Interoperability between EGNOS and WAAS: Tests Using ESTB and NSTB

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ABSTRACT

Europe, US/Canada and Japan are currently developing their own regional Satellite Based Augmentation System (SBAS). Although all of them can operate as stand-alone, regional systems, there is an increasing interest in establishing adequate ways for co-operation and co-ordination among the different SBAS providers. One of the objectives of this co-operation is to provide SBAS interoperability, and, in turn, produce a more effective implementation and a part of a seamless world-wide navigation system. SBAS co-operation is currently co-ordinated through the so-called Interoperability Working Groups (IWG). A recent IWG meeting proposed a joint international test activity to analyse the interoperability between the US SBAS, WAAS (Wide Area Augmentation System), and the European one, EGNOS (European Geostationary Navigation Overlay Service).

The first step of this test activity consists on the definition of several candidate EGNOS-WAAS interoperability scenarios. Each interoperability scenario can be conceived as a way to provide a pre-defined navigation service level (e.g. Non Precision Approach, NPA) in the EGNOS-WAAS interoperability area (i.e. the oceanic regions outside the nominal SBAS service volumes). Taking into account that the implementation of these scenarios shall be considered realistic by the SBAS providers, two major interoperability scenarios are considered (they have been numbered according to IWG standards). In the scenario 2.2, the information provided by both SBAS is combined in the user receiver. In the scenario 2.4, each SBAS expands its service to the interoperability area by placing additional reference stations.

Once the interoperability scenarios have been defined, their performances are evaluated by means of off-line tests using real data from the WAAS National Satellite Test Bed (NSTB) and the EGNOS System Test Bed (ESTB). In view of these performances, and taking into account the deviations that each interoperability scenario introduces to the actual SBAS baseline, the feasibility of SBAS interoperability is analysed.

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 Information 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 [5]):

- **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-WAAS interoperability case is shown. Previously, other interoperability analyses have been performed considering EGNOS-MSAS case (see [6] and [7]). These interoperability tests have been conducted independently by EGNOS and the Stanford University WAAS laboratory based on the same real data sets collected from ESTB and NSTB. The agreement of the major conclusions in each study successfully consolidates the understanding of characteristics among SBAS.

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, 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 target service levels are Non Precision Approach (NPA) and Non Precision Approach with Vertical Guidance (NPV-I). 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.

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 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 evaluated.

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.

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).

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.

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. The issue is 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).

The solution selected is the use of a degradation factor 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 is included in the SBAS SIS (e.g. MOPS message 27).

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] and the EGNOS System Test Bed (ESTB) facility [4]. 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. The ESTB is a real time mock-up of the EGNOS system. It is based on a network of reference stations that collects real time data which is transmitted to a central processing centre where differential corrections and integrity information are computed.

SBAS ground segment data has been provided by EGNOS and WAAS test beds: EGNOS System Test Bed ESTB and National Satellite Test Bed respectively. Data analysed corresponds to the day 28th of August 1999. Figure 1 shows the location of the ESTB stations considered in the analysis. Figure 2 shows the location of the NSTB stations considered in the analysis. For the user segment, nineteen IGS stations located in the interoperability area have been considered (figure 3). Analysis areas considered are shown in figure 4.

