Interoperability Test Analysis between EGNOS and MSAS SBAS Systems

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BIOGRAPHY

Jorge Nieto and Joaquín Cosmen received their MS from the Escuela Técnica Superior de Ingenieros Aeronáuticos (Universidad Politéctnica de Madrid, Spain). Ignacio García holds MS in mathematics from the Universidad Complutense de Madrid, Spain. They joined GMV and currently work in the GNSS Unit. In particular, Mr. Cosmen is the manager of this unit. GMV has a vast experience in the satellite navigation field being a member of the European industrial consortium created for EGNOS (European Geostationary Navigation Overlay Service).

Javier Ventura-Traveset holds a MS in Telecom. Engineering from the Polytechnic Univ. of Catalonia (Barcelona, Spain, 1988); a M.S.E in Signal Processing by Princeton University (Princeton, NJ) in 1992; and a PhD in Electrical Engineering by the Polytechnic of Turin (Italy) in 1996. Since March 1989, he is working at the European Space Agency (ESA) involved in mobile, fix, earth observation and satellite navigation programs; he is currently Principal System Engineer of the EGNOS Project. Dr. Ventura-Traveset holds 4 patents and has co-authored over 80 technical papers. He is a member of the IEEE and the Institute of Navigation.

Isabel Neto has graduated in Electrotechnical Engineering in Instituto Superior Técnico (Universidade Técnica de Lisboa, Portugal). She has joined ESA in June 1998, where she has worked within the EGNOS Project Team as a system Engineer. She is presently working on the 3rd generation mobile system S-UMTS.

Kazuaki Hoshinoo is the Chief of the Onboard Apparatus Section, Satellite Navigation Division, Electronic Navigation Research Institute (ENRI), Ministry of Transport of Japan. He has been engaged in study on the development of GNSS Integrity Channel Network and augmentation of GNSS by a geostationary satellite from 1992. He received a BE in electronics from Okayama University in 1972. He joined the ENRI on April in 1972 and was engaged in the research and development of mobile satellite communication and positioning system by 1992.

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 architectural and technical interoperability options. In particular, an assessment of different interoperability options between EGNOS and MSAS SBAS systems will be presented. This assessment is based on the use of both EGNOS and MSAS respective test beds.

SBAS providers guarantee only adequate service provision in their nominal service volumes. In spite of this, SBAS broadcast signals will be available anywhere in their respective GEO footprints. In the case of EGNOS and MSAS the GEO visibility areas is extended to the whole Asian continent. In that intermediate region (interoperability area), signals for both GEO (i.e. from both SBAS) are available but none of the SBAS providers considers it as part of its nominal service area. It means that the level of service available in this region is not defined. Taking into account that these intermediate regions are not covered by any other SBAS, the possibility of providing a minimum service level in the intermediate region by means of SBAS interoperability is a main concern of the interoperability analyses. For this purpose, several scenarios can be conceived. These are discussed and analysed through this paper.

The choice of one or another scenario may imply several important consequences for the design of the different SBAS, as well as standardisation activities, e.g. user's receiver algorithms. In this context, an 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) and the Japanese ENRI GNSS Test System. 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.

Although the analysis here are 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 is currently being performed.

INTRODUCTION

There are three different Satellite Based Augmentation Systems (SBAS) to GPS (and GLONASS) currently under development:

1. 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;
2. 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);
3. In Japan, the Japanese Civil Aviation Bureau is implementing Japanese MTSAT Satellite Based Augmentation System (MSAS), which shall cover the Flight Instrumental Region (FIR) associated to Japan.

