On the performance of dual-frequency multi-constellation SBAS: real data results with operational state-of-the-art SBAS prototype

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BIOGRAPHIES

Javier Simon received his MSc. degree in Telecommunications Engineering from the Polytechnic University of Madrid, Spain, in 2006. Since then, he has worked in GMV in the Advanced Systems Division (GNSS). He has participated in several projects for the study and design of future GNSS algorithms and systems like ARCTIC and MLUTB (Multi-Constellation Regional System Land Users Test-Bed) for ESA, GSC (Galileo Service Consolidation) for the European Commission and SACCSA (Augmentation System for Caribbean, Central and South America) for ICAO. His main interests include RAIM concepts and algorithms for SBAS systems.

Javier Ostolaza has currently finished the Master in Space Technology at Polytechnic University of Madrid. He got his MSc. degree in Telecommunications Engineering in 2007 at University of Cantabria. He has been working at GMV within the GNSS Business Unit, since 2008, where along these years he has got an extensive experience in GNSS demonstrators such as ***magicSBAS*** and SPEED contributing to their real-time and communication algorithms and integrating the emerging network of NTRIP stations to ***magicSBAS***. He has also collaborated in the adaptation of the ***magicSBAS*** algorithms to cover different service areas (South America, South Africa, Australia and New Zealand, Korea) adapting also some GMV performance analysis tools such as Teresa, ***magicGEMINI*** and Eclayr.

Jorge Morán received his MSc. degree in Telecommunications Engineering from the University Of Oviedo, Spain, in 2008. Since then, he has been working at GMV within the GNSS Business Unit, where along these years he has participated in several projects for the technical and operational validation of EGNOS such as ATPAIV or TERESA, as well as other GMV tools for SBAS performance assessment like ECLAYR or magicGEMINI. He has also been involved in the evolution of EGNOS Data Access Service (EDAS) for the European Commission.

Miguel A. Fernández received his MSc. degree in Telecommunications Engineering from the Polytechnic University of Valencia, Spain, in 2006. Until 2008, he worked for the Spanish Industry Ministry monitoring Satellite Radio- frequency signals. Since then, he has been working in GMV in the Advanced Systems Division (GNSS). He has participated in several projects for the study and design of future GNSS algorithms and systems like FEATURE, GENESI and MLUTB for ESA. He has also contributed to the implementation and evolution of GNSS demonstrators such as SPEED and ***magicSBAS***. Since 2011, he is responsible for EGNOS ASQF (Application Specific Qualification Facility) evolutions at GMV.

Jose Caro took his Ph.D. in Theoretical Physics in 1996. He joined the company GMV in 1998. Since then, he has worked in satellite navigation related projects, most of them in the EGNOS programme, the European SBAS, being one of the designers and developers of the EGNOS central processing subsystem. In 2009, he was awarded with the Galileo Masters prize. He is currently the head of the GNSS Advanced Systems Division at GMV.

Alberto Madrazo received his Ph.D. in Physics in 1997. Since 2001 he is working in GMV, where he has been involved in different GNSS related project, most of them related to the EGNOS programme. He is currently the team leader of a group of project mainly devoted to the engineering analysis related to future evolutions of SBAS systems. In particular, he is the product manager of the ***magicSBAS*** tool suite.

ABSTRACT

The analysis of the current trends observed in the navigation community suggests that, for the coming years, the GNSS integrity solutions may rely on Satellite Based Augmentation Systems (SBAS), Ground Based Augmentation Systems (GBAS), Receiver Autonomous Integrity Monitoring (RAIM) or new techniques including integration with other sensors. In the aviation community, SBAS already enjoyed recognition at regulatory level and is considered as a reference navigation aid. Recently, ICAO has developed the Performance Based Navigation concept – PBN – and established an international schedule for APV at all instrument runway ends either as the primary approach or as a back-up for precision approaches. Most countries are producing their PBN implementation plans to meet

ICAO recommendation and the use of the SBAS technology seems to be the most adequate solution for many countries.

Development and deployment of a SBAS system in any region of the world could be a serious technological challenge. Besides, each region may have different characteristics and requirements. The ionosphere behavior is, for instance, a key issue for implementation of SBAS in some regions. At the current moment, WAAS in US, MSAS in Japan, and EGNOS in Europe have been declared operational and available for civil aviation. These systems augment the navigation service of the primary GPS constellation but, at the same time, the development of new GNSS constellations, like GLONASS, Galileo and COMPASS is on its way. This is an important driver for investigating the definition of new generation SBAS systems. The current discussions on SBAS evolution rely on enhancements towards multi-constellation and dual-frequency capabilities.

As a consequence of the technological challenge, it is usual that SBAS development plans envisage the deployment of SBAS testbeds (e.g.; WAAS NSTB, EGNOS ESTB) and pre-operational, non-certified, services at the initial stages of the operational system development. Testbeds offer numerous advantages, in particular provide the system developers with powerful platforms to early validate new concept architectures, first design solutions and performance assumptions, thus greatly mitigating design risks and helping to optimize the design to satisfy the requirements of the region.

magicSBAS is a state-of-the-art operational SBAS testbed developed by GMV to offer non-safety critical SBAS augmentation to any interested region. The algorithms implemented in ***magicSBAS*** have been fully developed by GMV and are the result of more than 15 years of experience in the development of EGNOS and other SBAS programs. The ***magicSBAS*** algorithms, originally designed to mimic EGNOS performances over the ECAC service area, have been further optimized and tuned to provide the best performances in other regions of the world (South America, South Africa, Russian Federation, etc).

Recently, ***magicSBAS*** has been upgraded with new capabilities, as the generation of SBAS message MT28, the capability to augment several primary constellations (GPS+GLONASS) and the provision of a service to dual-frequency users. The paper shows first that ***magicSBAS*** is representative of EGNOS performances. This is achieved by comparing EGNOS and ***magicSBAS*** performances maps (availability and continuity) for the same period of time. Once the representativeness is proven, different analyses are run to show SBAS service improvements using the new ***magicSBAS*** capabilities:

- Generation of SBAS message MT28 vs. the provision of service using MT27 message.
- Incorporation of the GLONASS constellation for the computation of the ionosphere monitoring, which is one of the drivers for SBAS performances.
- Provision of service to dual-frequency users. Dual-frequency users are capable of getting rid of the ionosphere delay and consequently they do not need from ionosphere corrections and integrity parameters (GIVD and GIVE). Although a standard for these users is not yet available, the paper will detail the assumptions made for simulating these service to users.
- Service availability using a second augmented constellation at user level (GPS+GLONASS).

