Interoperability Test Analysis between EGNOS and MSAS SBAS Systems

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Abstract:

Europe, US/Canada and Japan are currently developing their own regional Satellite Based Augmentation Systems (SBAS). Although all SBAS are regional systems, it is recognised the necessity to establish adequate ways for co-operation and co-ordination among the different SBAS providers, in order to provide SBAS interoperability, and, in turn, produce a more effective implementation and a part of a seamless world-wide navigation system.

Although interoperability implies a large variety of complex issues (such as certification, standards, safety, operations,...), in this paper we discuss only technical interoperability options. In particular, an assessment on interoperability options between EGNOS and MSAS SBAS systems will be presented. A quite complete interoperability test activity has been defined between EGNOS and MSAS service providers. In particular, real data has been simultaneously collected from: the reference stations of the EGNOS System Test Bed (ESTB), the Japanese ENRI GNSS Test System, real commercial flights equipped with SAPPHIRE receivers [9] and IGS stations. Using this real data a post-processing analysis (matched to all conceived scenarios) has been performed using the EGNOS Early Test System (ETS) platform which includes prototypes of the EGNOS Central Processing Facility (CPF) algorithms and EGNOS receiver. In parallel, these scenarios have been evaluated considering simulated data. The main objectives of these tests are to propose recommendations for the design of SBAS systems and the evaluation of performances in the interoperability area. It is shown that with simple interoperability implementation scenarios, Non-Precision Approach service level (with sole means availability) could be provided at the intermediate region between EGNOS and MSAS.

1 - INTRODUCTION

There are three different Satellite Based Augmentation Systems (SBAS) are currently under development:

- In Europe, the European tripartite Group (ETG, composed of the European Union, the European Space Agency and Eurocontrol) is in the process of developing the European Geostationary Navigation Overlay Service (EGNOS). EGNOS will cover the European Civil Aviation Conference (ECAC) region;

- In the US, the Federal Aviation Administration (FAA) leads the development of the Wide Area Augmentation System (WAAS), covering essentially continental US (CONUS) area and Canada (Canadian WAAS – CWAAS);

- In Japan, the Japanese Civil Aviation Bureau is implementing the MTSAT Satellite Based Augmentation System (MSAS), which shall cover the Flight Instrumental Region (FIR) associated to Japan.

Although all SBAS are regional systems, it is commonly recognised the need to establish adequate co-operation/co-ordination among SBAS providers so that their implementation becomes more effective and part of a seamless world-wide navigation system. SBAS co-operation is currently co-ordinated through the so-called Interoperability Working Groups (IWG). Although interoperability implies a large variety of complex issues (such as certification, standards, safety, operations,…), EGNOS, WAAS, CWAAS and MSAS SBAS providers have agreed on the following list of objectives concerning technical interoperability and co-operation among SBAS (see [2] and [8]):

Objective 1: Validate SBAS performance and SIS (Signal in Space) consistency;

Objective 2: Define/assess the service level available in intermediate regions between SBAS;

Objective 3: Improve individual system performance though SBAS data interchange;

Objective 4: Improve SBAS prediction capability though SBAS data interchange;

Objective 5: Identify possible future improvements.

In this paper, we will discuss the interoperability objective 2. Some related conceivable technical scenarios are presented, together with their implications on the SBAS and users. A preliminary assessment of these scenarios for the EGNOS-MSAS interoperability case is shown.

2- OBJECTIVE 2: DEFINE/ASSESS LEVEL OF SERVICE IN INTERMEDIATE REGIONS

Although SBAS providers guarantee only adequate service provision in their nominal service volumes, SBAS broadcast signals will be available anywhere in their respective GEO footprints. In the case of EGNOS, for instance, the EGNOS message will be broadcast through Inmarsat AOR-E , Inmarsat IOR and ESA's Artemis satellite [10], whose footprints cover together half of the globe. This fact, together with the fact that EGNOS/MSAS/WAAS intermediate regions are not covered by any other SBAS system, originates the debate about the possibility of providing a minimum service level in the intermediate region by means of SBAS interoperability.