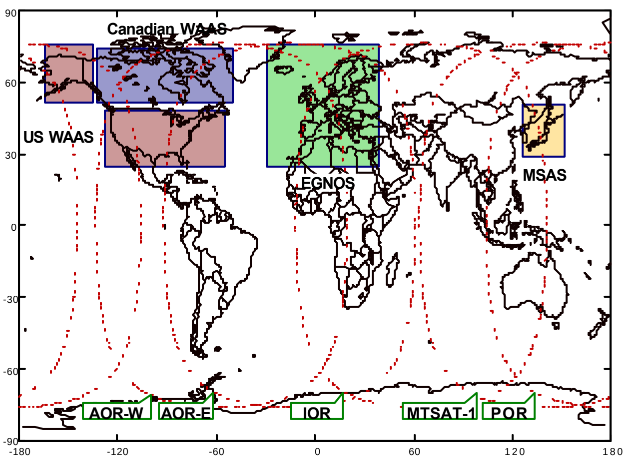

Fig. 1. EGNOS, WAAS, Canadian WAAS and MSAS.

Figure 1 illustrates schematically the world service areas planned to be covered by these SBAS. 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 [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. The preliminary assessment of these scenarios for the EGNOS-MSAS interoperability case is shown.

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 and Inmarsat IOR, 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. They are discussed hereafter where we will talk about interoperability between SBAS-A and SBAS-B, and we will consider that the minimum desirable service level is Non Precision Approach (NPA). 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 are presented after the scenarios.

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 GEO, including non-EGNOS GEO. Thus, we may consider that this interoperability scenario is feasible if current EGNOS stations deployment is enough to monitor that non-EGNOS GEO.

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. Certainly, then, the number of GPS satellites that are globally monitored may be large enough so that with no extra reference stations, NPA service level is available in the intermediate regions.

The implementation of this scenario is as follows: SBAS-A and SBAS-B provide their own broadcast navigation messages, which can be used by the navigation receiver simultaneously. Corrections and integrity information from the navigation messages of two different SBAS can safely be used simultaneously in the determination of the user position (see figure 2).

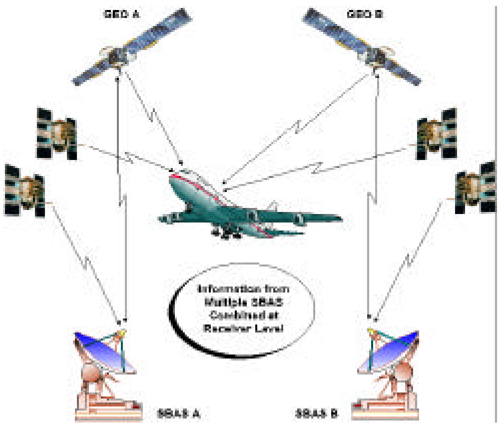

Fig. 2. Scenario 2.2.

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).

Although in terms of final user performance the two scenarios above (2.2 and 2.3) could be equivalent, the implications of those are very different. Indeed, scenario 2.2 implies a rather limited (if any) interface between the two SBAS, while it implies the need to define a minimum avionics requirement where this simultaneous use of SBAS signals is contemplated (today RTCA MOPS [3] does not consider clearly this case). Scenario 2.3, instead, could eventually be completely transparent to the user receiver (which is actually getting the signal from only one SBAS) but would imply a very complex interface between SBAS with many safety implications. Based on these considerations, scenario 2.2 is a priori more attractive.

Scenario 2.4: Installing own monitoring 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. SBAS interoperability in this case could improve both continuity and availability of service in the intermediate regions. In fact, this scenario can be considered as the expansion of the service provided by each SBAS to the interoperability region.

Extending the 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 GEO 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:

<u>Option 1</u>: 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. The obvious implication of that approach is that the UDRE values will be increased, which, in turn, could affect the availability in the nominal service volume of Precision Approach.

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). The analysis of this scenario requires the understanding and assessment of possible pathological cases, i.e., those in which based on geometry visibility considerations, a satellite error in a particular dimension occurs in such a way that it can not be observed by the monitoring network but still affect the user.

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).

It is worth mentioning that the issue of integrity broadcast outside the service volumes is not only an issue related to this interoperability scenario but a more global one. Indeed, even if SBAS do limit their committed service provision to their nominal service volumes, the broadcast signals will be available anywhere in the footprints of the SBAS GEO satellites. Thus, unless provisions are standardised to inform the receivers whether they are or not in the service volume of a particular SBAS (and so whether they are or not allowed to use the SBAS broadcast signal), nothing prevents a receiver to access and process these data, with all the associated integrity related problems.

