SBAS DFMC performance analysis with the SBAS DFMC Service Volume software Prototype (DSVP)

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BIOGRAPHIES

Daniel Salos received the M.S. degree in telecommunication engineering from the University of Saragossa (Spain) in 2006 and the Ph.D. degree from the University of Toulouse (France) in 2012. He works in the field of Global Satellite Navigation Systems (GNSS) since 2007 and on aircraft navigation activities since 2014. Daniel joined Egis Avia in 2014, where he has been involved in GNSS integrity monitoring activities, the development of a GBAS ionospheric threat model, EGNOS performance assessment as well as Performance Based Navigation (PBN) activities for the DSNA (the French Air Navigation Service Provider).

Mikael Mabilleau is the navigation services manager in Egis Avia. He is actively participating in activities of the main civil aviation standardisation bodies. He is involved in several projects looking at GNSS evolutions for civil aviation operations such as Advanced RAIM and dual frequency multi-constellation simulator prototypes for ABAS, SBAS and GBAS systems evolutions. He has acquired experience in the international development of GNSS through its involvement in the SAFIR project which has created the EGNOS/Africa Joint Programme Office in Dakar. His main fields of interest are GNSS standardisation and integrity monitoring concept for the mitigation of GNSS threats.

Catalina Rodriguez is a Satellite Navigation System Engineer at CNES, the French Space Agency. She has been working over 10 years on SBAS. She is involved in many activities linked to SBAS standardization, EGNOS extensions and development of EGNOS services. She is also Co-chair of the CNES Technical Skills Community "Satellite Positioning and Timing" (CCT PDS).

Hugues Secretan an expert in GNSS, working at CNES (French Space Agency) in the Navigation System Engineering department since 1995. He graduated from ESTP in Paris with an engineer diploma in mechanics-electricity. He joined CNES in 1983 as Project Engineer in Kourou, working on several projects of the Ariane Space Center. From 1987 to 1995 he worked in the flight dynamics division in Toulouse, in charge of mission analysis and orbit positioning maneuvers for geostationary satellites. In 1995 he joined the GNSS system department, responsible of EURIDIS project. From 2000 to 2010, he worked in the ESA EGNOS Project Office as ESTB (EGNOS System Test Bed) Manager, then as SPEED project manager. Since 2012, he is in charge of SAGAIE project for the characterization of the ionosphere in equatorial area in cooperation with ASECNA, and contributes to new EGNOS developments such as EGNOS in Africa and EGNOS V2.4.2.

Norbert Suard joined the CNES in 1983. He is a Senior Expert in the CNES Navigation System Division where he has over 25 years of experience in development, studies, performances analysis of navigation system augmentation like CE-GPS, EURIDIS, ESTB and now EGNOS, WAAS and GAGAN. He is currently more specifically in charge of the CNES Navigation and Time Monitoring Facility (NTMF) designed to monitor GPS and SBAS Signals In Space and Performances, He is member of the WGC of the UE-US agreement in the promotion, provision and use of civil GPS and GALILEO navigation and timing signals and services.

ABSTRACT

The deployment of new dual-frequency GNSS constellations (modernized GPS, Galileo, GLONASS, Beidou) will support in the coming years aeronautical navigation services with an improved positioning performance and robustness.
The definition and analysis of the GNSS augmentation systems evolution to operate in this new dual-frequency multi-constellation (DFMC) environment is on-going. In the case of the SBAS evolution, the SBAS Interoperability Working Group (IWG) has worked on the development of an SBAS DFMC L5 Interface Control Document (ICD) in order to initiate the standardisation of the future SBAS DFMC system and services. Other working groups such as the EUROCAE WG-62 and the RTCA SC 159 have also started the development of

International Technical Symposium on Navigation and Timing (ITSNT) 2017
14-17 Nov 2017
ENAC, Toulouse, France

standards to support the introduction of future SBAS DFMC user receivers.
A SBAS DFMC Service Volume software Prototype (SBAS DSVP) has been developed by Egis Avia under a CNES contract as a tool to support the consolidation of the SBAS DFMC standardisation activities. The prototype is compliant with the most recent documentation produced by the IWG, and generates the sequence of broadcast SBAS DFMC messages and calculates the broadcast parameters required to analyse the availability and continuity of APV and CAT I operations in the SBAS service area. The prototype user module computes Horizontal and Vertical Protection Levels (HPL/VPL) from the SBAS L5 messages elaborated by the ground module.
This paper presents first the SBAS DSVP tool and secondly the SBAS DFMC performance analysis carried out with the SBAS DSVP under different system configurations carried out with the SBAS DSVP, including a potential single-frequency L5 SBAS back-up service.

