An efficient approach for the development and deployment of a multi-constellation augmentation system: *magicSBAS*

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## BIOGRAPHIES

Javier Ostolaza is currently studying a Master in Space Technology at Universidad Politécnica de Madrid. He got his degree in Telecommunications Engineering in 2007. He has been working at GMV in the GNSS Business Unit, since 2008, where along these years he has got an extensive experience in SBAS demonstrators such as *magicSBAS* and SPEED. He has contributed to their real-time and communication algorithms and has integrated the emerging network of NTRIP Stations to *magicSBAS* and developed the SISNET Server used to broadcast the SBAS corrections. He has also collaborated in the adaptation of the *magicSBAS* algorithms to cover different service areas adapting also some GMV analysis tools such as *teresa*, *magicGEMINI* and *eclayr*. He has recently become the EDAS (EGNOS Data Access Service) project manager.

Ignacio Alcantarilla has a degree in Aeronautical Engineering. He has been working in SBAS for more than 10 years: EGNOS, SACCSA, SDCM, others. He has been the technical and project manager of the CPFPS (the central processing facility of the EGNOS system). From 2008, he has been the *magicSBAS* product manager. He accomplished the transformation of *magicSBAS* into a real-time testbed fed with real-time data obtained from Internet (NTRIP format) and with a SISNET broadcast. Recently, he has been involved in business development activities around *magicSBAS*.

José 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 program, the European SBAS, being one of the designers and developers of the EGNOS central processing subsystem. Awarded with the Galileo Masters prize in 2009, he is currently the head of the GNSS Advanced Systems Division at GMV.

Juan R. Martín is the GNSS Business Development manager at GMV Aerospace and Defense. He holds a MSc in Aeronautical Engineering from the Polytechnic University of Madrid, Spain (1995) and has followed an Executive Education Program in general management at the IESE Business School (2010-11). Prior to his current position, Juan was the project manager at GMV for the development of the Galileo Orbitography and Synchronization Processing Facility (OSPF) and of the Galileo Integrity Processing Facility (IPF), and participated in all the previous Galileo concept definition and system architecture definition studies. He also has given support to organizations like Aena (Spanish Air Traffic services provider) and Eurocontrol in the operational implementation and validation of EGNOS for civil aviation applications.

## ABSTRACT

The development and deployment of a SBAS system in any region of the world is not a simple task. The development of the current operational SBAS systems has required significant time and effort. Besides, each region may have different characteristics and requirements. The ionosphere behavior is, for instance, a key issue for the implementation of an SBAS in some regions.

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 in parallel to the operational system development. Testbeds provide the system developers with powerful platforms to validate architecture, design and performance assumptions. Testbeds also permit users to benefit from early SBAS services, representative of the final augmented performance and useful in many applications (e.g.; precision agriculture) which do not require a formal certification process. Even for aviation users, which required a certified system, a testbed is a very useful tool to better understand and demonstrate to the relevant communities the operational benefits of the SBAS solution. However, despite the numerous advantages, the development of an SBAS testbed is also a complex task which has taken years in the case of WAAS and EGNOS.

This paper presents the current status and performance of *magicSBAS*, a SBAS operational testbed developed by GMV that permits to deploy a pre-operational SBAS service and experimentation platform anywhere in a very short time frame and with a reduced cost. *magicSBAS* incorporates all the experience gained by GMV in the development of EGNOS and other SBAS in different regions.

## INTRODUCTION

The current picture of satellite navigation systems includes global (GPS, GLONASS, Galileo), regional (SBAS, QZSS, QZSS, etc.), and local areas.
Compass, IRNSS) and local systems (GBAS, hybrid systems combining GNSS and other sensors). The use of GNSS for safety critical applications requires given levels of confidence on the positioning obtained by the user equipment. This is possible by complementing the core GNSS signals with other systems or techniques to produce a solution with the needed level of integrity. The analysis of the current trends observed in the navigation community suggest that, for the coming years, the GNSS integrity solutions may rely on SBAS, GBAS, RAIM or new techniques including integration with other sensors. In this global GNSS picture, SBASs appear as feasible solutions to regionally augment the GNSS constellations to provide increased accuracy with integrity.