Several scenarios may be conceived to meet this objective. These are briefly discussed in the next paragraphs where, for the sake of generality, we will talk about interoperability between SBAS-A and SBAS-B, and where we will consider that the minimum desirable service level is Non Precision Approach (NPA). Each interoperability scenario allows different technical solutions for the system implementation which are also discussed. A major issue for all the investigated scenarios is how to guarantee the service integrity out of the nominal service volume. An analysis of the potential concepts to cope with it and their implications in the SBAS systems is presented after the scenarios.

2.1 - Scenario 2.1: SBAS-A provides integrity for the visible GEO satellites of SBAS-B

In this scenario, SBAS-A provides in the broadcast signal integrity (and corrections) for SBAS-B GEO satellites which are visible to the SBAS-A monitoring network. This increases the number of monitored satellites in the intermediate region, which, in turn, may increase the NPA service availability.

Considering today's EGNOS baseline design, the system is dimensioned to consider the monitoring of up to 8 GEOs, including non-EGNOS GEOs. Thus, we may consider that this interoperability scenario is feasible if current EGNOS stations deployment is enough to monitor that non-EGNOS GEOs. For this reason and due to some limitations of the algorithm generation platform, Scenario 2.1 has not been implemented.

2.2 - Scenario 2.2: Airborne receiver has access to all monitored satellites from SBAS-A and SBAS-B

This scenario assumes that the integrity information on the GPS satellites generated by SBAS-A and SBAS-B may simultaneously be accessed by the avionics at the intermediate region. In order to determine the navigation solution in this case, the receiver may use simultaneously GPS satellites that are monitored by SBAS-A and GPS satellites that are monitored by SBAS-B. Two technical issues need to be consolidated:

1. The criteria for the selection of corrections for those satellites which are simultaneously monitored by both SBAS.
2. The effect of different SBAS reference time for satellite clock corrections, which may degrade user's performance.

For the *first issue* , three different approaches have been considered:

1. Maximise the maximum number of satellites monitored by the same SBAS;
2. Maximise the minimum number of satellites monitored by the same SBAS;
3. Select the SBAS providing the minimum UDRE.

For the *second issue* (time offset between SBAS), two approaches have been analysed:

1. Time offset is not estimated. In this case, standard navigation algorithm (four unknowns: user's location and receiver clock bias) is considered;
2. Time offset is estimated. In consequence, navigation algorithm is modified in order to estimate five unknowns: user's location, receiver clock bias w.r.t. SBAS-A and the time offset between SBAS-A and SBAS-B.

In the second approach, GPS measurement equation presented in the Appendix E of MOPS [3] has been modified (see [11] for details.)

2.3 - Scenario 2.3: Airborne receiver has access to all monitored satellites from SBAS-A and SBAS-B through a single SIS

The concept behind this scenario is similar to the previous one, but the implementation is completely different: SBAS master stations do provide to each other the relevant information, which is introduced in each SBAS message independently. For instance SBAS-B master station sends to SBAS-A master station corrections and integrity information on GPS satellites which are not visible to SBAS-A. SBAS-A then considers this information in the generation of its navigation signal (adding the integrity information on those non-visible satellites).

As it happens in the scenario 2.2, it is required to decide if the time offset between SBAS is going to be estimated or not.

For this scenario, the following approaches have been analysed:

1. Time offset is not estimated. This case is similar (from performance point of view) to the one analysed in scenario 2.2.

2. The ground segment estimates time offset. Once this offset has been estimated, the broadcast clock information is corrected in the ground segment to eliminate this term. In consequence, from user's point of view, all the satellites are similar and standard navigation algorithm is considered.

2.4 - Scenario 2.4: Installing own reference stations by each SBAS provider and providing dual service.