1 INTRODUCTION

The modernization and deployment of different GNSS constellations (modernized GPS, Galileo, GLONASS, Beidou) broadcasting at least in a dual-frequency mode over Aeronautical Radio Navigation Service (ARNS) bands will support in the coming years aeronautical navigation services with an improved positioning performance and robustness (thanks to an increased number of available signals with improved geometry, ionospheric delay mitigation, etc.).
The definition and analysis of the GNSS augmentation systems evolution to operate in this new dual-frequency multi-constellation (DFMC) environment is currently carried out by several international working groups. In the case of the SBAS evolution, the SBAS Interoperability Working Group (IWG) has worked on the development of an SBAS DFMC L5 Interface Control Document (ICD) in order to initiate the standardisation of the future SBAS DFMC system and services [1][2]. Other working groups such as the EUROCAE WG-62 and the RTCA SC 159 have also started the development of standards to support the introduction of future SBAS DFMC user receivers.
In Europe, the EGNOS Version 3, designed as an SBAS DFMC system, is expected to be operational at the horizon of the completeness of the 24 GPS L1/L5 constellation (approximately in 2024) [3]. A consolidated SBAS DFMC standard is a key element to define the system design according to the targeted aeronautical services, as well as to assure the interoperability among other DFMC SBAS systems in the future to maximise the benefits of SBAS DFMC avionics.
Within this framework, the tool SBAS DFMC Service Volume software Prototype (SBAS DSVP) has been developed to support the SBAS DFMC standardisation activities.
The behaviour and performance of SBAS DFMC systems as defined in the latest IWG documentation have been analysed with the SBAS DSVP for different system configurations. The performance analysis is based on different indicators such as the service availability and continuity, the bandwidth occupation by the different Message Types or the time to first valid position fix (TTFF). Different system configurations have been tested to investigate the impact of different elements on the SBAS DFMC performance, such as the number of augmented constellations, a potential single-frequency L5 SBAS back-up service, and the presence of equatorial ionospheric scintillation.

2 SBAS DSVP DESCRIPTION

2.1 SBAS DSVP architecture

The SBAS DSVP has been designed to be used as validation platform to support SBAS DFMC standardisation activities. The prototype is compliant with the SBAS DFMC L5 ICD v1.3 produced by the IWG [1], and generates the sequence of broadcast SBAS DFMC messages and calculates the broadcast parameters required to analyse the availability and continuity of APV and CAT I operations in the SBAS service area as well as other system performance variables.
The tool has been developed following a modular approach in order to increase the flexibility of the tool for future evolution and adaptation of the final version of the SBAS DFMC concept of operation.
The Ground module manages the SBAS DFMC message sequence and computes the necessary parameters to be broadcast within the messages. The User module processes the SBAS L5 messages elaborated by the ground module and computes the Horizontal and Vertical Protection Levels (HPL/VPL). The Export module collects the broadcast SBAS L5 messages and save them in RINEX b v3 format. The Analysis module collects and processes the outputs generated by the different modules to create meaningful outputs for system performance analysis, such as availability and continuity maps, the chronogram of broadcast messages or the bandwidth occupation rate per Message Type. The inputs are managed by a specific interface which allows creating various operational scenarios to assess the impact in the user side. All these modules result into an end to end SBAS DFMC simulation platform providing for a selected set of GNSS core constellations the sequence of broadcast SBAS DFMC message types, the final user protection levels (PL) as well as performance indicators such as the availability for different aeronautical operations.
Figure 1 provides an overall architecture of the SBAS DSVP tool.