![Image](image.png)

**Figure 1 – Current and potential SBAS around the world.**

In the aviation community, SBAS already enjoy recognition at regulatory level and are considered as a reference navigation aid. Recently, ICAO has developed the Performance Based Navigation concept – PBN [1] – and established an international schedule for APV (Approach Procedure with Vertical Guidance) at all instrument runway ends either as the primary approach or as a back-up for precision approaches by 2016 with intermediate milestones of 30 per cent by 2010, and 70 per cent by 2014. Most countries are producing their PBN implementation plans to meet ICAO recommendation and the use of the SBAS technology seems to be one of the most adequate solution.

However, the development and deployment of a SBAS system in any region of the world is a complex challenge. The development of the current operational SBAS systems has required significant time and effort. 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.

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 in parallel to the operational system development. Testbeds offer numerous advantages, in particular:

1. Testbeds provide the system developers with powerful platforms to validate architecture, design and performance assumptions, thus mitigating design risks and helping to optimize the design to satisfy the requirements of the region.
2. Testbeds permit users to benefit from an early SBAS service, representative of the final augmented performance and useful in many applications (e.g.; precision agriculture) which do not require a formal certification process.
3. Tesbeds help to build a user community and confidence in the system.
4. Even for aviation users, which required a certified system, testbeds are very useful tools to better understand and demonstrate to the potential users, service providers and regulators the operational benefits of the SBAS solution and learn how to exploit them.

Some years ago, GMV initiated an internal R&D activity to define the basic requirements of an SBAS testbed system that could permit regions interested in SBAS to have a powerful engineering tool to support the system feasibility and early definition studies, being also capable to provide pre-operational and demonstration services.

The basic requirements for such a SBAS testbed system would be the following:

- It should be capable to produce SBAS, corrections and integrity data in real time, supporting relevant standards such as RTCA-MOPS and ICAO-SARPs.
- It should provide state-of-the-art performance and be fully representative of a operational SBAS system such as WAAS or EGNOS.
- It should anticipate potential SBAS evolutions. For instance, it should augment not only GPS but also GLONASS, Galileo and other systems to come in the next years. Besides, it should provide basic single-frequency services and also anticipate future standards for dual-frequency services.
- It should provide different channels for dissemination of the SBAS message, including satellite (like in a classical SBAS) and other means such as internet using the SISNET format [8], GPRS/3G, etc.
- It should benefit from existing ground and CORS stations networks. Hence it should support common standards such as NTRIP.
- It should be able to work in real-time and in post-processing mode. The post-processing mode would be quite useful to support engineering studies as well as for troubleshooting.

The above were the initial requirements considered for the development of magicSBAS, the SBAS operational testbed solution developed by GMV over the last years.

The paper describes later the features of the current magicSBAS platform as well as the planned evolutions. The paper also provides examples of use in different studies and SBAS demonstrations performed by GMV in different regions.
SBAS OVERVIEW

A SBAS (Space Based Augmentation System) augments the navigation service provided GNSS satellites (such as GPS or GLONASS and in the future Galileo, Compass, QZSS, etc.) by providing ranging, integrity and correction information via geostationary satellites.

The classical SBAS architecture includes:

- A ground segment that comprises the needed ground infrastructure for GNSS data acquisition, processing and dissemination.
- A space segment, usually comprising several geostationary satellites endowed with SBAS transponders, and
- A user segment composed of SBAS receivers.

The ground infrastructure includes the monitoring and processing stations, which receive the data from the GNSS satellites and compute wide area correction and integrity data, and generate the GEO signal-in-space (SIS). The SBAS satellites then relay the SIS to the SBAS user receivers, which determine position and time information from the augmented constellation(s) and SBAS GEO satellites. The SBAS receivers acquire the ranging and correction data and apply these data to determine the integrity and improve the accuracy of the estimated 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 ephemeris, clock and ionospheric propagation errors. The user will apply these corrections to improve the position estimation and its level of confidence.

DEVELOPMENT OF A SBAS SYSTEM: CRITICAL ISSUES

The implementation of a SBAS system is a complex challenge. A key issue is usually to build the confidence of the final users from the beginning. Frequently, the development of an SBAS system takes too long thus penalizing the users’ confidence and the system acceptance by the relevant communities.