One of the key advantages of ***magicSBAS*** is the capability to process raw data in standard formats like NTRIP, RINEX, EDAS, SPEED or EGNOS formats. There are currently hundreds of Continuous Operating Reference Stations (CORS) worldwide providing data in these formats that can be used together with ***magicSBAS*** to quickly evaluate the SBAS performances. This capability has been used during the study to show EGNOS service improvements in areas like Africa and Eastern Europe thanks to the new ***magicSBAS*** capabilities. It is important to remark that all performances shown in this study have been obtained using real data.

Thanks to all these analyses, the study provides a clear picture of the performances that will be reached by future SBAS systems, once the multi-constellation and multi-frequency capabilities are developed. Because of the extensive use of real data, and because of having based the algorithms proposed on EGNOS, the authors are confident that the results shown in this paper are representative of the ones expected in the future operational SBAS evolutions.

INTRODUCTION

The objective of this paper is to investigate future performances achievable by multiconstellation dual-frequency SBAS systems. Some previous studies as [1] and [2] have investigated on this topic based on service volume simulations. This study goes a step further as it is fully based on the use of real data. For that purpose, a SBAS demonstrator called ***magicSBAS*** has been used by analyzing input real GPS+GLONASS L1 and L2 data. ***magicSBAS*** is a state-of-the-art operational SBAS testbed developed by GMV to offer non-safety critical SBAS augmentation to any interested region.

Recently, ***magicSBAS*** has been upgraded with new capabilities, being the major ones the generation of SBAS message MT28, the multi-constellation capability and the provision of service to dual-frequency users. After showing that ***magicSBAS*** is representative of a state of the art SBAS (i.e. we are able to reproduce EGNOS performances over the same service area), the paper will provide ***magicSBAS*** performances figures for all SBAS algorithm evolutions mentioned previously. Real data will be used extensively in the analyses.

The paper is organized as follows. First, an introduction to SBAS system and ***magicSBAS*** GMV tool will be provided. Then, performances for upgraded ***magicSBAS*** will be presented. First it will be shown that ***magicSBAS*** is representative of EGNOS performances. This is achieved by comparing EGNOS and ***magicSBAS*** availability and continuity maps for the same period. Once the representativeness is proven, different analyses will show improvements with the new capabilities:

1. Service area improvements not related to multiconstellation, SBAS message MT28 or dual-frequency capabilities. These service area improvements have been obtained after several years of evolution and tuning of ***magicSBAS*** original algorithms.
2. Multiconstellation performances. Performances improvements with the incorporation of the GLONASS constellation for the computation of the ionosphere monitoring. Also service availability using a second augmented constellation at user level (GPS+GLONASS).
3. Generation of SBAS message MT28 and the provision of service to dual-frequency users. Dual-frequency users are capable of getting rid of the ionosphere delay and consequently they do not need from ionosphere corrections and integrity parameters (GIVD and GIVE). Although a standard for these users is not yet available, the paper will detail the assumptions made for simulating this service to users.
4. Other areas analyses. Thanks to the ability of ***magicSBAS*** to process data from reference stations in different formats (NTRIP, RINEX or EDAS) it will be shown the performances that can be achieved by a dedicated SBAS system in South Africa.
5. 4-GNSS multiconstellation augmentation. Despite a SBAS standard for augmenting four constellations at the same time (4-GNSS augmentation) is not available yet, ***magicSBAS*** has been upgraded to allow the internal processing of 4-GNSS constellations (GPS, GLONASS, Galileo and COMPASS). This section will provide some system indicators for the SBAS performances that can be obtained with this number of augmented satellites. This analysis has been performed with simulated data generated with the End To End EEGNOS Simulator (EETES) which is a tool used for the EGNOS validation. It is important to point that this is the only analysis in the paper executed with no-real data.

The paper will finish with the conclusions obtained after the work performed.

WHAT IS AN SBAS SYSTEM?

A Space Based Augmentation System (SBAS) is in charge of augmenting the navigation information provided by different satellite constellations (such as GPS or GLONASS and in the future Galileo and COMPASS) by providing ranging, integrity and correction information via geostationary satellites. In order to achieve this objective, the system is composed of:

1. Ground infrastructure,
2. SBAS geostationary satellites
3. SBAS receivers.

The ground infrastructure includes the monitoring and processing stations, which receive the data from the navigation satellites, and a central processing component that computes integrity, corrections and ranging data to build the SBAS signal-in-space (SIS).

The GEO SBAS satellites relay the Signal In Space (SIS) from the ground infrastructure to the SBAS user receivers, which determine position and time information from core satellite constellation(s) and SBAS SIS. The SBAS receivers acquire the ranging and correction data and apply these data to determine the integrity and improve the accuracy of the derived position.

The SBAS ground infrastructure measures the pseudorange between the satellites and a set of SBAS reference receivers at known location and provides separate corrections and levels of confidence for satellite position errors, satellite clock errors and ionospheric errors. The user will apply these corrections to improve its position estimate and its level of confidence.

EGNOS is the European implemented SBAS, which has equivalent counterparts in other regions, like the Wide Area Augmentation System (WAAS) developed by the US Federal Aviation Administration (FAA) over North America, or the Japanese Multi-transport Satellite-based Augmentation System (MSAS) over Asia. The following figure shows these SBAS systems as well as other planned SBAS systems in regions like Russia, South America or Africa.

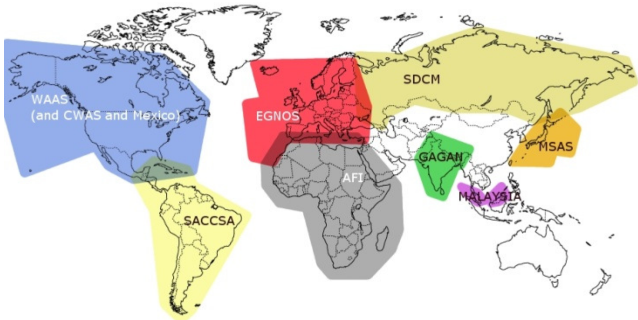

Fig. 1: Current and future SBAS systems

The following figure shows the GEO coverage and the applicability region of EGNOS, designed for the European Civil Aviation Community (ECAC) users.

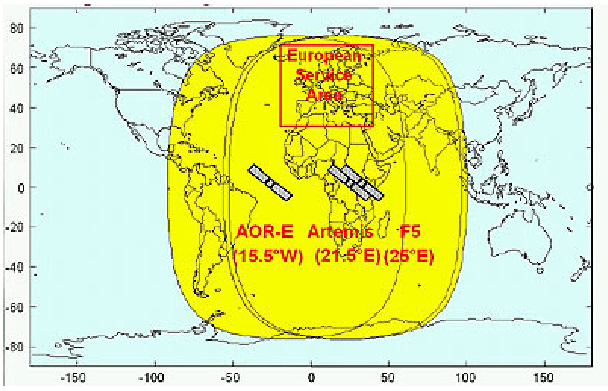

Fig. 2: ENGOS coverage area

WHAT IS *MAGICSBAS*

magicSBAS is a low cost SBAS prototype that collects real time raw data in standard formats and computes wide area SBAS corrections and integrity parameters fully compliant with RTCA/DO-229D [4] and ICAO SARPs [5] standards. The algorithms implemented in ***magicSBAS*** have been fully developed by GMV and are the result of more than 15 years of experience in the development of EGNOS and other SBAS programs. The ***magicSBAS*** algorithms have been optimized to provide the best performance in the most demanding conditions and have been tested in many regions of the world.