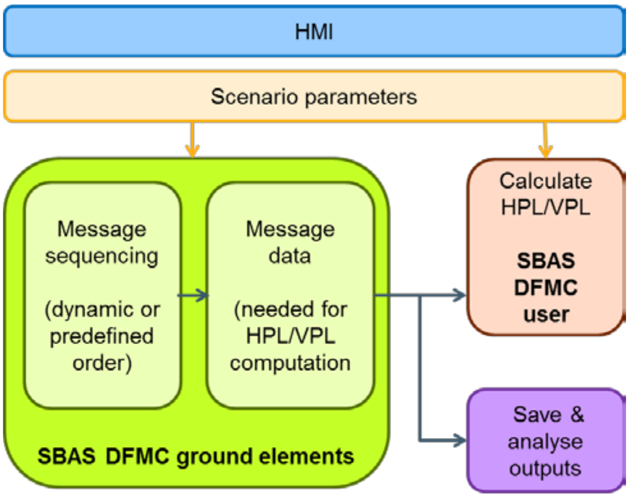

Figure 1 – SBAS DSVP architecture

The platform can be easy operated through the interface providing a pre-selected configuration. Expert users are also able to define their own default settings of the DFMC SBAS simulator.

2.2 SBAS DSVP functional description overview

The SBAS DSVP has been designed to be used as validation platform to support the consolidation of the SBAS DFMC standardization activities.

The SBAS DSVP interface allows configuring the space, ground and user segments, as well as selecting the outputs to be generated. Figure 2 shows the SBAS DSVP graphical interface that allows the prototype configuration.

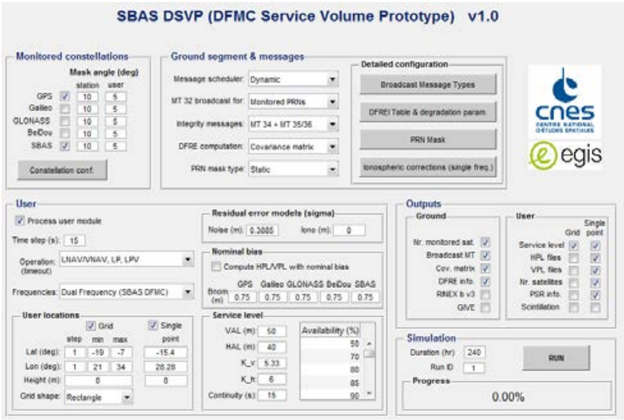

Figure 2 – SBAS DSVP graphical interface

Space segment

The prototype is able to simulate SBAS DFMC monitoring up to four core constellations. Satellite orbits are defined through an almanac file for each constellation. In addition, the operator can also configure the coordinates of SBAS geostationary satellites to be considered in the simulation. In addition the mask angle can be tuned separately for the ground and user segments, for each constellation individually. The whole space segment can be controlled so sensitivity analysis can be performed on the number of constellations augmented, on the number of satellite per constellation augmented and on the position of the GEO satellites with respect to the intended service area.

The prototype allows simulating SBAS satellites with and without ranging functionality.

Ground segment

The coordinates of the SBAS DFMC ground reference stations are defined by the operator through a configuration file.

The ground segment is in charge of the elaboration of the SBAS L5 message sequence.

The simulator computes at each epoch the DFREI of monitored satellites and the associated covariance matrix. This computation can be done following two methodologies. The first one is a look-up table function based on the number of visible ground stations defined by the operator. The second one is based on the estimation of the satellite clock-ephemeris covariance matrix estimated according to the network of ground stations [4]. The latter option has been used in the analyses presented in this paper.

The prototype implements different strategies for broadcasting correction messages (MT 32). The solution adopted in [1] is used in this paper: SBAS correction messages are provided for all PRNs selected in the mask and monitored by the system (the SBAS DSVP considers a satellite is monitored by the system if it is visible by at least a minimum number of reference stations, which has been set to 5 in this paper). Such approach allows testing of multiple operational scenarios in order to assess the impact of each correction transmission options on the end user performances.