In this case, SBAS-A and SBAS-B systems implement some additional reference stations (in adequate sites) in such a way that both SBAS provide service in the intermediate SBAS region independently. The interoperability, in this case, may consist only in the provision of service redundancy, allowing the user to jump to the alternate SBAS signal in case of continuity problems with the current SBAS signal in use. Regarding this scenario, two issues need to be consolidated:

1. The location of the additional monitoring stations. They can be co-located with stations belonging to the other SBAS (in order to reduce cost as e.g. common security, maintenance, surveying, etc.), or not (in order to optimise performance through an adequate deployment).

2. The management of the two possible solutions, e.g. the criteria for switching from one solution to the other or the use of one solution to monitor the other.

The tests have been performed considering four additional stations per SBAS. In real data analysis, only co-located case has been analysed. In the simulated data analysis, three different cases have been considered: four co-located stations, three co-located plus a new one and two co-located plus two new ones.

For the management of the two possible solutions, it is proposed to compute both simultaneously and then:

- If only one solution is available (HPL < HAL), this solution is selected.
- If both solutions are available, two approaches are considered:

    1. Select the same solution than in the previous epoch;
    2. Cross-check both solutions, i.e. check the coherence between the estimated user's locations and the associated protection levels. This technique could improve integrity but decreasing availability.

2.5 - Extending integrity data outside SBAS nominal service volumes (UDRE out of zone degradation)

Any of the scenarios linked to Objective 2 assumes that the integrity information provided by the SBAS is available in a larger area than the nominal service volume definition. In the extreme, we may assume that the integrity information should be valid anywhere in the GEOs footprint associated to a given SBAS. Assuming again that Objective 2 interoperability is limited to the provision of En-route to NPA service, the issue is then linked to: 1) the validity of the UDRE bounds (validity of satellites corrections integrity) in that extended area and more importantly 2) the validity of the Horizontal Protection Level (HPL) (validity of the user navigation integrity). Related to that, several options may be considered:

Option 1: UDRE is computed considering not only the target service area but also the whole GEO footprint or the interoperability area, i.e. SBAS requirements are modified so that UDRE bounds are valid everywhere within footprints.

Option 2: Formally demonstrate that keeping UDRE values (as determined for the nominal service volumes) the worst-case error in the GEO footprints is always small relative to the allowances included in the HPL equation associated to NPA (these allowances are essentially to account for possible ionospheric errors).

Option 3: Apply a degradation factor for En-route to NPA to account for the possible UDRE degradation. Ideally, this degradation factor shall be applied outside the SBAS nominal service volume (not to impact PA) and should have no availability impact. This factor could be applied by the receiver without the need to be transmitted in the SBAS message. Alternatively, the factor could be included in the SBAS SIS (e.g. an adaptation of the former MOPS message 27 has currently been proposed for that).

3 - ASSESSMENT OF THE INTEROPERABILITY SCENARIOS ASSOCIATED TO THE OBJECTIVE 2

In order to assess the interoperability scenarios, they have been implemented in the EGNOS Early Test System (ETS) platform [1]. The ETS is a functional end-to-end EGNOS prototype that implements major EGNOS functions, paying special attention to the different algorithms that will be implemented in the Central Processing Facility (CPF) of EGNOS. Two different analyses have been carried out, one based on real data and the other based on simulated data.

3.1- Real data analysis

SBAS ground segment data has been provided by EGNOS and MSAS test beds: EGNOS System Test Bed ESTB [4] and ENRI GNSS Test System respectively. Data analysed corresponds to the day 15th of February 1999. This data has been processed in the ETS facility, in order to generate the emulated SIS for EGNOS and MSAS for the different interoperability scenarios. Figure 1 shows the location of the stations considered in the analysis: five of them correspond to EGNOS and the other five to MSAS. For the user segment, fourteen IGS stations located in the interoperability area have been considered (Figure 2).