In the technical domain, there are several critical issues that may impact the overall performance and cost of the system and need to be carefully managed. These issues usually include:

- Number and location of the monitoring stations
- Ionospheric conditions in the region
- Performance of the SBAS algorithms
- Safety and certification requirements

It is usual that SBAS development plans envisage the deployment of SBAS testbeds (e.g.; WAAS NSTD, EGNOS ESTB) and pre-operational, not-certified, services in parallel to the operational system development. Testbeds provide the system developers with powerful platforms to validate architecture, design and performance assumptions. Testbeds also permit users to benefit from an early SBAS service, representative of the final augmented performance and useful in many applications (e.g.; precision agriculture) which do not require a formal certification process. Even for aviation users, which required a certified system, a testbed is a very useful tool to better understand and demonstrate to the relevant communities the operational benefits of the SBAS solution. Despite the numerous advantages, the development of an SBAS testbed is also a complex task which has taken years in the case of WAAS and EGNOS and maybe also an expensive development.

In order to simplify the implementation of SBAS testbeds, GMV has developed magicSBAS, a SBAS operational testbed that permits to deploy a pre-operational SBAS service and experimentation platform anywhere in a very short time frame and with a reduced cost. magicSBAS incorporates all the experience gained by GMV in the development of EGNOS and other SBAS in different regions.

magicSBAS implements state of the art algorithms and it can be implemented in any region of the world in a very short time frame. It works with data in standard formats, for instance the NTRIP real time data protocol can be used. Many regions of the world already have a network of stations; if this were the case, a SBAS test solution based on magicSBAS can be implemented in a few weeks. magicSBAS provides state of the art performance due to the continuous incorporation of new functionalities and improvements that go one step beyond what current SBAS provide, such as the capability to augment GLONASS and Galileo. magicSBAS corrections can be disseminated to users in different ways. As an example they can be disseminated using the SISNET protocol via the Internet, in a more realistic scenario corrections can be disseminated via a GEO satellite. The main objective is to provide an operational non safety of life service in the shortest timeframe possible.

Using magicSBAS, a pre-operational SBAS test and demonstration service can be deployed very quickly and at a reduced cost. magicSBAS also provides a powerful engineering environment to perform complex engineering tasks such as the identification of the optimum number and location of the ground stations, and the SBAS algorithms tuning to optimize the performance.

The results obtained with magicSBAS will provide a realistic indication of the final performance that can be achieved, will help to estimate the total cost of the system, and will permit to assess the main benefits, major risks and identify the main issues to tackle in a certification process. The possibility to provide an early pre-operational service, even if not safety of life, will allow building the credibility and gain the confidence of the user communities.
**magicSBAS DESCRIPTION**

*magicSBAS* is a low cost multi-constellation Satellite Based Augmentation System (SBAS) testbed that collects real time raw data in standard formats and computes wide area SBAS corrections and integrity parameters fully compliant with RTCA DO-229D [3] and ICAO SARPs [4] standards. *magicSBAS* implements the SBAS algorithms developed by GMV and widely proven in EGNOS and in different SBAS studies carried in different regions of the world.

![Figure 2 - magicSBAS architecture.](image)

The *magicSBAS* augmentation message can be disseminated to users via internet, using the SISNET protocol, 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 [5].

One of the key advantages of *magicSBAS* is the capability to process raw data in standard formats like NTRIP, RINEX or EDAS. The NTRIP format in particular is a widely extended, open format designed to disseminate GNSS streaming data to stationary or mobile users through the Internet.

Real-time NTRIP data and stations are currently widely available worldwide, either free or under subscription as it can be seen in Figure 3.

![Figure 3 - Stations providing data in NTRIP format.](image)

Note that by using NTRIP, it may not even be necessary to deploy sensor stations if sufficient NTRIP data is available over the desired area to augment. If necessary, a variety of low cost, commercially available NTRIP stations exist which may be deployed and processed by *magicSBAS*.

*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 real-time pre-operational SBAS test and demonstration 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* [6] and *magicGEMINI* [7].

*eclayr* is a system and service performance analysis tool that assesses accuracy, integrity, continuity and availability performance of the SBAS service both in the range (UDRE and GIVE) and user domains. The following are the main features of the *eclayr* tool:

- Runs in post-processing mode
- Detects and reports system events
- User friendly, easy-to-use graphical interface
- Reports in HTML format
- Windows operating system

![Figure 4 - *eclayr* performance analysis tool.](image)

*magicGEMINI* is a user-level performance analysis tool which analyzes user performance augmented with SBAS messages, being the main inputs the user data and the SBAS message. The following are the main features of the *magicGEMINI* tool:
- Computes accuracy, integrity, continuity and availability performance at defined user locations
- User friendly, easy-to-use graphical interface
- Runs in real time and post-processing modes
- Windows operating system

Figure 5 - magicGEMINI performance analysis tool.