The SBAS DSVP generates as well the sequence SBAS L5 messages broadcast during for the whole duration of the simulation. The operator can define the list of message type as defined in the current SBAS L5 ICD [1] through the "Broadcast Message Types" window accessible via the message frame in the main panel control. The message type (MT) number, timeout, maximum update time and associated PRN options can be set in order to schedule properly the message flow (see figure 4 left part). It provides the capacity to introduce new and/or additional message type in order to assess the impact in the bandwidth and overall message flow. The message scheduler implemented generates SBAS L5 message type either in a dynamic mode taking into account of the maximum update rate and timeout characteristic of each messages or in a static mode through a predefined MT sequence.

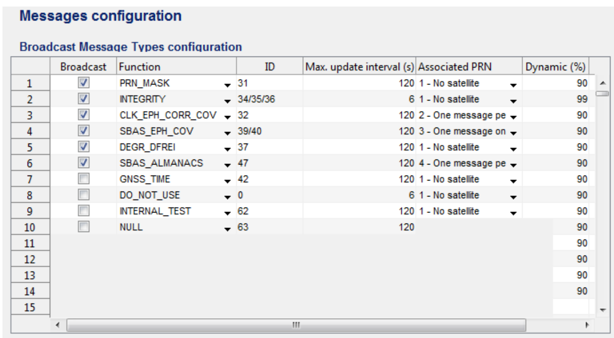

Figure 3 – SBAS DSVP Message Type configuration interface

Specific message type parameters such as the DFREI scale table, OBAD information and degradation parameters are configurable as well. These values have been set to match the closest possible values currently broadcast by EGNOS for the analyses shown in this paper.

User Segment

The operator can define the user coordinates via user grid points and/or specific location to compute simulation results worldwide, regionally or in a given location.
The user error models are tunable also.
The operator can configure as well the parameters of interest for the computation of end user performance, such as the VAL, HAL and the continuity window.

Main outputs

Several products are available as the result of a given simulation in order to support the analysis of the SBAS DFMC system and user performances. Those products are:

- SBAS message analysis products
    - Bandwidth occupation per message type
    - Distribution of the time to first fix
    - Observed update intervals per message type
    - Number of satellites selected in the PRN mask and monitored by the ground
- SBAS correction analysis products
    - Distribution of DFRE before discretization and DFRE discretization error
    - Plots of sigma DFRE versus visible stations or GDOP
- User service analysis products
    - Availability maps for various alert limits
    - VPL and HPL statistical maps
    - Pseudorange error distribution at specific locations

3 SBAS DFMC PERFORMANCE ANALYSIS

Different system configurations have been tested to investigate the impact of different elements on the SBAS DFMC performance, such as the number of augmented constellations, a potential single-frequency L5 SBAS back-up service, and the presence of equatorial ionospheric scintillation. The SBAS DFMC ground station network is assumed to be located at the same coordinates as for current EGNOS. Two SBAS DFMC GEO satellites are used located at longitudes 31.5°E and 5°E respectively without ranging function.

3.1 Impact of number of monitored constellations

The dual constellation GPS (27 SV) and Galileo (24 SV) configuration has been compared against the four constellation case including GLONASS (23 SV) and BeiDou (27 SV) constellations.

One of the main differences between both analysed scenarios is that in the dual-constellation case the PRN Mask contains 51 selected satellites, which allows broadcasting integrity messages through MT 35. The four constellation case contains 92 selected satellites in the PRN mask, which requires broadcasting MT 34. Indeed the SBAS DFMC dual-frequency range error (DFRE) model for a given satellite can be broadcast in two different ways: the complete value (as in MT35/MT36), or a change indicator relative to a previous value (as in MT 34). The first solution allocates more bits per satellite in the message, which requires up to two messages to provide the information for more than 51 monitored satellites. The second solution broadcasts the integrity information for all monitored satellites in a single message, but requires users to have previously received and stored a valid reference value.

Dual constellation configuration

In dual constellation configuration, the SBAS DFMC ground network monitors between 18 and 28 satellites at a given epoch. Most of the bandwidth is occupied by satellite corrections (approximately 55% of broadcast messages are MT 32) and of integrity messages (approximately 35% of broadcast messages are MT 35) (Figure 4). The observed update intervals of each Message Type are below the requirements given in [1].