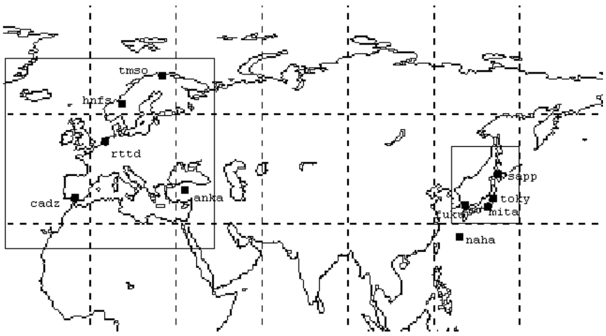

Fig. 1. EGNOS & MSAS ground segment for real data

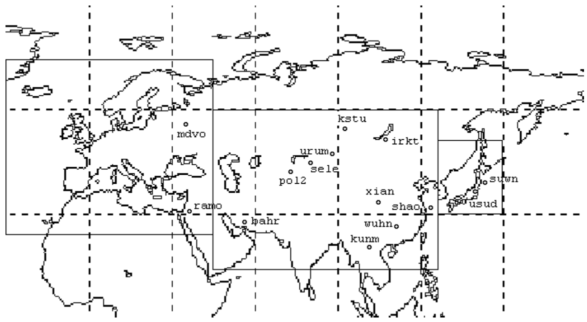

Fig. 2. IGS stations for real data analysis.

3.2 - Simulated data analysis

The second assessment of the interoperability scenarios has been performed considering simulated data. EGNOS and MSAS ground segments (Figures 3 and 4) and user segment have been realistically simulated. Simulation tool considered is the EGNOS End-to-end Simulator (EETES) [5].

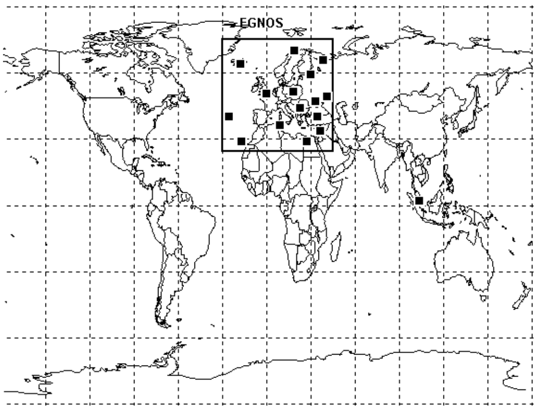

Fig. 3. EGNOS Ground Segment for simulated data

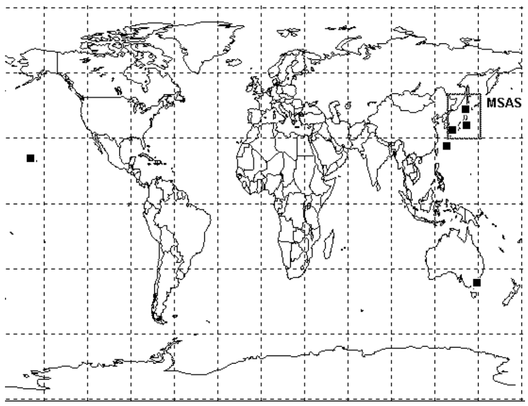

Fig. 4. MSAS ground segment for simulated data analysis.

3.3 – Real and simulated flight data collection

In order to support ESA in their activity to investigate EGNOS/MSAS interoperability, EUROCONTROL provided representative flight trajectories between European and Asian cities through their flight trial project SAPPHIRE (Satellite & Aircraft Database Project for System Integrity Research [9]). SAPPHIRE's goal is to develop a statistically representative database of Global Navigation Satellite System (GNSS) and other navigation sensor measurements to investigate system integrity, availability and continuity of service aspects in order to contribute to the GNSS safety regulation process. In order to achieve this, dedicated SAPPHIRE equipment is being installed on commercial aircraft to record GNSS and other sensor data. At the time of writing, a Lufthansa A340-300 and a British Airways B747-400 have been accordingly equipped and some of the recorded data covers flights between Europe and Asia. In particular, to support this interoperability activity GPS data collected from three commercial flights was used. In addition, 10 representative flight path between major European and Asian cities were simulated to support also the simulation analysis. Table 1 provides some information on both the real and simulated flight paths considered.