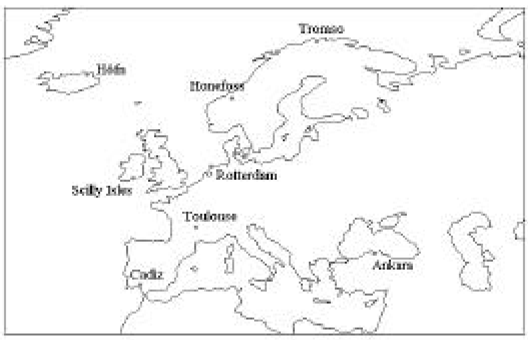


Figure 1: ESTB stations

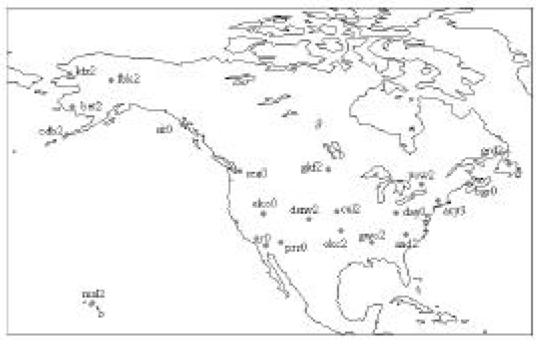


Figure 2: NSTB stations

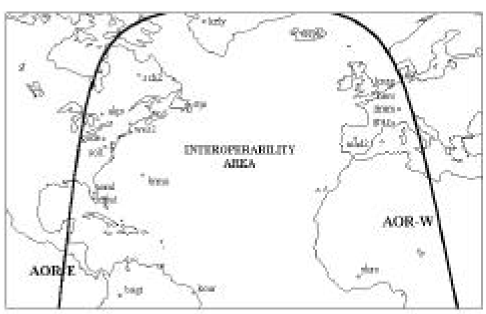


Figure 3: users: IGS stations

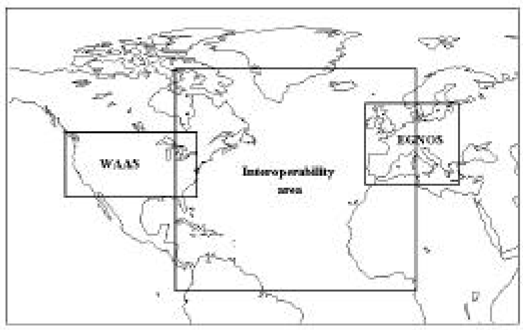


Figure 4: analysis areas

Two different analyses have been performed:

1. Analysis of NPA performances: it is based on the ETS platform. The objective is to evaluate the optimum scenario for EGNOS-WAAS interoperability taking into account that the level of service required is NPA.

2. Analysis of NPV-I performances: it is based on the ESTB platform. The objective is to evaluate the feasibility of reaching the NPV-I performances through EGNOS-WAAS interoperability.

RESULTS FOR NPA ANALYSIS

The assessment of the interoperability scenarios for NPA performances has been based on the execution of a set of tests in the ETS platform. 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).

Taking into account that the objective of this analysis is NPA performance, SBAS broadcast information includes satellite clock and orbit corrections (slow and fast) and integrity data (UDRE), but neither ionospheric corrections (GIVD) nor integrity data (GIVE) is generated. Instead of this, users correct the ionospheric delay using Klobuchar's ionospheric model, and its error is bounded according to MOPS ([3]). MOPS message 27 includes a UDRE degradation factor of 10 (the same for EGNOS and WAAS) to be applied by the interoperability users.

Reference scenario ("do nothing")

In order to compare results, a reference scenario has been proposed. It assumes that each SBAS (EGNOS and WAAS) 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 WAAS information.

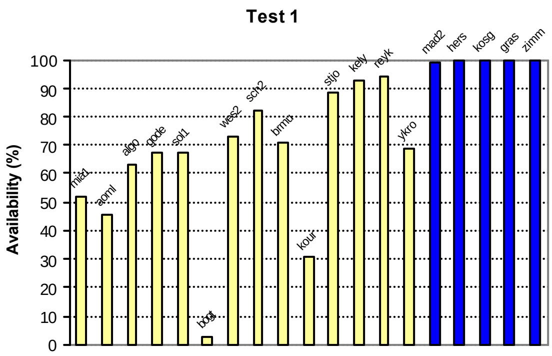


Figure 5: EGNOS SIS

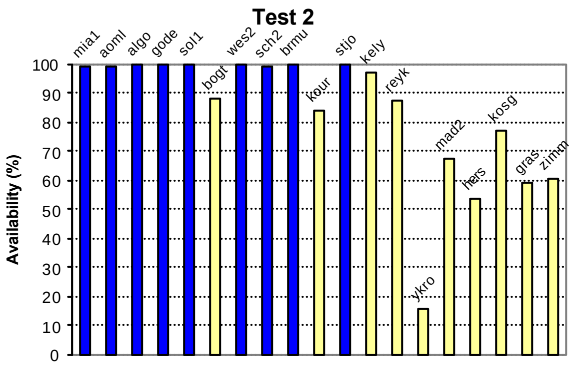


Figure 6: WAAS SIS

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 5 and 6 present the availability for each user (dark bars represent those users which availability is above 99%). In spite of these averaged values can not be considered as the actual system performances, they can be useful for comparison purposes.