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 mainly addressed to investigate the EGNOS performance at user level in terms of accuracy, integrity and availability. It implements major EGNOS functions, paying special attention to the different algorithms that will be implemented in the Central Processing Facility (CPF) of EGNOS. This facility can be easily adapted to analyse the performance associated to any other SBAS. In particular, the interoperability case considered is the one between EGNOS [6] and MSAS [7] systems. Two different analyses have been carried out, one based on real data and the other based on simulated data.

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. Figure 3 shows 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 4).

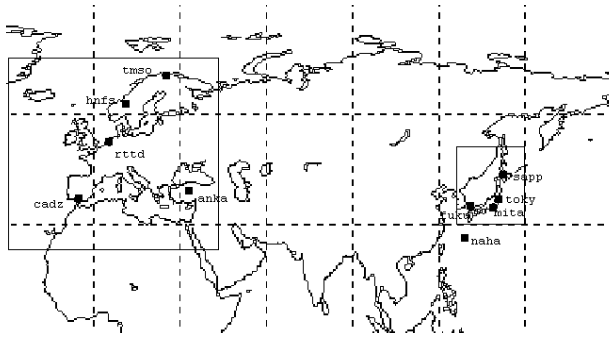

Fig. 3. EGNOS and MSAS ground segment for real data.

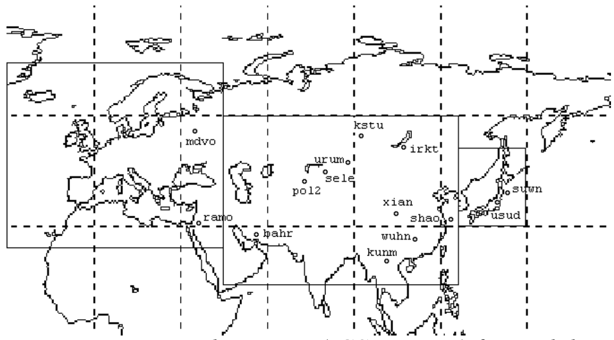

Fig. 4. User ground segment (IGS stations) for real data.

Simulated data analysis

The second assessment of the interoperability scenarios is performed with simulated data. EGNOS and MSAS ground segments (figures 5 and 6) and user segment have been realistically simulated. Simulation tool considered is the EGNOS End-to-End Simulator, EETES [5].

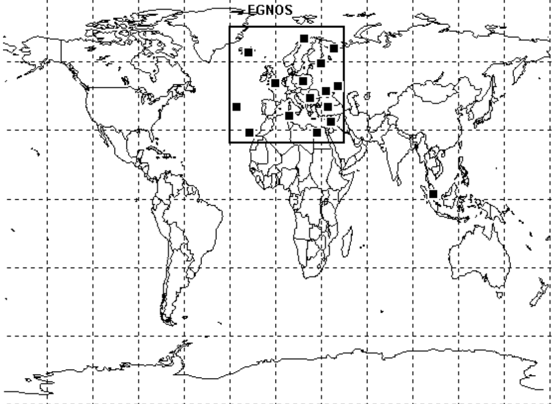

Fig. 5. EGNOS ground segment for simulated data.

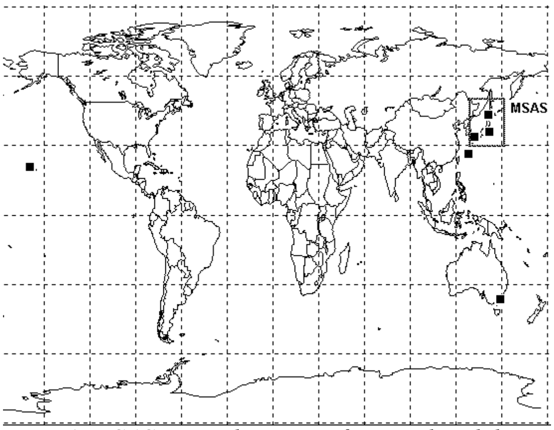

Fig. 6. MSAS ground segment for simulated data.