**magicSBAS ALGORITHMS**

The algorithms implemented in *magicSBAS* are the result of 15 years of GMV experience in different SBAS Programs such as EGNOS, SACCSA, SDCM and GAGAN. They have been optimized to provide the best performance in the most demanding conditions and have been tested in many regions of the world.

*magicSBAS* algorithms include:

a. **Preprocessing and Validation algorithms:** They ensure that the input data such as raw measurements and ephemeris meet the required performance by performing quality checks on them. They also form the basic observables used in the different processes by removing the ionosphere, Inter Frequency Biases (IFB), and troposphere delays, also reducing the measurements noise by phase-smoothing.

b. **Corrections and Integrity Computation algorithms:** They run after preprocessing, and include:
   i. On one side, the ionosphere and IFB estimation, wide area ionospheric corrections generation and GIVE (Grid Ionospheric Vertical Error) estimation.
   ii. On the other side, the satellite orbit determination, time synchronization and UDRE (User Differential Range Error at Worst User Location) estimation.
   iii. Quality of Service estimation together with different Internal Checks for the different processes.

c. **Message Generation algorithms:** They produce the SBAS message to be broadcast according to applicable standards such as RTCA-MOPS and SARPs, and taking into account the priorities of the different messages, the configuration of the system and its status. It is worth mentioning that *magicSBAS* always works in test mode, i.e., always generates message type 0 every six seconds as a fundamental safety barrier to ensure that no user terminal could use *magicSBAS* signal in a safety-critical operation.

**magicSBAS PERFORMANCE**

As mentioned before, *magicSBAS* performance is fully representative of the performance provided by current SBAS systems like WAAS and EGNOS. The performance can be even enhanced due to the possibility of adding new stations and new functionalities (such as GLONASS augmentation, improved ionosphere algorithms, etc).

One of the key SBAS performance parameters is the so-called service availability. Service availability is a measurement of the percentage of time during which the system broadcasts a valid navigation message and the resulting user horizontal and vertical protection levels (HPL/VPL) do not exceed the prescribed alert limits (HAL/VAL) for the desired service level. Several examples of *magicSBAS* availability maps for different regions of the world are presented hereinafter.

*magicSBAS* service area is fully configurable and then can provide SBAS services in any region of the world. The figures below show examples of SBAS solutions obtained with *magicSBAS* fed with real data in several regions: Europe, Latin America, South Africa and Australia. In most of the cases, publicly available NTRIP stations have been used as shown in the figures.

In the European case, it can be seen that *magicSBAS* provides a large service area which proves the goodness of the *magicSBAS* solution.

Figure 6 - *magicSBAS* APV-I availability over Europe.

In all cases, it can be seen that *magicSBAS* provides 99% of APV-I availability and with no compromise on integrity in the data analyzed.
The magicSBAS GEO broadcast capability has been developed in collaboration with Inmarsat. This new capability was tested in October 2010, when a magicSBAS test signal was transmitted from Inmarsat-3F4 over the Caribbean, Central America, and South America regions.

The obtained performance and Inmarsat-3F4 broadcast area are shown in the figures below.

**Figure 7** - magicSBAS APV-I availability over Latin America.

**Figure 8** - magicSBAS APV-I availability over South Africa.

**Figure 9** - magicSBAS APV-I availability over Australia.

**Figure 10** – magicSBAS performance during GEO broadcast over Latin America.

**Figure 11** - Location of Inmarsat GEO satellite (54ºW)

With the new GEO broadcast capability, magicSBAS is endowed now with the elements required to quickly deploy a SBAS test signal in space anywhere.

**NEW 2011 FUNCTIONALITIES**

As a result of the continuous improvements done in magicSBAS, new relevant functionalities are being incorporated during 2011. The new functionalities include the possibility to transmit MT28 to increase the service area, and new multi-constellation features derived from the augmentation capabilities for Galileo and Compass. Also, dual-frequency augmentation is being incorporated to test the performance that future SBAS will provide.