Scenario 2.2

After the evaluation of this scenario, it is concluded that it is an acceptable way to provided

SBAS interoperability up to NPA level. Several possible implementations of this scenario have been tested. These implementations can be classified in two different groups:

- User computes the navigation solution for WAAS and EGNOS independently and, at each epoch, it selects one of them (e.g. the one with minimum HPL). This implementation is a simple way to provided SBAS interoperability, in spite of its performances are below the other implementation: figure 7 shows the user's availability.
- User computes a single navigation solution using simultaneously EGNOS and WAAS monitored satellites. It is required to correct the difference in the time reference for clock corrections, i.e. the offset between EGNOS Network Time and WAAS Network Time. The implementation of this scenario is more difficult (implications depend on the way to correct this time offset) but better performances are obtained: figure 8 shows the user's availability.

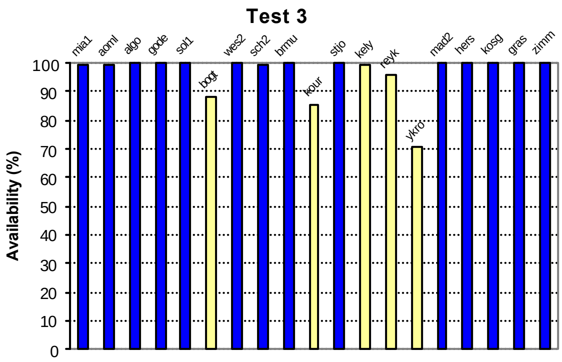


Figure 7: 2.2 selection of one SBAS

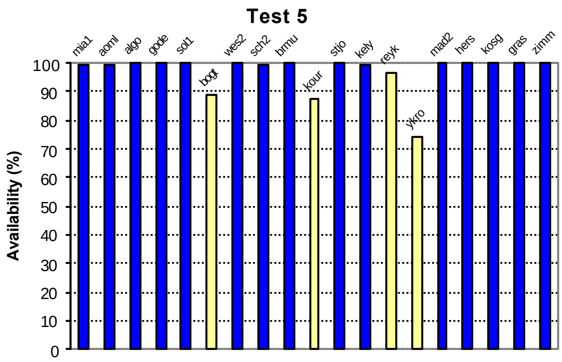


Figure 8: 2.2 combination of both SBAS

Scenario 2.4

After the evaluation of this scenario, it is concluded that it is an acceptable way to provided SBAS interoperability up to NPA level. In this case, it is recommended to deploy a number of additional stations above the minimum number of stations required to declare a satellite as monitored. Figure 9 presents the availability results when both SBAS, EGNOS and WAAS, deploy three additional stations in the interoperability area. The three additional stations have been selected by optimising the depth of coverage of a satellite seen by a certain number of stations. In this case, the user computes the navigation solution for WAAS and EGNOS independently and, at each epoch, it selects one of them (e.g. the one with minimum HPL).