IMPLEMENTATION ASPECTS

Each interoperability scenario allows different technical solutions for the system implementation. The description of those different options is presented for each scenario. Due to the limitations of the ETS, Scenario 2.1 has not been implemented.

Scenario 2.2

In this scenario, users access simultaneously to both SBAS SIS, and combine their information in a single navigation solution. Regarding this scenario, 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 (SBAS selection for satellites doubly monitored), three different approaches have been considered (figures 7 and 8 illustrate the two first approaches):

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.

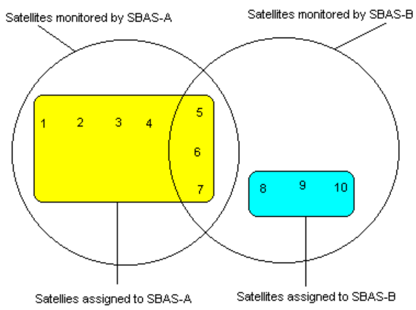

Fig. 7. Maximisation of the maximum number of satellites: SBAS-A seven, SBAS-B three.

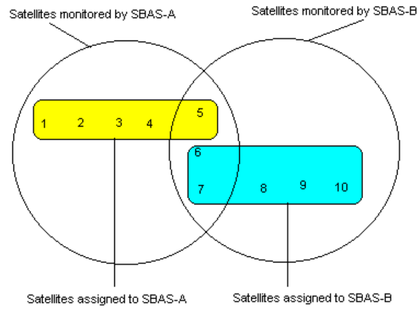

Fig. 8. Maximisation of the minimum number of satellites: SBAS-A five, SBAS-B five.

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] is modified as follows:

$$y = G \cdot x + \boldsymbol{e}$$

$$G_i = \left[\cos El_i \cos Az_i \;\; \cos El_i sinAz_i \;\; sinEl_i \;\; 1 \;\; \boldsymbol{z}_i\right]$$

where x is a five dimensional position vector (north, east, up, clock w.r.t. SBAS-A and clock of SBAS-B w.r.t. SBAS-A) and

$$\boldsymbol{z}_i = \begin{cases} 0 & \text{if SBAS - A corrections are applied} \\ 1 & \text{if SBAS - B corrections are applied} \end{cases}$$

Scenario 2.3

In this scenario, users access simultaneously only to one SBAS SIS, but this SIS includes the information from both SBAS. It means that the information generated by SBAS-B is used by SBAS-A to complete its SIS with those satellites not monitored by A but monitored by B.

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.

In the second approach, the ground segment estimates the time offset (B_{A-B}) as follows:

$$B_{A-B} = \frac{\sum_{i=1}^{p} \left(b_{A,i} - b_{B,i}\right)}{p}$$

where b_A and b_B are the satellite clock corrections for SBAS-A and B and i=1 ... p are those satellites that are simultaneously monitored by both SBAS.

Scenario 2.4

In this scenario, both SBAS implement additional stations in order to provide independently the required navigation service in the interoperability area. In consequence, users have access to two navigation solutions, one per SBAS. 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.

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: 95^{th} 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. Main results and conclusions derived from the tests are presented hereafter.

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. Figures 9 and 10 show the horizontal accuracy associated to the simulated data tests. Table 1 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.

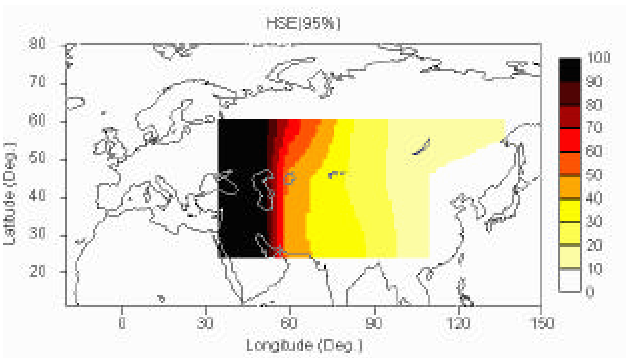

Fig. 9. Horizontal accuracy (meters) associated to MSAS SIS, simulated data.