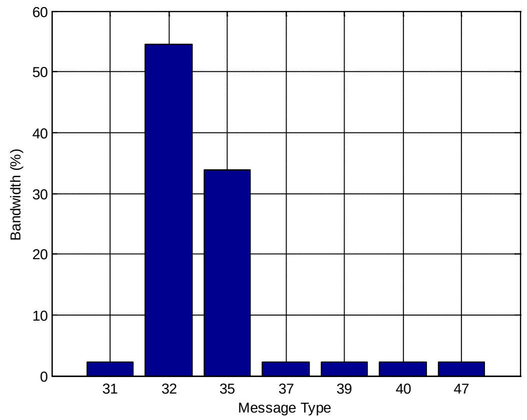

Figure 4 – Bandwidth occupation per Message Type (dual constellation)

The horizontal availability with a HAL of 40 m is of 100 % over the European region (Figure 5). The vertical availability with a VAL of 10 m is of 99% in most of the European region, and of 99.9% in most of the European region, with lower availability rates in the South West and for latitudes above approximately 60° (Figure 6).
The availability maps represent the location of ground stations with a cross. The four solid black lines define the availability boundary 99%, 99.5%, 99.9% and 99.99% respectively.

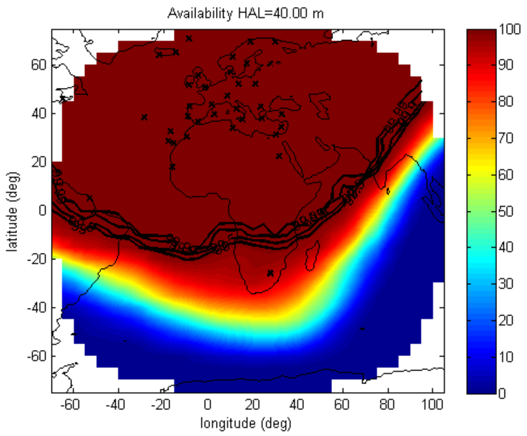

Figure 5 – Horizontal availability (%) (dual constellation)

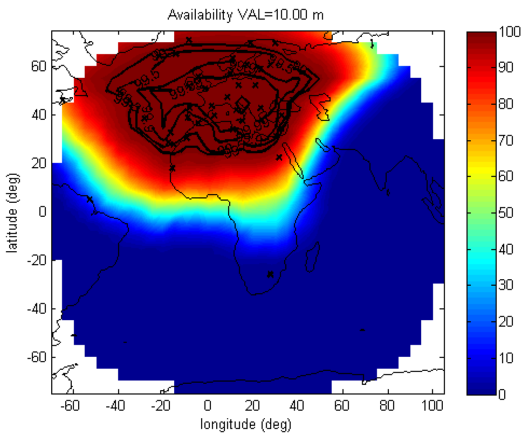

Figure 6 – Vertical availability (100%) (dual constellation)

<u>*Four constellation configuration*</u>

The SBAS DFMC ground network monitors between 33 and 48 satellites at a given epoch. Most of the bandwidth is occupied by satellite corrections (approximately 66% of broadcast messages are MT 32) and of integrity messages (approximately 26% of broadcast messages are MT 34) (Figure 7). The percentage of broadcast MT 35 over the total number of broadcast messages is approximately 0.0025% which means MT 35/MT36 had to be broadcast instead MT 34 22 times during the 10-day simulation. The observed update intervals of each Message Type are below the requirements given in [1].

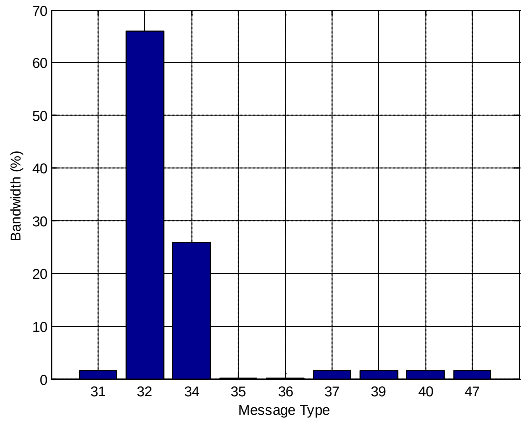

Figure 7 – Bandwidth occupation per Message Type (four constellations)

The horizontal availability with a HAL of 40 m is of 100 % over the European region and a significant part of Africa (Figure 8). The vertical availability with a VAL of 10 m is higher than 99.9% over the European region and north of Africa (Figure 9).