No	Description of Flights	Take Off	Flight-Duration
1.	LH A340 Frankfurt – Seoul	Week 7	10h 29' 58"
2.	LH A340 Seoul – Frankfurt	Week 7	11h 51' 54"
3.	BA B747 Singapore– Heathrow	Week 7	14h 19' 14"
4.	Paris CDG – Tokyo (Narita)	14/02/99 00:00	10h 30' 58"
5.	Tokyo (Narita) – Paris CDG	14/02/99 12:00	10h 30' 58"
6.	Madrid – Osaka	14/02/99 12:00	11h 34' 04"
7.	Osaka – Madrid	15/02/99 12:00	11h 34' 04"
8.	London LHR – Nagoya	15/02/99 00:00	10h 18' 05"
9.	Nagoya – London LHR	15/02/99 12:00	10h 18' 05"
10.	Tokyo - Frankfurt	04/03/99 00:00	10h 08' 31"
11.	Frankfurt - Tokyo	04/03/99 12:00	10h 08' 31"
12.	Rome – Tokyo	05/03/99 00:00	10h 42' 29"
13.	Tokyo – Rome	05/03/99 12:00	10h 42' 29"

Table 1: List of real (shadowed) and simulated flight used through the interoperability tests analysis.

4 - RESULTS

The assessment of the interoperability scenarios has been based on the execution of a set of tests in the ETS platform, considering both real and simulated data. For each test, the following user's performances have been evaluated:

- Horizontal accuracy: 95th percentile of the horizontal positioning error distribution.
- Availability: relative frequency of the number of cases where the NPA navigation service was available (HPL < HAL=556m).
- Integrity: relative frequency of the number of cases where the NPA navigation service was declared available and positioning errors were below their corresponding protection levels (horizontal error < HPL).

As it has been commented before, NPA phase of flight has been considered as the reference for all the tests.

4.1 - Reference scenario ("do nothing")

In order to compare results, a reference scenario has been proposed. It assumes that each SBAS (EGNOS and MSAS) is providing the nominal navigation service in their respective service areas. There is not any special provision regarding those users located in the interoperability area. In spite of this, users located outside these service areas are able to use EGNOS or MSAS information.

In this case, the degradation of user performance for those users located outside the service areas (i.e. in the interoperability areas) can be observed. This degradation increases when the users are located far from the respective service areas. The degradation of performance is clearly associated to the reduction of the number of monitored satellites for these users. Table 2 presents the average of the performance figures obtained for all the users. In spite of these averaged values can not be considered as the actual system performances, they can be useful for comparison purposes.

SIS	Horizontal accuracy (m)	Availability (%)
MSAS	87.9	66.0
EGNOS	139.9	51.0
MSAS	55.4	69.0
EGNOS	15.3	93.4

Table 2. Mean user's performance for real (shadowed) and simulated data. (with a larger number of stations).

4.2 - Scenario 2.2

After the evaluation of this scenario, the following recommendations are proposed:

- ✓ It is recommended to estimate the time offset between SBAS-A and SBAS-B. Otherwise, positioning errors increase up to unacceptable levels. As far as each SBAS time is within 50 nanoseconds (15 meters) of GPS time (Appendix A of MOPS [3]), this result could have been expected.
- ✓ The combination of satellites monitored by different SBAS degrades performances: it is required to estimate an additional parameter, reducing the number of redundant measurements. It has implications on availability and accuracy performances. Under these conditions, it is recommended to maximise the maximum number of satellites monitored by the same SBAS. This approach reduces the number of cases where both SBAS are used simultaneously.

Figure 5 shows the horizontal accuracy associated to the simulated data tests. Table 3 presents the mean values associated to the real (with a limited number of stations) and simulated data users.

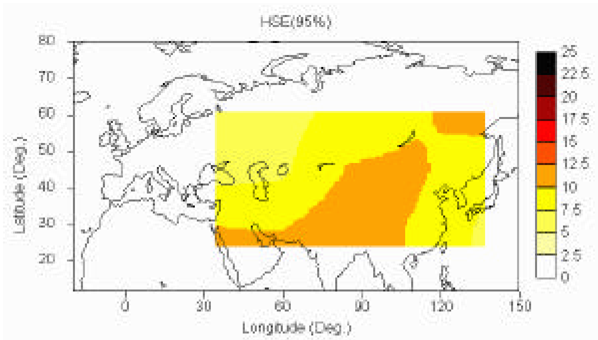

Fig.5. Horizontal accuracy (meters) in scenario 2.2.