Fig. 3: Schematic representation of *magicSBAS*

The ***magicSBAS*** augmentation message can be disseminated to users via internet, using the SISNET protocol [6], or make it available in binary format for broadcasting through a GEO satellite. ***magicSBAS*** also offers the capability to emulate virtual DGPS stations producing local corrections in RTCM SC-104 v2.3 format [7]. This is in line with latest ideas seeking for multi-modal applications of SBAS services. DGNSS provision thanks to SBAS infrastructure is a major cost-reduction driver of DGNSS services for maritime users.

magicSBAS can be run both in real-time and fast post-processing replay modes. In real-time mode, ***magicSBAS*** can be used to provide a SBAS service. In fast post-processing replay mode, magicSBAS is the ideal tool to support SBAS engineering and feasibility studies.

The complete ***magicSBAS*** product suite includes a real-time service monitor and two performance analysis modules called ***Eclayr*** [8] and ***magicGEMINI*** [9].

Eclayr is a system and service performance analysis tool that assesses accuracy, integrity, continuity and availability performances of the SBAS service both in the range (UDRE and GIVE) and user domains. The main features of the tool can be summarized as:

- Post-processing mode.
- Detection and reporting of system events.
- User friendly, easy-to-use graphical interface.
- Reports in HTML format.
- Windows operating system.

magicGEMINI purpose is to analyze user performance augmented with SBAS messages, being the main inputs the user data and the SBAS message. The main characteristic of the tool can be summarized as:

- Computation of accuracy, integrity, continuity and availability performances at defined user locations.
- User friendly, easy-to-use graphical interface.
- Real time and post-processing modes.
- Windows operating system.

One of the main advantages of ***magicSBAS*** is the capability to process raw data in standard formats like NTRIP, RINEX, EDAS, SPEED or EGNOS formats. There are currently hundreds of Continuous Operating Reference Stations (CORS) worldwide providing data in these formats that can be used together with ***magicSBAS*** to quickly evaluate the SBAS performances. The NTRIP format in particular is a widely extended, open non-proprietary format designed to disseminate GNSS streaming data to stationary or mobile users on the internet.

Real-time NTRIP data and stations are currently widely available worldwide, either free or under subscription. This capability has been used during this study to show EGNOS service improvements in areas like Africa and Eastern Europe thanks to the new ***magicSBAS*** capabilities. The use of real data guarantees that the results shown in this paper are representative of the ones expected in the future operational SBAS evolutions.

REPRESENTATIVITY OF *MAGICSBAS* WITH RESPECT TO EGNOS OPERATIONAL PERFORMANCES

We show in this section the representativity of the ***magicSBAS*** tool with respect the current performances of an operational SBAS. To this end, we have computed the EGNOS performances from the operational Signal In Space (SIS) data using appropriate analysis tools such as ***Eclayr*** Existing EGNOS performances over ECAC were firstly assessed in terms of service availability and continuity (see Fig. 5 and Fig 7, respectively). Service level considered was APV-I: alarm limits were set to 40 m in the horizontal component and 50 m in the vertical component. Service was thus said to be available at a certain epoch when calculated protection levels HPL < 40m and VPL < 50m. The continuity risk is computed as the probability of having a continuity event (PL>AL) during the period [T0, T0+15 sec] provided that the service was available at T0 (PL<AL).

APV-I service level availability (Fig. 5) and continuity (Fig. 7) have been then evaluated for ***magicSBAS*** running with a set of processing algorithmic functions that mimic the processing facilities of the current EGNOS baseline. As input data, ***magicSBAS*** was feed from real Ranging and Integrity Monitoring Stations raw data (same configuration for the ground system monitoring station network that EGNOS).

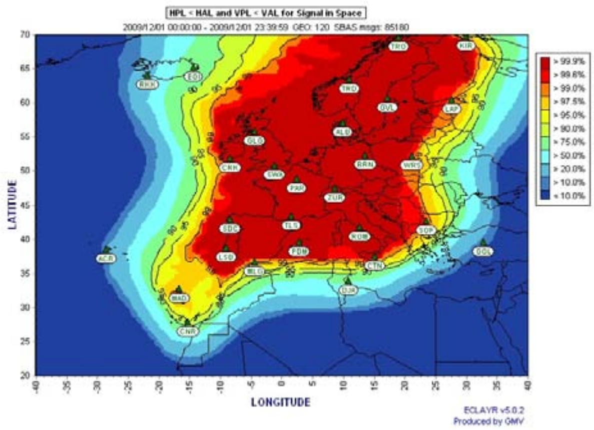

Fig. 4: EGNOS APV-I availability

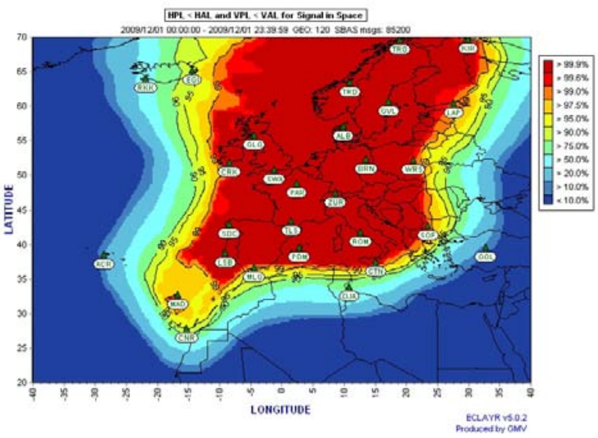

Fig. 5: magicSBAS APV-I availability

The aforementioned ***Eclayr*** tool was used for the performances evaluation using ***magicSBAS*** outputs. The same tool was used for the EGNOS and ***magicSBAS*** performance analyses to allow a proper comparison between both systems.

The similarity of availability and continuity performances between EGNOS and ***magicSBAS*** can be observed in figures from Fig. 4 to Fig. 7 assuring the representativity of the ***magicSBAS*** tool.

