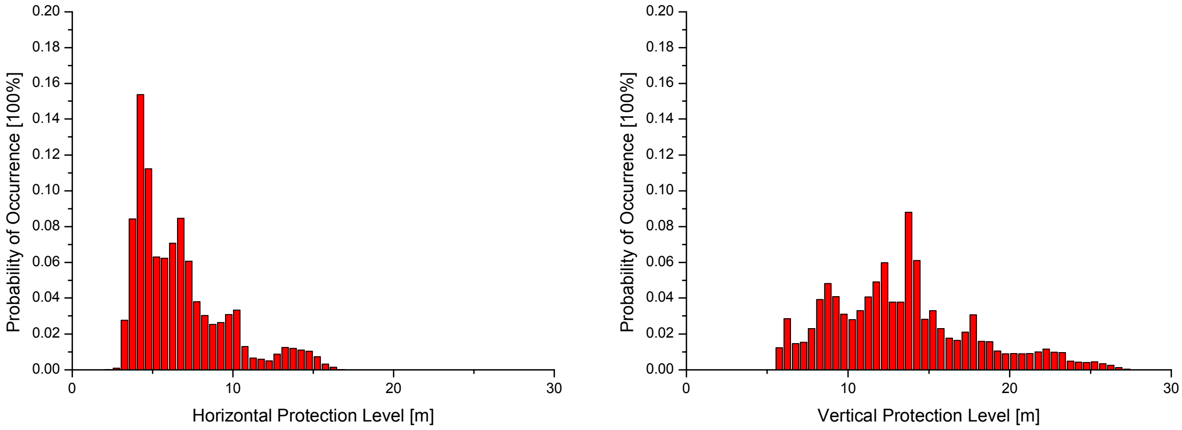

Figure 10: Nominal RAIM protection level for horizontal navigation (left) and vertical navigation (right); fault-free case; application of GIC integrity flags by users

For a DOC4 ground station network, DOC (i.e. number of simultaneous observations per satellite) histograms are shown in Figure 8 with respect to four different IMS elevation masks. As can be seen from this figure, the number of simultaneous observations per satellite decreases with an increasing IMS elevation mask.

As an example for the results at user level, Figure 9 shows the results of the performed simulation with respect to the nominal RAIM availability at user level for the fault-free case in a spatial representation regarding a specified grid. Note that the users applied the GIC integrity flags (i.e. satellites with GIC integrity flags set to “Not Monitored” or to “Don't Use” were not used by the users) in this simulation.

The colour code for each simulation results picture is under the corresponding simulation results picture and has a linear range where the lower limit of the colour code range is on the left side of the concerning colour code and the upper limit of the colour code range is on the right side of the concerning colour code. It must be noted that a grid point is represented by grey colour when this grid point did not lie within the investigated region. The spatial dependency of the nominal RAIM availability at user level can be seen immediately from this figure. In addition to this, Figure 10 shows the nominal RAIM protection level histograms, which were also obtained by this nominal RAIM availability simulation, for horizontal navigation as well as for vertical navigation.

CONCLUSIOINS

This chapter tries to draw some conclusions based on the results obtained during the project. The maturity of the statements given here of course depends strongly on the environmental conditions that have been assumed in the simulations. For this reason all conclusions drawn here have to be considered under the limitation that no real data have been used and, thus, no realistic error characteristics could be used. Of course, the simulator has been configured to model all effects as realistic as possible within the scope of this work.

The following main conclusions with respect to integrity performance assessment may be drawn from this project:

1. **SISA representation (scalar/vector):** A slight improvement of integrity performance can be obtained by making use of the vector SISA representation. This improvement, however, is only small and will be biggest for the global integrity case. Considering the cost in computations and transmission bandwidth, our proposal therefore is to stick with the scalar SISA approach in the global integrity case also.

2. **SISA update rate:** From the integrity-checking point of view, the SISA update rate is not critical with respect to GIC level. The important issue here is just, that there is enough margin between expected orbit and clock errors on the one hand and the broadcast SISA on the other hand. Our proposal here is, that, if a long SISA update rate (several minutes) is used, then a timely varying SISA scheme should also be used to account for increasing orbit and clock error effects, while making use of the good orbit and clock estimation quality at the beginning of the update interval. If a short SISA update rate is used (several seconds only), then a graduated SISA approach like UDRE in EGNOS or WAAS could be envisaged. It must be noted that the availability at user level decreases with an increasing SISA so that the SISA update time interval should not be extremely long.

3. **SISA margin:** The current SISA margin assumption (30%) that is put on top of the orbit determination and time synchronisation (OD&TS) UERE budget of 72 cm to allow for instantaneous integrity checking suffices to reach a good performance assuming orbit and clock error expectations as assessed by the latest early trials studies. It seems that this margin is well chosen and our proposal is to keep it to keep the false alarm probability at ground segment level low.