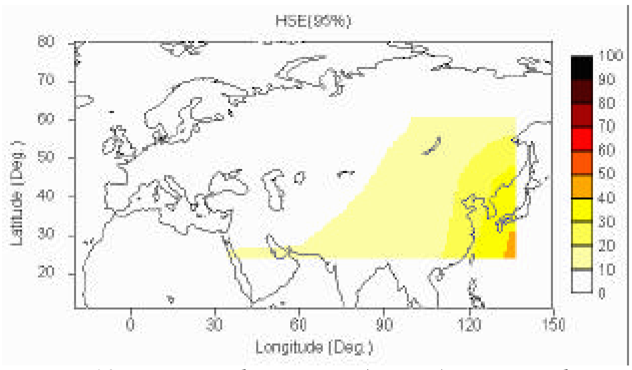

Fig. 10. Horizontal accuracy (meters) associated to EGNOS SIS, simulated data.

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

Scenario 2.2

After the evaluation of the different approaches considered for 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.

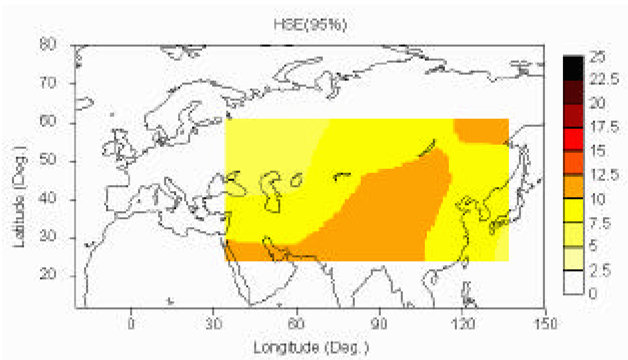

Fig. 11. Horizontal accuracy (meters) in scenario 2.2.

Figure 11 shows the horizontal accuracy associated to the simulated data tests. Table 2 presents the mean values associated to the real (with a limited number of stations) and simulated data users.

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

Table 2. Mean user's performance for real (shadowed) and simulated data.

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 12 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.

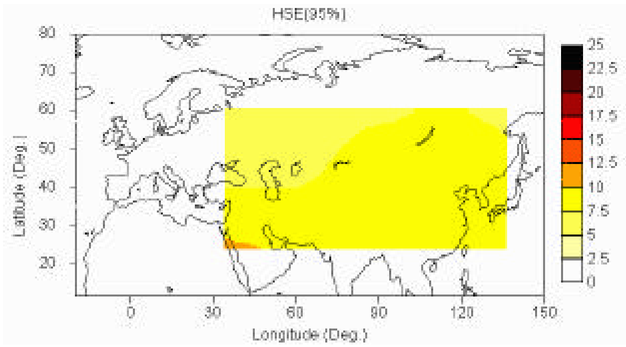

Fig. 12. Horizontal accuracy (meters) in scenario 2.3.

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

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

Scenario 2.4

After the evaluation of the different approaches considered for 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 13 and 14 show the horizontal accuracy associated to the simulated data tests, for EGNOS and MSAS SIS. Table 4 presents the mean values associated to the real (with a limited number of stations) and simulated data users.