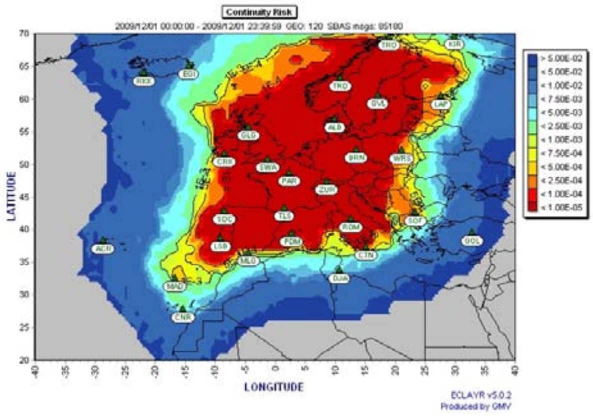

Fig. 6: EGNOS APV-I continuity

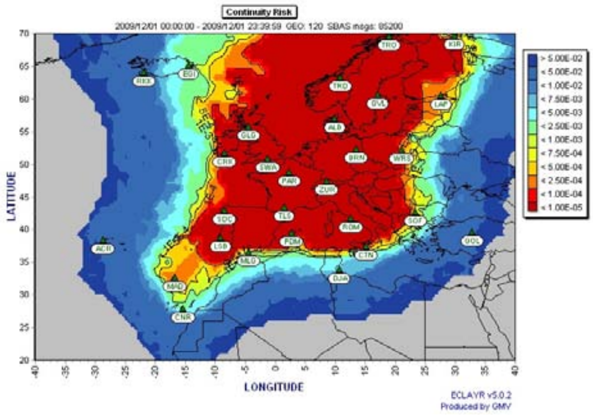

Fig. 7: magicSBAS APV-I continuity

MONOCONSTELLATION (GPS) *MAGICSBAS* SERVICE AREA IMPROVEMENTS

magicSBAS has been continuously evolving and upgrading along the last years, for instance in order to improve its underlying algorithms to optimize final user performances near the ECAC borders including the Canary and Azores Islands, Eastern Europe countries and North Africa.

Several algorithmic modifications to ***magicSBAS*** have been explored with and without considering the addition of new RIMS stations. The challenge has been always to improve availability and continuity figures both in the original and extended service area by keeping the integrity safety margins. This has been achieved by characterizing the high-level processing functions which are key contributors to the final user performances and concluding on the best suited modifications to improve such performances.

By modifying the navigation kernel algorithms (mainly ionosphere ones) big gains in availability and continuity were obtained. This situation is represented in Fig. 8 and Fig. 9. Fig. 8 provides ***magicSBAS*** availability performances running with a set of baseline navigation kernel algorithms. Fig. 9 provides availability performances obtained with ***magicSBAS*** enhanced algorithms to improve the service availability. The availability upgrade is clearly visible in the entire ECAC border. In particular, the coverage area is extended to the West (Azores Islands) and to the South (Canary Islands and North Africa). An even more appreciable service extension can be observed in the Eastern ECAC zone with just the introduction of one single additional reference station in Lugansk (Ukraine).

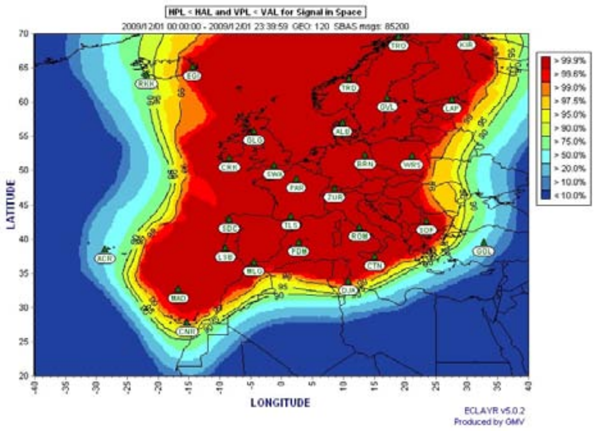

Fig. 8: *magicSBAS* APV-I availability for baseline navigation kernel

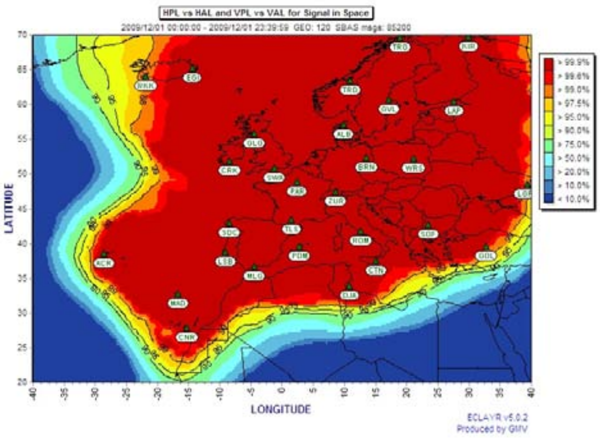

Fig. 9: Enhanced *magicSBAS* APV-I availability with algorithms improvements plus additional station in Lugansk (Ukraine)

MAGICSBAS MULTICONSTELLATION (GPS+GLONASS) PERFORMANCES

The objective of this section is to show performances improvements when multiconstellation features are included in the computation of the augmentation service. We have studied two interesting cases:

- GPS L1 SBAS user with internal use of GLONASS at system level. Study of the improvement in the internal corrections estimation algorithm when using GPS and GLONASS input measurements. This is particularly important for the computation of the ionosphere monitoring, which is one of the drivers for SBAS performances.
- GPS+GLONASS L1 user. This part will evaluate performances using a second augmented constellation at user level (GPS+GLONASS).

For this purpose a network of reference 31 stations has been selected. Data for running this analysis has been obtained from EUREF network [10], which provides real input data for both GPS and GLONASS constellations.

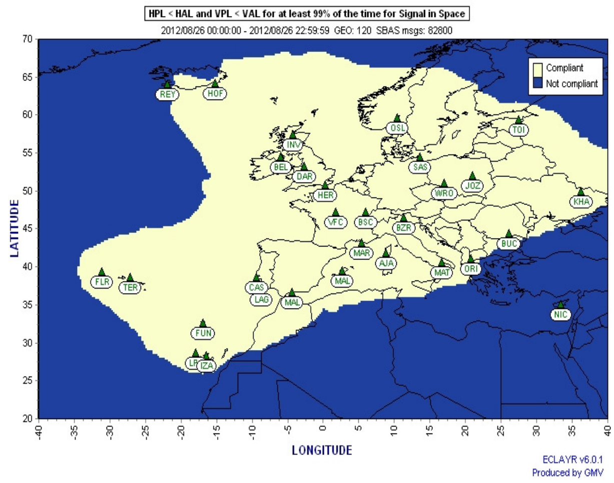

Fig. 10: *magicSBAS* APV-I availability (99% requirement) with GPS.