Scenario	Horizontal accuracy (m)	Availability (%)	Integrity (%)
2.2	8.6	94.9	100.0
2.2	9.2	99.9	100.0

Table 3. Mean user's performance for real (shadowed) and simulated data.

4.3 - Scenario 2.3

After the evaluation of the approaches considered for this scenario, it is recommended to estimate the time offset between SBAS-A and SBAS-B. This approach reduces the positioning errors. Additionally, it has the advantage of not reducing the number of redundant measurements at user level, as users do not require to estimate that offset.

Figure 6 shows the horizontal accuracy associated to the simulated data tests. Table 4 presents the mean values associated to the real (with a limited number of stations) and simulated data users.

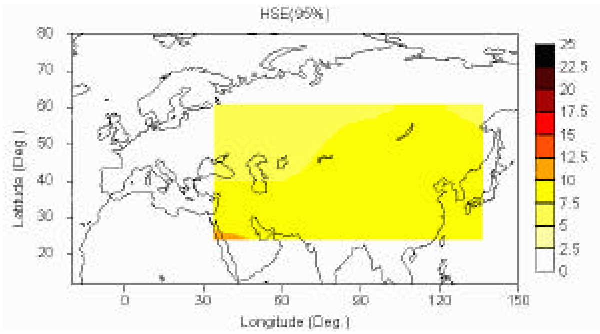

Fig.6. Horizontal accuracy (meters) in scenario 2.3.

Scenario	Horizontal accuracy (m)	Availability (%)	Integrity (%)
2.3	9.8	99.2	99.8
2.3	8.3	100.0	100.0

Table 4. Mean user's performance for real (shadowed) and simulated data.

4.4 - Scenario 2.4

After the evaluation of this scenario, the following recommendations are proposed:

- ✓ The location of the additional stations seems to have a small influence in the performances. Each SBAS could take the advantage of the existing stations of the other SBAS in order to share costs.
- ✓ No special improvements are shown by the cross-check technique. The selection of one of the available solutions is a simple and effective selection method.

Figures 7 and 8 show the horizontal accuracy associated to the simulated data tests, for EGNOS and MSAS SIS. Table 5 presents the mean values associated to the real (with a limited number of stations) and simulated data users. Figure 9 presents the horizontal protection levels (HPL) versus horizontal positioning errors for real data when the users are allowed to select, at each epoch, one of the available solutions (EGNOS or MSAS). In this case, availability performance is 99.2 % and horizontal accuracy is 6.9 meters (100 % and 8.2 meters respectively for simulated data).

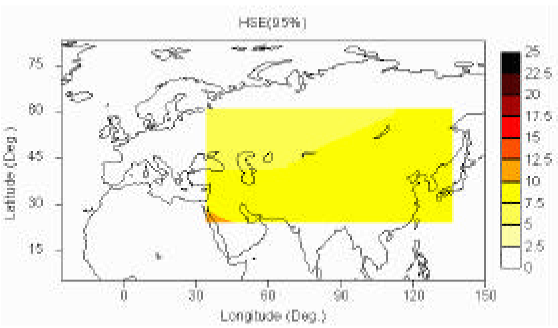

Fig. 7. Horizontal accuracy (meters) in scenario 2.4 for EGNOS (four additional stations).

SIS	Horizontal accuracy (m)	Availability (%)	Integrity (%)
MSAS	7.5	97.8	100.0
EGNOS	7.0	98.7	100.0
MSAS	8.8	99.7	100.0
EGNOS	8.2	100.0	100.0

Table 5. Mean user's performance for real (shadowed) and simulated data.