As an example, the figure below shows an magicSBAS APV-I 99% availability map when the algorithms are customized to replicate EGNOS performance augmenting GPS, using the EGNOS stations network, with MT28 enabled and in dual frequency mode.

We want to stress the fact that the performance shown has been generated with real algorithms fed with real
observation data, and not just produced by means of an SBAS service volume simulator.

Figure 12 - magicSBAS showing EGNOS performance (with current stations network) in L1/L5 dual-frequency mode with MT-28 enabled.

PAST AND CURRENT USES OF magicSBAS

magicSBAS is a success story; the tool has been extensively used over the last years and the interest is growing.

Past and current projects where magicSBAS has been used include the following:
- EGNOS performance evaluation, troubleshooting, fine tuning and quick prototyping of algorithm improvements.
- ICAO’s SACCQA Program: Feasibility analysis of a SBAS system in Central, Caribbean and South America.
- EEGS Study for the European GNSS Agency (GSA): Feasibility of EGNOS extension to Eastern Europe.
- SBAS real-time prototype in Brazil and Argentina for demonstration purposes (customer: European Commission).
- EGNOS extension to GLONASS and multi-constellation benefits for SBAS (customer: ESA).
- EGNOS service area and performance improvement over Spain (customer: Aena).
- EGNOS Land User Testbed (customer: ESA).

CONCLUSIONS

Today it is possible to use already developed SBAS products to deploy a SBAS operational test system in any region of the world in a short period of time and at an affordable cost. magicSBAS is a state of the art SBAS testbed able to provide a real-time augmentation service with an unprecedented level of accuracy. It has been designed to improve the performance of existing SBAS systems and to be flexible. It currently supports multiple GNSS constellations and already anticipates the main SBAS trends such as dual frequency augmentation.

magicSBAS is the perfect tool to quickly and efficiently deploy a SBAS testbed in any region and to provide early pre-operational test and demonstration service. It is also the perfect tool to support the design of new SBAS systems.

magicSBAS is a product developed as part of GMV’s R&D effort. It is a component of GMV’s magicGNSS suite, which also includes solutions for GNSS precise orbit determination and time synchronization, Precise Point Positioning (PPP) and GNSS performance evaluation. More information about the magicGNSS suite can be found in http://magicgnss.gmv.com

magicSBAS LINKS

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

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

First Broadcast of SBAS Test Signal in the Caribbean, Central America, and South America: http://www.gpsworld.com/gnss-system/augmentation-assistance/news/first-broadcast-sbas-test-signal-caribbean-central-america-

REFERENCES


ACRONYMS

Aena Aeropuertos Españoles y Navegación Aérea (Spanish Airports and Air Navigation)
APV Approach with Vertical Guidance
CORS Continuously Operating Reference Station
CPFPS Central Processing Facility – Processing Set
DGPS Differential GPS
EGNOS European Navigation Overlay Service
ESA European Space Agency
ESTB EGNOS System Test Bed
FAA Federal Aviation Administration
GBAS Ground Based Augmentation System
GIVE Grid Ionospheric Vertical Error
GLONASS Global Navigation Satellite System
GNSS Global Navigation Satellite System
GPS Global Positioning System
GSA European GNSS Agency
HAL Horizontal Alert Limit
HPL Horizontal Protection Level
ICAO Internation Civil Aviation Organization
IFB Inter-Frequency Bias
IPF Integrity Processing Facility
IRNSS Indian Regional Navigational Satellite System
NSTB National Satellite Test Bed
NTRIP “Networked Transport of RTCM via Internet Protocol
OSPF Orbitography and Synchronization Processing Facility
PBN Performance Based Navigation
PPP Precise Point Positioning
QZSS Quasi-Zenith Satellite System
RAIM Receiver Autonomous Integrity Monitoring
RINEX Receiver INdependent EXchange
R&D Research & Development
SACCSA Sistema de Aumentación para el Caribe, Centro y Sudamérica (Augmentation System for the Caribbean, Centre and South America)
SARPs Standards and Recommended Practices
SBAS Satellite Based Augmentation System
SDCM System of Differential Correction and Monitoring
SIS Signal In Space
SISNET Signal in Space through the Internet
UDRE User Differential Ranger Error
VAL Vertical Alert Limit
VPL Vertical Protection Level
WAAS Wide Area Augmentation System
WUL Worst User Location