Fig. 10 provides performances for the GPS only case (reference computation). The white area in the figure is the area in which APV-I is available (HPL < 40m and VPL < 50m) for at least 99% of the simulation time[1].

It will be shown now how the incorporation of a second constellation in the internal estimation processing improves service coverage area. Fig. 11 shows performances when GLONASS and GPS data is used within ***magicSBAS*** for the ionosphere estimation, while only GPS is used at user level. It is noticeable that the service area is increased notably with respect to Fig. 10. The use of GLONASS within ***magicSBAS*** allows

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[1] The APV-I coverage area has been reduced with respect to the computations of the EGNOS performances. This is due to the reduced number of available ground reference stations providing GPS and GLONASS input data with respect the EGNOS network size (only GPS constellation being monitored)

monitoring more IGPs, specially is the borders of the coverage area, as measurements between GLONASS satellites and reference stations are now available for ionosphere estimation. This is particularly relevant in this case in the north of the service area, where there are almost no reference stations.

Fig. 12 shows performances when GLONASS is also used at user level together with GPS. The coverage area is also extended with respect to the previous step. Now, this plot is much more similar Fig. 9, in which a denser network of reference stations was used.

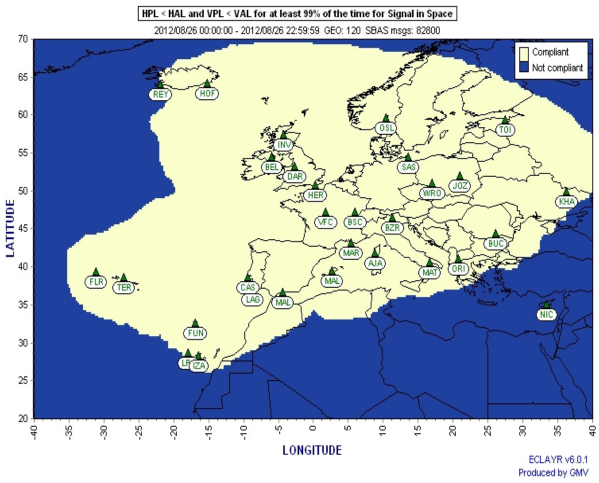

Fig. 11: *magicSBAS* APV-I availability (99% requirement) with GPS. GPS+GLONASS input data used for iono estimation.

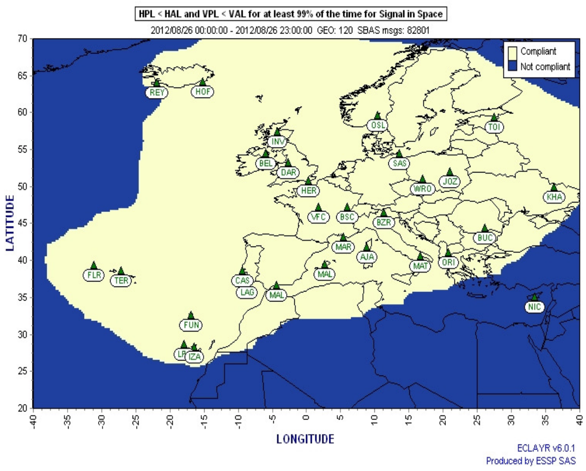

Fig. 12: *magicSBAS* APV-I availability (99% requirement) with GPS+GLONASS. GPS+GLONASS used for iono estimation.

It can be concluded that the multiconstellation capability is a desirable option in order to improve the performances. In case the user only works with GPS, a second constellation as GLONASS can be used at system level to improve the service coverage area, by increasing the number of lines of sight for monitoring more IGPs. In case the second constellation can be used at user level the performances are further improved. Another conclusion that can be reached is that the multiconstellation capability can be a solution to reduce the number of SBAS reference stations without reducing the service coverage area.

MAGICSBAS MT28 AND DUAL-FREQUENCY PERFORMANCES

The advantage of MT28 message is that each user can compute its own specific satellite orbit and clock error bound instead of using the error bound for the Worst User Location (WUL) in the service area. For some users this can result in a reduction of the final UDRE by an important factor, improving service availability. The advantage of dual-frequency users is that they are capable of getting rid of the ionosphere delay and consequently they do not need SBAS SIS ionosphere corrections and integrity parameters (GIVD and GIVE). This section will show how SBAS service area can be widely extended when SBAS MT28 is broadcasted and service to dual-frequency users is provided.

For mono-frequency users ***magicSBAS*** estimates a L1 clock. Based on this L1 clock estimation, ***magicSBAS*** traditionally sent clock corrections for a L1 user. For dual-frequency users ***magicSBAS*** has been upgraded to estimate a dual-frequency L1-L2 clock. Based on this estimation, ***magicSBAS*** now sends corrections for L1/L2 user. This is done taking into account that GPS L1-L2 users correct pseudoranges by means of Δt_{SV}, but not by T_{GD} as described in GPS ICD [3]

It is important to point out that ***magicSBAS*** uses L1C and L2P GPS measurements for the estimation of the GPS L1-L2 clock. Additionally, ionosphere SBAS messages MT18 and MT26 are no longer generated, as bi-frequency users are capable of getting rid of ionospheric delay by means of the iono-free combination. This gives ***magicSBAS*** extra bandwidth than can be used for a more frequent update of the rest of SBAS messages. Protection Levels are computed at user level following MOPS standard [4] but without applying any σ_{UIRE} factor. Additionally, the σ_{noise} factor is incremented by the increase of the measurement noise given by the iono-free combination of measurements at L1 and L2 frequencies.

Fig. 13 provides the service availability for the case in which MT28 is broadcasted instead of MT27 for the GPS only case (reference computation). This analysis has been run with the EGNOS ground reference stations network, and will be the reference for comparison with the rest of the analyses of this section, when dual-frequency and GLONASS capabilities are incorporated. It can be seen that the coverage area has not changed significantly with respect to plot from Fig. 9. This is because service availability is dominated by the ability of the system to monitor the ionosphere at the edge of the service area.

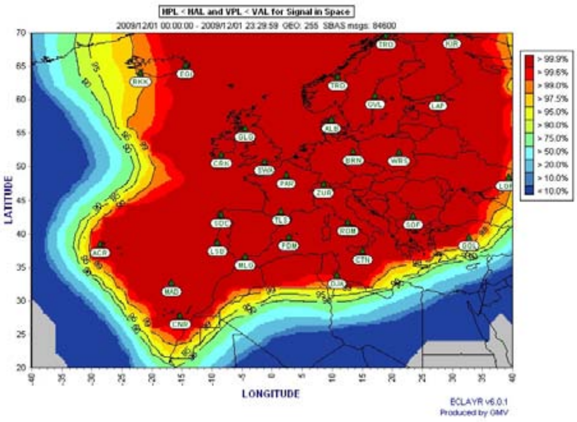

Fig. 13: *magicSBAS* APV-I availability for GPS L1 user and MT28.