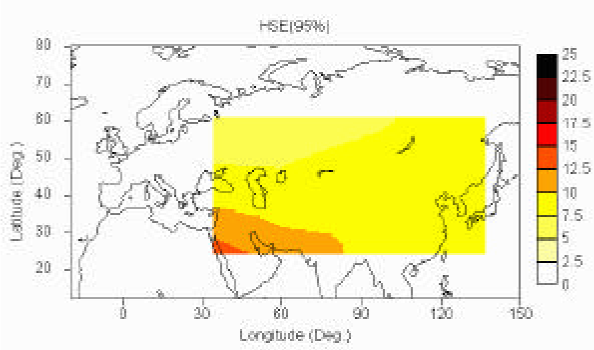

Fig. 8. Horizontal accuracy (meters) in scenario 2.4 for MSAS (four additional stations).

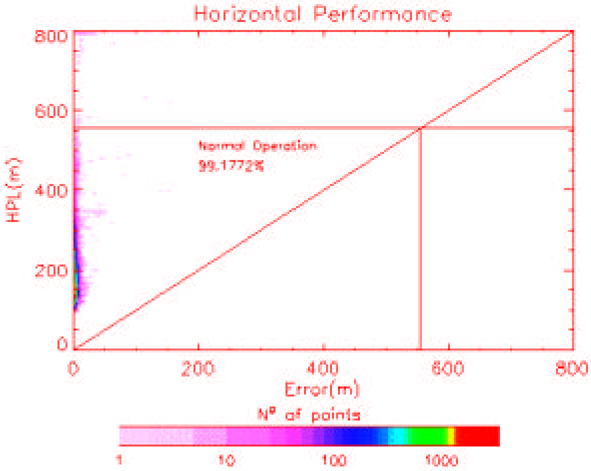

Fig. 9. HPL versus horizontal positioning errors.

4.5 - UDRE out of zone degradation

The results previously presented have been performed considering the option 3 (see Section 2.5) of UDRE out of zone degradation: the extension of the UDRE for out of zone users is performed at user level considering a constant but SBAS dependant factor. Additional tests have been performed considering the other two options: option 1, computation of UDRE to bound errors in both, service and interoperability areas; option 2, no expansion, i.e. using everywhere the UDRE values computed for the service area. Space limitations preclude us to include here the detailed results of these tests which can be obtained from [11]. We detail here the main conclusions of this complementary tests:

- The computation of UDRE to bound errors in both, service and interoperability areas (option 1) could be critical for PA users, which are located in the original service area of each SBAS. In this case, the margins are quite reduced and the influence of UDRE term in the protection levels is important. Therefore, this option is in principle rejected in order to avoid any degradation in the performance of the nominal service volume.
- Option 2 is not recommended as advantages in availability are minor but effect in integrity could be critical in the case of extreme conditions (e.g. worst case ionosphere), even though, integrity is guaranteed for the analysed scenarios.
- In consequence, our recommendation is to consider a degradation factor at user level (option 3): it can be used to guarantee integrity under extreme conditions, without affecting significantly availability under normal conditions. This degradation factor could be either fixed and implemented in the user (as in our tests) or broadcast by the SBAS ground segments (e.g. by allowing a redefinition of MOPS message 27).

4.6 – Results obtained applying the interoperability scenarios to the real commercial flight data

Real and commercial flight data described in Section 3.3, was analysed through this interoperability activity. For the sake of illustration we show in Figs. 10 and 11 the HPL values which would be displayed during the real Frankfurt-Seoul flight (using the actual collected data) when interoperability scenario 2.4 is implemented vs. those HPL values which would be obtained when no-interoperability is implemented (in this case considering EGNOS only and do-nothing case).