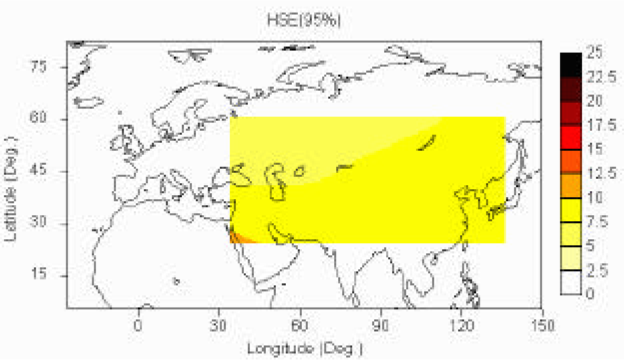

Fig. 13. Horizontal accuracy (meters) in scenario 2.4 for EGNOS (four additional stations).

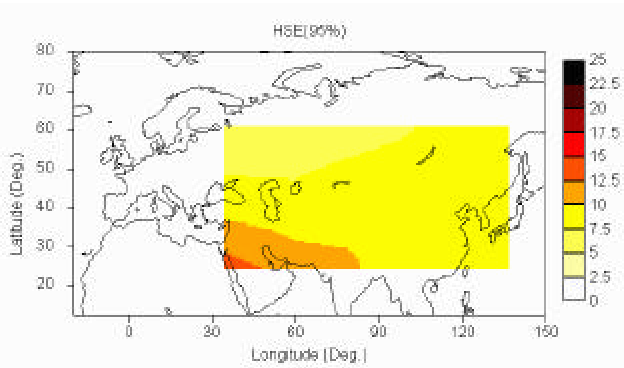

Fig. 14. Horizontal accuracy (meters) in scenario 2.4 for MSAS (four additional stations).

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

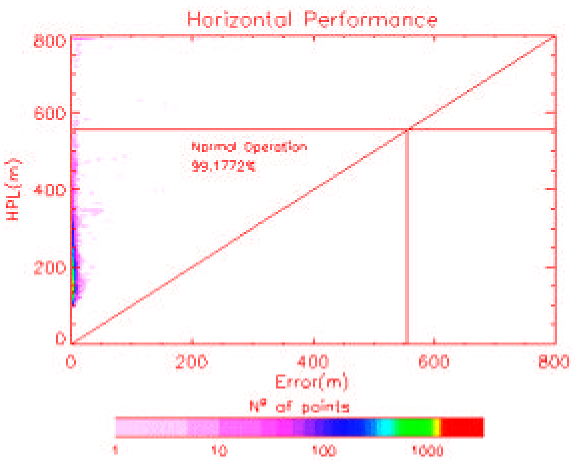

Fig. 15. HPL versus horizontal positioning errors.

Figure 15 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).

UDRE out of zone degradation

The results previously presented have been performed considering the option 3 (see related section above) 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.

While options 1 and 3 should provide the required integrity performance (considering appropriate measurements have been taken to guarantee these performances), tests for option 2 will be useful to evaluate if that integrity performance is achieved, and only in that case measured availability performance will be meaningful.

Table 5 presents the user's performances associated to the real and simulated users for the different UDRE out of zone degradation options. Option 2 has only been analysed with real data. Scenario considered is the 2.4, selecting one of the available solution at each epoch.

UDRE option	Horizontal accuracy (m)	Availability (%)	Integrity (%)
1	7.0	99.4	100.0
2	6.9	99.4	100.0
3	6.9	99.2	100.0
1	8.2	100.0	100.0
3	8.2	100.0	100.0

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

Taking into account the results of these tests, the following points can be concluded:

- ✓ For NPA phase of flight, UDRE represents a small contribution in the protection level computation. It is deduced from the fact that availability performance are slightly influenced by the different approaches considered.
- ✓ It means that the major part of the error budget in the protection levels is absorbed by the other terms, especially ionosphere. Therefore, it does not seem to be critical to refine UDRE values to obtain a very adjusted orbital and clock error budget.
- ✓ The same effect can be observed from integrity point of view. For accuracy, effect is minimum, as the

unique effect is shown through the weighting factors in the weighted least squares algorithm.

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).