The situation changes dramatically when SBAS service is extended to dual-frequency users is provided as shown Fig. 14. In this case service availability is not driven by the availability of ionosphere corrections, and consequently the service area can be extended to places far away from the regions with a dense number of reference ground stations. This figure clearly shows the possibility to extend SBAS service area with the provision of service to dual-frequency users. In addition, a satellite orbit and clock correction and integrity estimation customized to the user location is provided by the generation of SBAS message MT28. The area with good service continuity is also widely extended for L1-L2 users with MT28 as shown in Fig. 15.

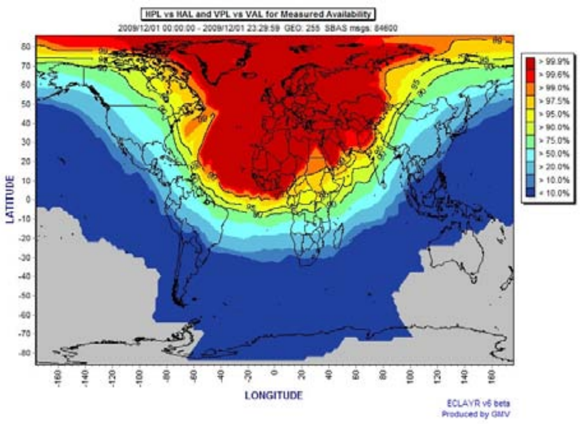

Fig. 14: *magicSBAS* APV-I availability for GPS L1-L2 user and MT28

Fig. 16 shows the service availability performances for the case in which augmentation is provided for GPS and GLONASS satellites with MT28 and for a dual-frequency user. As these performances have been obtained using EGNOS RIMS data no GLONASS L2 measurements are available at the reference stations used by ***magicSBAS***. In order to solve this problem, GPS+GLONASS ***magicSBAS*** augmentation information has been generated as for a single-frequency user, but Protection Levels have been computed at user level as for a dual-frequency user (i.e. no GIVE term is applied in the Protection Levels computation). Comparing Fig. 14 and Fig. 16 it can be concluded that the augmentation of a second constellation can be used to slightly extend the service area. Nevertheless, at the light of this and previous analyses it seems that the service area extension is driven by the dual-frequency and MT28 capabilities more than by the GPS+GLONASS multiconstellation augmentation.

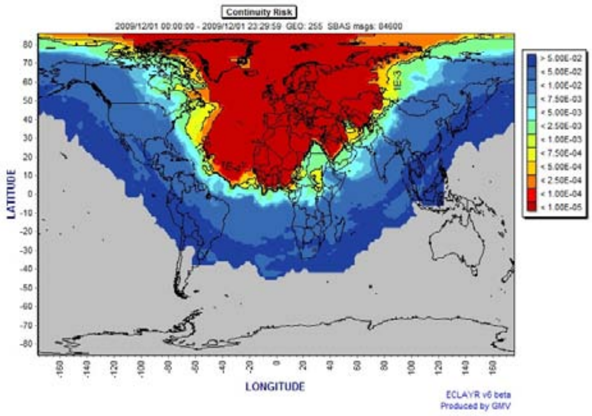

Fig. 15: *magicSBAS* APV-I continuity for GPS L1-L2 user and MT28

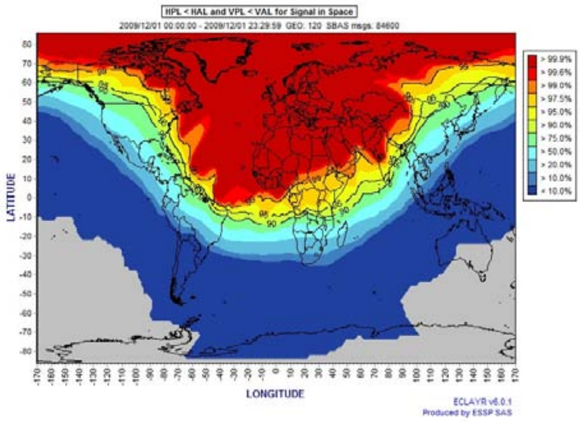

Fig. 16: *magicSBAS* APV-I availability for GPS/GLO L1-L2 user and MT28

Next configuration will show the possibility to extend the service area even more to the south with the inclusion of additional reference stations. Fig. 17 shows an extended network of 58 reference stations. This extended network is mainly composed of a dense set of reference stations in Europe (similar to EGNOS network) plus several stations in South Africa.

Fig. 18 provides APV-I availability for GPS L1-L2 users with MT28 and for the extended network of 58 reference stations. As can be seen the area with APV-I performances is widely extended to the south if compared to Fig. 14. These performances are outstanding and they show the possibility to develop a dual-frequency SBAS system covering Europe and Africa at the same time, just with the addition of a few reference stations in Africa. It is important to point that these performances are achieved even with a non-optimal distribution of reference stations over Africa.

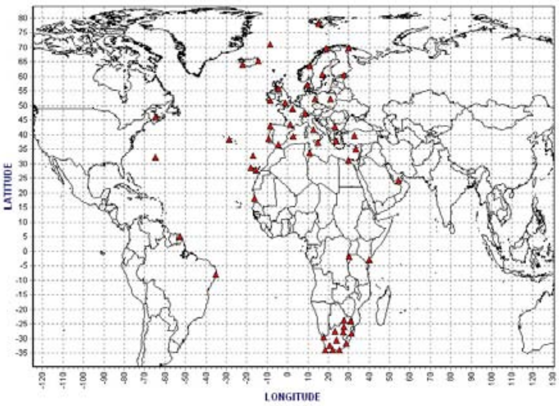

Fig. 17: Extended network of 58 reference stations

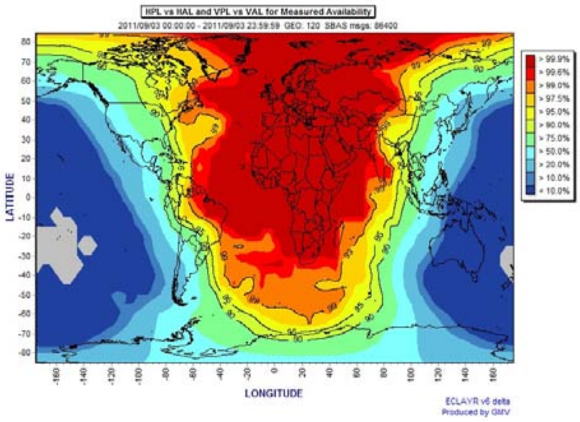

Fig. 18: *magicSBAS* APV-I availability for L1-L2 user and MT28 with 58-station network

Fig. 19 is the same as Fig. 18 but for the case in which GEO visibility at longitude 15.5º West is taken into account. This figure shows that the service are can be importantly restricted by the GEO visibility. GEO visibility is an important factor to be taken into account when defining an SBAS system.