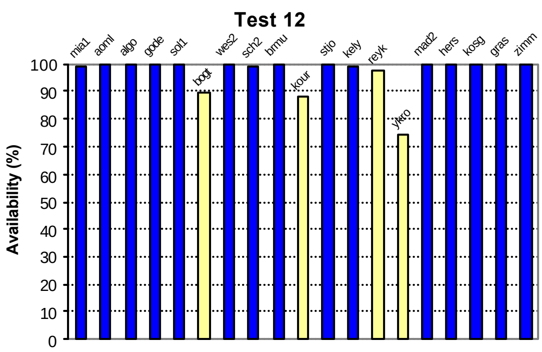


Figure 9: 2.4 SBAS expansion

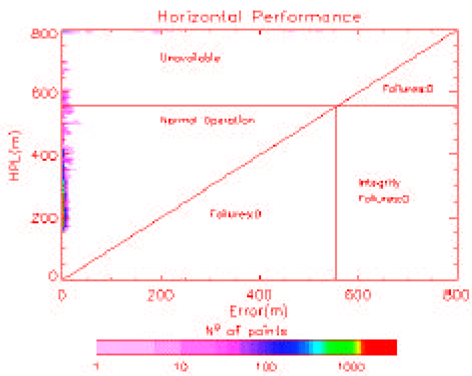


Figure 10: error versus HPL

Conclusions

Main conclusion of this analysis is that EGNOS-WAAS interoperability is able to provide NPA service level in the EGNOS-WAAS interoperability area. This service level could not be achieved considering independently EGNOS or WAAS SIS in the reference cases. For this objective 2 of interoperability, two different scenarios have been tested. Both scenarios are considered as acceptable ones to achieve this objective. There are slight differences in their performances, although their consequence in SBAS design and user and SIS standardisation are quite different.

It is important to highlight that this analysis has been performed considering the message 27 for UDRE spatial degradation, as it is proposed in the latest version of MOPS ([3]). Format and characteristics of this message 27 fit quite well with the needs of interoperability users.

From this analysis (see figure 10), it is observed the margin existing between the positioning errors (around 10 meters in vertical and 5 meters in horizontal, 95%) and the protection levels (around 200 to 300 meters). Taking into account this point, it has been suggested the possibility of providing NPV-I service level in the interoperability area. From accuracy point of view, this level could be achievable, as reference figures for NPV-I are 220 meters in horizontal and 20 meters in vertical, 95%. This analysis is presented in the next section.

RESULTS FOR NPV-I ANALYSIS

The assessment of the interoperability scenarios for NPV-I performances has been based on the execution of a set of tests in the ESTB platform. 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 NPV-I navigation service was available (HPL < HAL=556m and VPL < VAL = 50m).

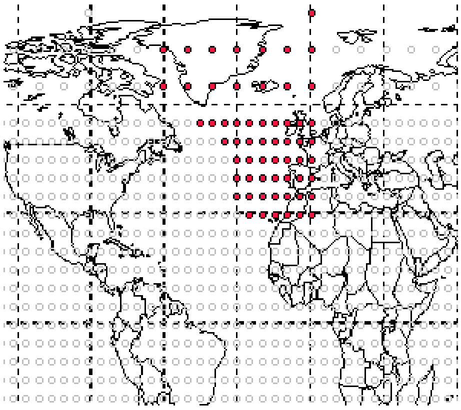
Taking into account that the objective of this analysis is NPV-I performance, SBAS broadcast information includes satellite clock and orbit corrections (slow and fast) and integrity data (UDRE), ionospheric corrections (GIVD) and integrity data (GIVE). Users apply this information according to MOPS ([3]) standards for Precision Approach (PA).

Reference scenario ("do nothing")

The performance analysis has been done in priority over the areas where NPV-I has been identified as an operational need. Alternative airports are needed in case of aircraft failures in North Atlantic routes: lack of vertical guidance in those airports has caused various accidents. NPV-I performance in areas where those alternative airports are located shall substantially improve safety. In consequence, NPV-I should be required in the following areas:

- North Atlantic area: Iceland, Greenland and north east part of Canada until 70ºN.
- Mid Atlantic area: Azores islands (mean co-ordinates 39ºN, 28ºW).
- Caribbean area: 10ºN to 28ºN, 55ºW to 86ºW.

Next figures show the areas where (ionospheric grid points, IGP) EGNOS and WAAS are able to provide ionospheric corrections and integrity data taking into account their reference stations. It can be observed that EGNOS NPV-I service can only be available in Iceland, Greenland and Azores, while WAAS NPV-I service can only be available in north east part of Canada and Caribbean.



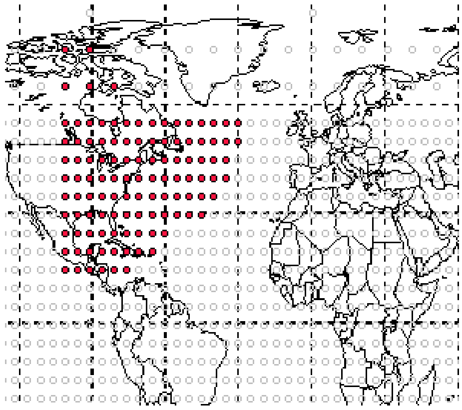


Figure 11: IGP for EGNOS Figure 12: IGP for WAAS

It can be concluded that, EGNOS alone or WAAS alone can not provide NPV-I service in all the EGNOS-WAAS interoperability area of interest.