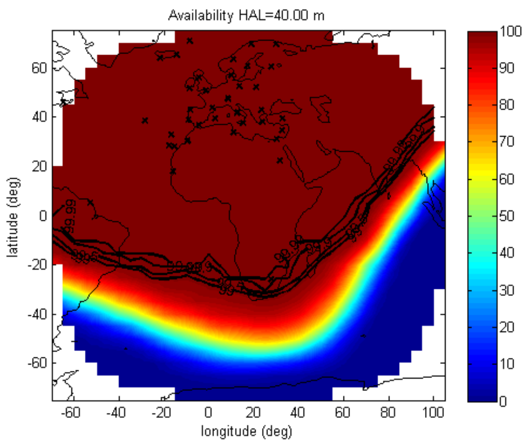

Figure 8 – Horizontal availability (%) (four constellations)

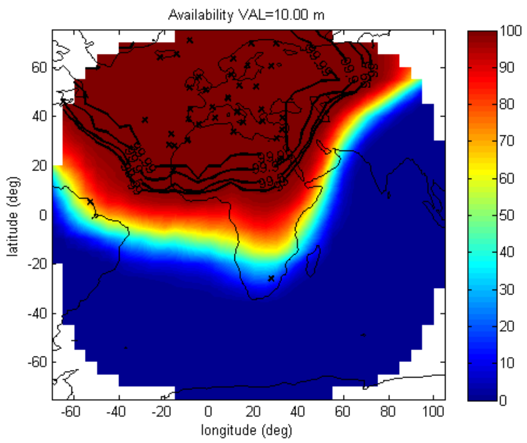

Figure 9 – Vertical availability (100%) (four constellations)

3.2 Impact of a potential single-frequency SBAS L5 service

The provision of single-frequency L5 ionosphere corrections is not considered in the SBAS DFMC L5 ICD [1]. However, it would provide a single-frequency SBAS back-up in case of loss of the L1 frequency band, with a better performance than an ABAS/RAIM solution. A single-frequency SBAS L5 mode has been implemented in the SBAS DSVP in order to test the feasibility of broadcasting in L5 single frequency ionospheric mask and correction messages equivalent to MT18/MT26, and to analyse the performance of such mode.

Most of the broadcast Messages Types are satellite corrections (MT 32, approximately 40%), integrity messages (MT 35, approximately 32%) and ionospheric corrections (MT 56, approx. 14%; MT 48 approx. 4%) (Figure 10).

The observed updated interval of each MT meets the requirements of [1]. No significant negative impact has been observed in the message update interval under the analysed conditions (dual-constellation, L5 IGP mask equivalent to the one currently used in EGNOS).

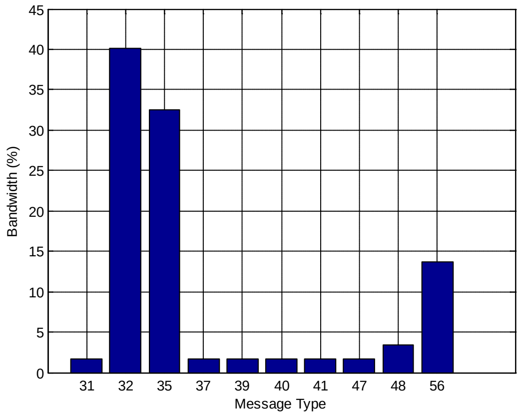

Figure 10 – Bandwidth occupation (dual constellation with SBAS L5 single frequency messages)

The horizontal availability with a HAL of 40 m is of 100 % over the continental European region, and of 99.9 % over the European region including Iceland and North of Africa. The system is unavailable outside that area, in part due to the L5 IGP mask limited to that area (Figure 11).