4. **IF spatial concept (global, regional):** A global integrity approach seems feasible. The current baseline integrity determination algorithm will perform according to the density of ground monitoring stations and measurement quality. Individual parameter tuning for different sizes of service areas is proposed for the regional case.

5. **IMS network:** Results have shown that a DOC4 network seems to be sufficient from ground segment integrity point of view. A DOC3 network sometimes does not provide the necessary redundancy to reduce measurement errors. A DOC5 network improves the performance significantly only in case of bad measurement quality or irregular atmospheric effects. Under the environmental conditions that have been used in the simulations, the results support the statement that a DOC4 network will be sufficient from integrity point of view. Our proposal therefore is to implement a DOC4 network for Galileo. Note, however, that a decrease of performance must be taken into account, when monitoring station failures are present. Furthermore, note that the statistical behaviour of real data and measurements is not known yet, and that the validity of this proposal depends on the applicability and appropriateness of all error models that model systematic measurement biases like ionosphere and troposphere model.

6. **IMS measurement quality:** Code range measurement noise is not of high importance to the integrity processing, as the measurements will be carrier-phase smoothed. The most important point here is that the systematic model errors of tropospheric and ionospheric model are small. The level of systematic model errors has to be verified and quantified with real data field experimentation.

7. **Navigation signal:** The navigation signal structure choice is not critical for the ground segment integrity performance, when a reasonable tracking behaviour of the receivers can be assumed (i.e. no evil wave-forms etc.). The code and carrier phase noise at reasonable signal power levels are within the limits of what has been assumed in the simulations. There will be a small impact on performance with regard to the ionospheric residual delays, as these are dependent on the frequency spacing of the signal, but this is only a minor effect (that also has to be validated when the first real Galileo signal generators are available). As there is no major effect on integrity, there is no recommendation on this point.

8. **Feared events:** The performance results are strongly dependent on the a priori probability mass that produces situations, where the SREW is in the range of the misleading information definition. While bigger errors can quite easily (and correctly) be detected, small errors lead to spoiling the false alarm (when they are below the misleading information definition

threshold) and the missed-detection probability (when they are just above the misleading information definition). The result obtained showed a missed detection of about 10^{-3} and a slightly better false alarm. As there is some tuning potential between these both probabilities, and as only small violations of the misleading information definition are not so severe to the user, a differentiated budgeting of the missed detection risk is proposed. Our proposal is to split the misleading information definition in two or three parts (e.g. small violations, medium violation, large violation) and to require a certain missed-detection probability at these levels. It will then be a Galileo system level issue to provide appropriate a priori probabilities for the occurrence of these events.

9. **User elevation mask:** The impact of the user elevation mask on ground segment integrity performance (via service area size) is only small. The main impact of course is the number of measurements available for user RAIM. According to the results obtained from the simulations for this use case, our proposal is to use a 10° user elevation mask.

10. **Monitoring station elevation mask:** The ground segment integrity performance turned up similar in all three cases that have been analysed (elevation mask 10°, 15° and 25°). The false alarm probability was somewhat higher for lower elevation masks, due to bigger biases on the measurements (due to atmospheric effects). Taking into account that this result is valid only for the assumed environmental conditions of use case GUC-10-0, our proposal is to set the ground monitoring station elevation mask to 15°.

ACKNOWLEDGEMENTS

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REFERENCES

Brenner, M. (1990). *Implementation of a RAIM Monitor in a GPS Receiver and an Integrated GPS/IRS*, Proceedings of The Third International Technical Meeting of The Satellite Division of The Institute of Navigation, ION GPS-90, Colorado Springs, CO, September 19-21, 1990, pp. 397-406.

GALILEO SRD (2001). *GALILEO System Requirements Document*, Document Reference No.: ESA-APPNS-REQ-00011, Issue No.: 1, June 27, 2001.

RTCA (1999). *Minimum Operational Performance Standards For Global Positioning System/Wide Area Augmentation System Airborne Equipment*, RTCA Document No.: RTCA/DO-229B, Prepared by RTCA Special Committee 159 (RTCA SC-159), RTCA, Inc., Washington, D.C., October 6, 1999.

Werner, W.; Zink, T.; Löhnert, E.; Pielmeier, J. (2001). *GALILEO Integrity Performance Assessment (GIPA)*, Proceedings of the 14th International Technical Meeting of the Satellite Division of The Institute of Navigation, ION GPS 2001, Salt Lake City, Utah, September 11-14, 2001, pp. 1838-1849.