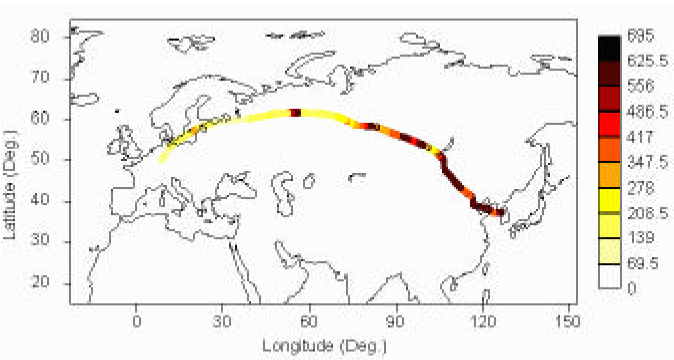

Fig. 10: HPL (in meters) for Eurocontrol flight considering EGNOS corrections

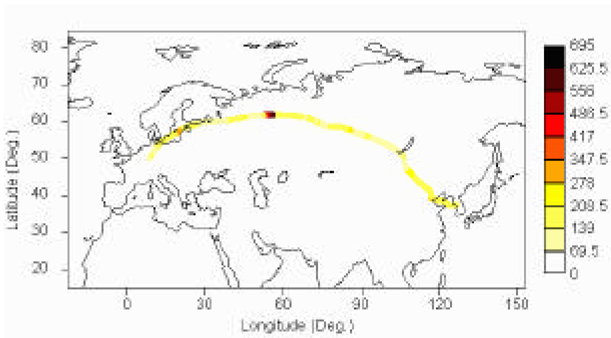

Fig. 11: HPL (in meters) for Eurocontrol real flight considering EGNOS and the implementation of Scenario 2.4.

Comparing the HPL against the alert limit (e.g. HAL=556 m for NPA) availability figures can easily be obtained. In this case the impact of interoperability is apparent with 100% availability of NPA in the case of scenario 2.4 versus 64.5% for the do-nothing case (EGNOS only with no-interoperability).

In addition, EUROCONTROL agreed to provide a number of simulated and real flight trajectories for ESA's analyses and to investigate the RAIM performance for these flights through SAPPHIRE in parallel. The SAPPHIRE analyses covered the predicted availability of RAIM Failure Detection (FD) and RAIM Failure Detection and Identification (FDI) with and without including baro-aiding and considering ranging information from the Inmarsat AOR-E, IOR, MT-SAT and ARTEMIS satellites. Results were also generated for two RAIM algorithms using the measurement data recorded during the real flights. A post processing analysis of the combination of EGNOS interoperability results and those obtained through RAIM indicate that the use of EGNOS/MSAS interoperability & RAIM (with no baro) allows availability figures of the order of 99.999% with full continuity&integrity over the whole interoperability area considered and for Non-Precision Approach.

5 – CONCLUSIONS

In this paper, objective 2 of SBAS interoperability, i.e. to define/assess the service level available in the intermediate regions between SBAS, has been analysed in some detail. In particular, three related interoperability scenarios have been compared considering real (including real commercial flights data) and simulated data for the case of EGNOS and MSAS interoperability. As a general conclusion for all the scenarios, interoperability may require modifications on current SBAS designs. These modifications come from the UDRE out of zone degradation. There is a need of common definition and standardization of UDRE out of zone with the objective of providing integrity even out of the nominal SBAS service areas. A redefinition of MOPS message 27 is currently under discussion for this purpose, and it is subject to analysis on a dedicated EGNOS-WAAS interoperability activity.

Numerical performances obtained are quite promising and it is anticipated that it is possible to provide an NPA service level in the interoperability area. Despite the limitations in the number of stations considered, availability figures for NPA in the EGNOS-MSAS intermediate region are of the order of 99.9% (which, in turn, result in availability figures of the order of 99.999% when RAIM is also considered as a back-up) for scenarios 2.2, 2.3 and 2.4. Scenario 2.4 provides a homogenous NPA performance distribution for all the users. Taking into account that the technical and conceptual changes required to implement it are less complex as those required for the other two scenarios, we consider this scenario (i.e. 2.4) as the most promising one for objective 2 of interoperability. Although the analysis here is oriented to the EGNOS-MSAS interoperability case, it may be anticipated that most of the conclusions are valid for any other interoperability case, such as EGNOS-WAAS or MSAS-WAAS. As a continuation of this analysis, a similar test bed activity EGNOS-WAAS (involving also real commercial flights) is currently being performed.

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