The vertical availability of single-frequency SBAS has been assessed with a VAL of 35 m, which corresponds to a service level equivalent to LPV-200, the target of single-frequency SBAS systems. The vertical availability with a VAL of 35 m is of 100% over the continental European region, and of 99.9% over the European region including Iceland and North of Africa. The system is unavailable outside that area (Figure 12).

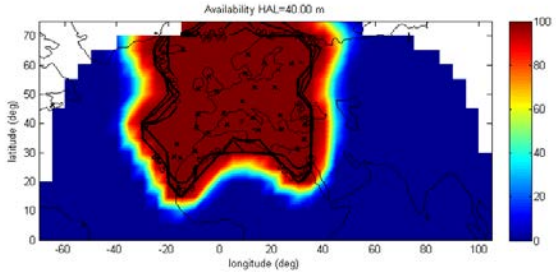

Figure 11 – Horizontal availability (dual constellation, single-frequency SBAS L5 users)

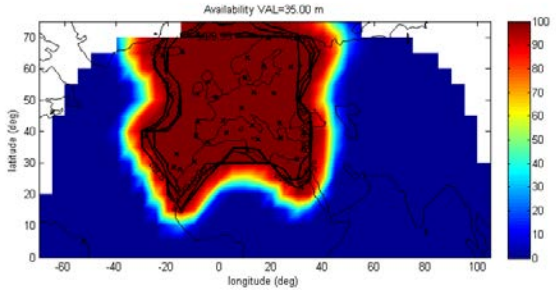

Figure 12 – Vertical availability (dual constellation, single-frequency SBAS L5 users)

3.3 Impact of equatorial scintillation

An equatorial scintillation degradation model has been implemented in the SBAS DSVP to analyse the impact of such phenomenon in the service level provided by SBAS DFMC. This model is based on the results of recent studies on the ionosphere behavior in African equatorial areas [5], and associates a probability of losing track of a satellite due to the effect of equatorial scintillation as a function of different parameters such as the user location, the satellite elevation angle and the time of the day.

The observed impact of the scintillation model in the availability performance is not significant. However it may degrade the performance of specific users at specific epochs.

4 CONCLUSIONS

An SBAS DFMC Service Volume software Prototype (DSVP) platform has been presented. The tool has been developed to support SBAS DFMC standardisation activities and implements the SBAS DFMC L5 ICD v1.3 [1]. The platform is flexible, so it can be adapted to the development of future SBAS DFMC standards. The tool allows the operator to configure a large number of system parameters to define analysis scenarios. The SBAS message flow can be completely controlled by the operator for validation of the final version of the ICD.

Initial results show a promising increase of coverage for stringent applications such as CAT I precision approach with a 10 m VAL in a dual constellation and a four constellation case. The analysis of the four constellation case shows that the system manages the message scheduling within the maximum update intervals, and that integrity information may need to be broadcast in some epochs within two messages (MT35/MT36).

Although a single-frequency SBAS L5 mode is not considered in [1], it would provide a back-up mode in case of loss of the L1 frequency band with a better performance than an ABAS/RAIM solution. The analysis of a SBAS DFMC system including a SBAS L5 ionospheric correction messages equivalent to those used in current SBAS has shown that no significant negative impact has been observed in the update interval of the different Message types under the analysed conditions (dual-constellation, L5 IGP mask equivalent to the one currently used in EGNOS).

The SBAS DSVP implements an equatorial scintillation model based on the results of recent studies on the ionosphere behavior in African equatorial areas [5]. The observed impact of the scintillation model in the availability performance is not significant, although individual users may see their performance degraded at specific epochs.

ACKNOWLEDGMENTS

The authors would like to thank the involvement and support of CNES, in particular Mr François Dufour, and of DSNA (the French Air Navigation Service Provider), in particular Mr Philippe Estival, for their advices in the frame of the SBAS DSVP design and development.
The opinions expressed in this paper reflect the authors view only. CNES and other referenced bodies are not liable for the use of any of the information included herein.

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