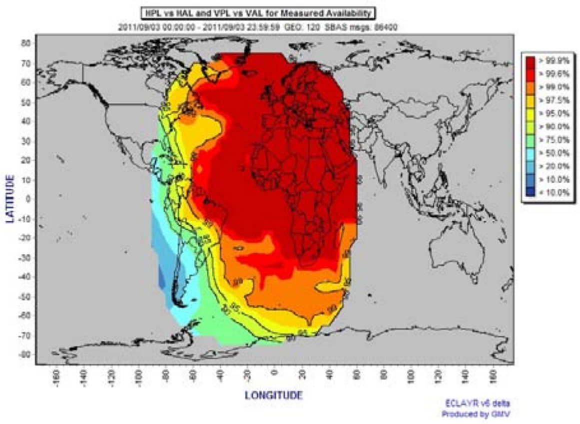

Fig. 19: *magicSBAS* APV-I availability for L1-L2 user and MT28 with 58-station network. GEO footprint considered

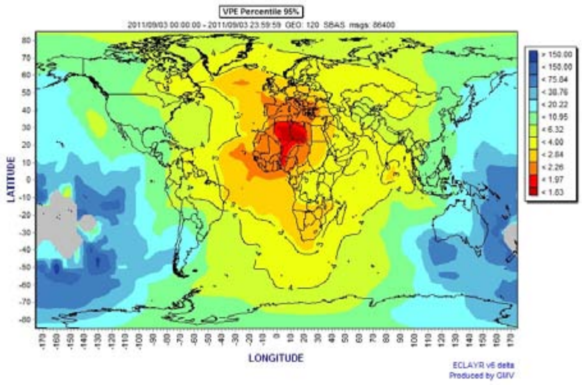

Fig. 20: *magicSBAS* accuracy performances for GPS L1-L2 user and MT28 with 58-station network

Fig. 20 provides accuracy performances for L1-L2 users with MT28 and for the extended network. It can be seen in the figure how the best accuracy performances are obtained in the center of mass of the reference stations used to build the corrections.

OTHER AREAS ANALYSIS

Other service areas have been analyzed using ***magicSBAS*** MT28 and dual-frequency capabilities, showing that ***magicSBAS*** can be easily set up within any service area and with the same level of performances as the obtained within the previous section. ***magicSBAS*** setup in any area is considered to be easy providing that a set of stations is already deployed in the analysis area and the 1Hz GPS (+GLO) L1-L2 data is available to be used by ***magicSBAS***.

Fig. 21 shows the APV-I service availability obtained with ***magicSBAS*** for L1 users with MT27 for a set of 25 reference stations in South Africa (reference stations location as green triangles in the plot). It can be seen that the service availability is driven by the reference station network.

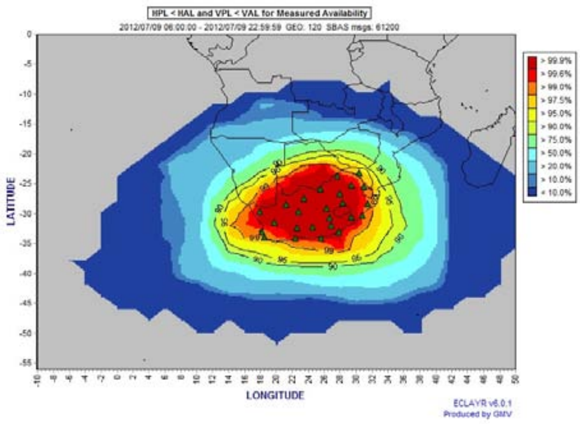

Fig. 21: *magicSBAS* APV-I availability for GPS L1 user and MT27 with 27-station network in South Africa

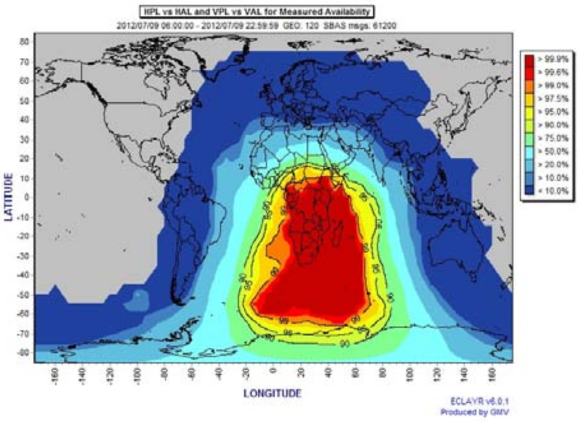

Fig. 22: *magicSBAS* APV-I availability for GPS L1-L2 user and MT28 with 27-station network in South Africa

With the same reference station network over South Africa (see figure Fig. 21), but configuring ***magicSBAS*** in dual-frequency mode and broadcasting SBAS message MT28, performances shown in Fig. 22 are achieved.

It can be concluded again that the service area is widely extended with the generation of SBAS message MT28 and the provision of service to dual-frequency users using ***magicSBAS***. Other service areas such as Australia and New Zealand, where 1Hz GPS (+GLO) L1-L2 data is available, have been additionally analyzed with ***magicSBAS***, reaching service availability performances of the same quality as the ones shown in this paper.

MAGICSBAS 4-GNSS AUGMENTATION ANALYSIS

As part of the new functionalities introduced in ***magicSBAS***, the provision of augmentation for up to 4 constellations, GPS, GLONASS, Galileo and COMPASS systems, has also been analyzed.

At the time of performing this analysis, there is not a 4-GNSS MOPS standard where SBAS augmentation for four constellations at the same time is defined. Thus, a bespoke format has been defined with the provision of all augmentation information for the 4-GNSS at 1 Hz rate. Once the 4-GNSS MOPS is defined, the ***magicSBAS*** message module in charge of formatting the output data will be modified accordingly.

Simulated data for the four constellations has been obtained from EETES (EGNOS End-To-End Simulator) tool. EETES is a fully qualified non real time EGNOS environment simulator designed for analyzing the navigation performances, specially accuracy and integrity. This tool was used in the qualification of EGNOS to build the validation scenarios including GPS and GLONASS core constellations. For the current analysis, EETES has been upgraded to produce simulated data for Galileo and COMPASS.

Taking advantage of the features presented previously, the 4-GNSS analysis has also considered a dual-frequency user and the generation of SBAS MT28 message for the four constellations.