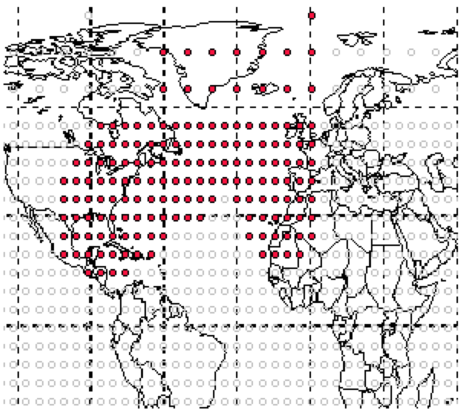
Scenario 2.2

For this interoperability analysis, only the case based on the selection of the available SBAS is considered. In this case user selects at each epoch one of the available navigation solutions without mixing corrections from different SBAS. In any case, it is worthwhile to mention that the last possibility (i.e. mixing corrections from different SBAS in a single navigation solution) is certainly of much interest for interoperability.

When this scenario has been analysed, it has been observed that it is a potential way to provide NPV-I service in all the interoperability area: EGNOS SIS is used in Iceland, Greenland and Azores, while WAAS SIS is used in north east part of Canada and Caribbean.

Scenario 2.4

In this scenario, both EGNOS and WAAS expand their service by using three additional stations: EGNOS plus three WAAS stations and WAAS plus three EGNOS stations. The three additional stations have been selected in order to optimise GIVE values over the areas that are objective for the analysis. This scenario is based on the selection of the available SBAS: user selects at each epoch one of the available navigation solutions without mixing corrections from different SBAS.



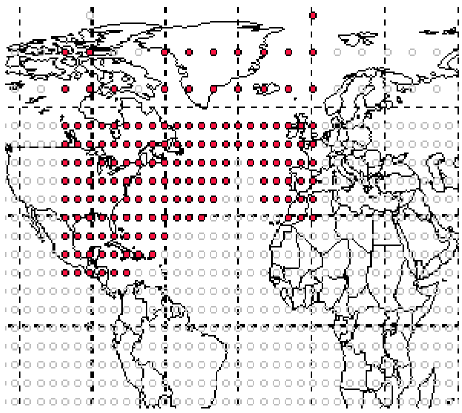


Figure 13: IGP for extended EGNOS Figure 12: IGP for extended WAAS

When this scenario has been analysed, it has been observed that it is also a potential way to provide NPV-I service in all the interoperability area as either EGNOS SIS or WAAS SIS can be used in the areas of interest.

Additionally, this scenario 2.4 provides better NPV-I user's performance than the previously considered scenario 2.2. It is mainly due to the dual availability of valid EGNOS and WAAS information, which allows switching from one SIS to the other if one of them becomes unavailable.

Conclusions

From these tests, it is observed that NPV-I service in the EGNOS-WAAS interoperability areas of interest can only be reached through adequate interoperability scenarios. Additionally, the results show the importance of some particular issues:

- It is required to extend significantly the monitoring of Ionospheric Grid Points (IGP) to the interoperability area. In particular, it is required to cover almost all the north Atlantic area. This point has important implications in issues as ionospheric algorithms, monitoring stations location and SIS bandwith.
- It is needed to make an appropriate use of UDRE out of zone degradation in Message 27. There is a small margin between computed protection levels and the NPV-I alert limits. In consequence, UDRE degradation factor shall not be very conservative (but it shall always preserve integrity). The advantage of Message 27 is that it provides high flexibility for the definition of several areas with specific degradation factors and avoiding the penalisation to areas which are close to the nominal service area.
- EGNOS and WAAS design shall be optimised for interoperability (for instance, the location of monitoring stations). In particular, it is recommended to select the interoperability scenario that provides better NPV-I performances, currently the 2.4.

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