It is worthwhile to mention here that the expansion of the service to the interoperability area implies another modification in the SBAS design, the UDRE computation function. The point here is that UDRE (considered as the bound of the orbit and clock error for the worst user in the service area) has no sense when the satellite is not visible in the service area. It could happen (e.g. in the scenario 2.4) that a satellite can be successfully monitored by the SBAS but it is only visible in the interoperability area. Our proposal for this issue has been to estimate the UDRE for this type of satellites as the bound of the orbit and clock error for the worst user in the interoperability area.

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 and simulated data for the case of EGNOS and MSAS interoperability. Main conclusions are outlined in the next paragraphs:

1. Taking into account the limitations of the real and simulated data analysed, numerical values should not be considered as absolute but only relatives ones (as comparison among different scenarios). It is important to observe that the results for both types of analyses (real and simulated data) are coherent: the relative positions of each scenario with respect to others is the same and, therefore, both type of analyses support the conclusions;

2. 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 standardisation 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.

3. According to our results, the recommended interoperability scenario is the 2.4 one, i.e. each SBAS implements some additional reference stations in such a way that both SBAS provide navigation service in the intermediate region independently from each other. Each SBAS is responsible for providing the required navigation service. Additional (to the one above stated) implications on SBAS and user design are more quantitative than qualitative:

   - ☞ Additional stations are needed. They could be co-located with stations belonging the other SBAS or a combination of co-located existing stations and independent new stations.
   - ☞ Additional SBAS computation power, i.e. CPU, is required. For EGNOS this is not a critical problem because its Central Processing Facility (CPF) is dimensioned up to 60 RIMS (when current baseline includes 39).
   - ☞ Additional information shall be included in the broadcast SIS. It does not seem to be critical, as the additional messages to broadcast are the long term corrections associated to the new satellites monitored. The typical refresh rate of this type of message is 2 minutes.
   - ☞ Additional user computations power could be required, in order to execute the navigation algorithm twice per second (one for each SBAS).

   As it can be observed, these modifications do not imply any technical innovation on SBAS or user design. Another major advantage comes from the certification point of view as each SBAS is fully responsible for the provision of a service in the interoperability area totally independent from the other SBAS.

4. Results associated to scenario 2.2 are slightly worse than those of scenario 2.3 and 2.4. The effect of the time offset between SBAS (and the subsequent loss of a measurement for its estimation) has critical consequences on the performances. It is important to highlight that the real data tests have been performed with a limited number of stations. With a more realistic situation in the simulated data tests (referred to the number and geometrical distribution of RIMS), availability results are improved but still below 100%. This is especially true in the proximity of MSAS service area, due to the low number of stations in MSAS ground segment (as compared to EGNOS

ground segment). From a conceptual point of view, this scenario could have important implications on user design, as it is the modification of standard navigation algorithm to include the estimation of the SBAS time offset. One possible solution to the SBAS time offset drawback is to include an additional requirement to each SBAS to reach a synchronisation closer to GPS time. In this case, users would not need to estimate the offset between SBAS, and the accuracy degradation would be minimised, taking into account that the SBAS time offset is below a certain limit

5. Scenario 2.3 provides better performances than scenario 2.2, as the users do not lose one measurement for offset estimation: availability and accuracy increase. In any case, this scenario 2.3 implies some important modifications on the SBAS design, as it is the case of the required link between SBAS. Each SBAS shall be able to send to the other orbit and clock corrections besides UDRE values for all the monitored satellites at each second. Additionally, latency in the delivery of this information should be minimised. From a practical point of view, this is considered as a very difficult to implement solution. A possible alternative for this scenario could be based on the following approach: each SBAS receives the information from the other through its SIS, estimates the time offset and broadcasts exclusively this time offset in, say, MOPS message type 12.

6. 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 homogeneous NPA performance distribution for all the users. While numerical availability values have been analysed from a relative point of view, it is truth that accuracy can be checked from an absolute point of view. Global accuracy values (horizontal around 7 meters for real data tests and 8 meters for simulated data tests, 95%) can be considered as excellent (taking into the characteristics of the data analysed). It is important to highlight that results could improve if, for instance, GEO ranging were included.

7. Although the analysis here are 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 is currently being performed.

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