The ***magicSBAS*** navigation kernel algorithms were evolved to include the 4G functionality. In particular, satellite clock estimation algorithms have been further extended for including the Galileo and COMPASS satellites corrections estimations. The clock offsets for all the satellites are computed with respect to EGNOS Network Time (ENT). The offsets between ENT and the system times for the four GNSS constellations are also computed. Consequently, the offsets between the system times for the four constellations are available within the system. These system time offsets are very important when a user combines corrections for satellites from different constellations. In terms of integrity, considering a dual-frequency user, the UDRE becomes the driver information to be provided by the SBAS system. The current ***magicSBAS*** algorithmic for GPS and GLONASS satellites has been extended to Galileo and COMPASS.

It has been also checked that the inclusion of the two additional systems (Galileo and COMPASS) does not degrade the user performances for the legacy systems (GPS and GLONASS) while provide a sensible larger number of monitored satellites. The following graphic shows the comparison between the number of monitored satellites available using former ***magicSBAS*** version (GPS and GLONASS) and the ones obtained with the evolved 4-GNSS ***magicSBAS*** version:

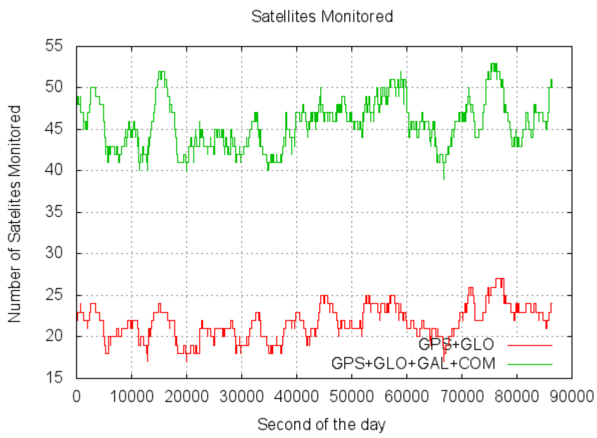

Fig. 23: Number of satellites monitored by the system

It can be seen that, as expected, the number of monitored satellites by the 4-GNSS magicSBAS version is around twice the number of satellites of the GPS+GLONASS magicSBAS version. This increase in the number of monitored satellites will have direct impact on the service availability. Additionally, this improvement in the number of monitored satellites can be very relevant in urban environments or for several RAIM algorithms requiring satellite redundancy.

Based on the system level analyses done with simulated data, it can be concluded that ***magicSBAS*** is ready to augment 4-GNSS constellation simultaneously. Some performances indicators have been shown at system level, while final user performances will depend on the 4-GNSS MOPS final specification. It is planned that once the 4-GNSS MOPS standard is defined, the ***magicSBAS*** message formatting module will be updated to have an operative 4-GNSS SBAS demonstrator.

SUMMARY AND CONCLUSIONS

The objective of this paper is to investigate future performances achievable by a multiconstellation dual-frequency SBAS systems using available real input data. For that purpose, a SBAS demonstrator called ***magicSBAS*** has been used. ***magicSBAS*** is a state-of-the-art operational SBAS testbed developed by GMV to offer non-safety critical SBAS augmentation to any interested region. Recently, ***magicSBAS*** has been upgraded with new capabilities, being the major ones the generation of SBAS message MT28, the multiconstellation capability and the provision of service to dual-frequency users.

The paper has first shown that ***magicSBAS*** is representative of EGNOS performances. Then, the paper has focused on investigating performances with different combinations of multiconstellation, SBAS MT28 message and augmentation to dual-frequency users, and for different services areas. It is important to point that all these analyses have been performed with real data. The major conclusions reached at the light of the analyses performed are:

- By modifying processing set algorithmic functions (mainly inospheric ones) big gains in availability and continuity can be obtained over the ECAC service area.
- A second constellation as GLONASS can be used at system level to improve the service coverage area, by increasing the number of lines of sight for ionosphere monitoring. In case the second constellation can be used at user level the performances are improved further. Additionally, the multiconstellation capability can be a solution to reduce the number of SBAS reference stations without reducing the service coverage area.
- Service coverage area does not change significantly when MT28 message is broadcasted instead of MT27. This is because service availability is still dominated by the ionosphere corrections, and those places with no ionosphere corrections still cannot benefit from the MT28 message.
- Service area can be widely extended with SBAS message MT28 and the provision of service to dual-frequency users, as now the users are not restricted by the availability of inospheric corrections. The feasibility of a dual-frequency SBAS system covering Europe and Africa has been shown even with a non-optimal stations network over Africa.
- Last analysis performed has concluded again that the service area is widely extended with the generation of SBAS message MT28 and the provision of service to dual-frequency users using ***magicSBAS***, in this case for a dedicated SBAS in South Africa.

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Thanks to all the analyses performed, and the extensive use of real data, the study provides a clear picture of the performances that will be reached by future SBAS systems, once the multiconstellation and dual-frequency capabilities are developed. It also shows the importance of state-of-the-art algorithms at system level to reach outstanding service performances. In this sense, ***magicSBAS*** is constantly evolving to improve its capabilities, as it is the case of 4-GNSS augmentation. Despite the fact that a standard for 4-GNSS augmentation is not available, this paper has also shown that the tool is already prepared for monitoring satellites for four GNSS constellations at the same time. Once a multiconstellation standard is available, it is only a matter of a relatively small effort to adapt ***magicSBAS*** outputs to the new standard.

TOOL REFERENCES

magicSBAS constitutes the perfect tool for building a Test Bed in any region and for establishing an early operational service. It is also the perfect tool for supporting the design of a new SBAS system to be integrated in any region of the World.

An overview of ***magicSBAS*** capacities and different versions (real-time, fast-replay) can be found at http://www.gmv.com/en/space/magicSBAS/index.html.

magicSBAS real-time performances can be explored at http://magicgnss.gmv.com/sbas.

magicSBAS is part of the GMV magic suite, covering not only SBAs systems, but also GBAS, PPP (Precise Point Positioning) and scientific applications, such as geodesy, timing, meteorology, etc. More information about the magic suite can be found in http://magicgnss.gmv.com

Eclayr is a system and service performance analysis tool that assesses accuracy, integrity, continuity and availability performance of the SBAS service using EGNOS messages and IGS products as references. More information can be found at http://www.eclayr.com.

magicGEMINI is an application able to process data from a network of GNSS receivers in order to analyse and monitor the navigation performance available in a configurable airspace, keeping track of service compliance both in real time and in post-operational processing. ***magicGEMINI*** design is multisystem oriented, hence it supports performance analyses for operational navigation based on GPS, GLONASS and GALILEO, as well as RAIM and SBAS augmentations. More information can be found at http://www.gmv.com/en/aeronautics/magicGEMINI/.

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