

Basic Research Utilities for SBAS (BRUS)

Manuel Hernández-Pajares, Miguel Juan, Jaume Sanz, Xavier Prats, Jordi Baeta

Research group of Astronomy and Geomatics (gAGE/UPC)
Departaments Applied Mathematics IV and Applied Physics
Universitat Politècnica de Catalunya

e-mail: jaume@mat.upc.es
C/. Jordi Girona, 1-3, Mod. C3
Campus Nord, UPC
08034 Barcelona, Spain

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Abstract

The software package BRUS (Basic Research Utilities for SBAS) to process WAAS and EGNOS data is being developed by gAGE/UPC. Some of the main characteristics of BRUS are its architecture design and functionalities that allow to obtain huge information for the different error source components (satellite coordinates, clocks, ionospheric corrections,...), providing wide possibilities for the SBAS performance analysis in both, SIS and position domain.

As an application, the performance of the EGNOS System Test Bed (ESTB) during 2002 is analyzed; using data sets collected in the ESTB Data Collection and Evaluation campaigns of EUROCONTROL (the European Organization for the Safety of Air Navigation). As an extension of BRUS, a Global Performance SBAS Monitoring Tool using public domain GPS networks data is going to be developed.

1. Introduction

The standalone GNSS positioning fails to meet the accuracy, availability and integrity requirements critical for precision and non-precision approach phases of flight. Marine and land users will also require some sort of augmentation for improving the GPS/GLONASS performances.

In order to meet such requirements, Satellite Based Augmentation Systems (SBAS) are being developed. These systems provide differential corrections and integrity data for satellite based aviation and their signal will be available free of charge to all other non aviation satellite positioning users. The US Wide Area Augmentation System (WAAS), the European Geostationary Navigation Overlay System (EGNOS), and the Japanese Multifunctional Satellite Augmentation System (MSAS) are the three existing SBAS systems.

This paper will describe the basic background of a software package of Basic Research Utilities for SBAS (BRUS) developed by our group gAGE/UPC. This tool works on the operative system LINUX and use free software packages (awk, gnuplot, GMT) for plotting and image generation. It is able to work in both, real time and in postprocess using SBAS receiver data, such as binary NovAtel files [2] or the NSTB TRS data files [3]. Its main components, architecture and capabilities, will be described in section 1.

This tool has been used in the ESTB Data Collection and Evaluation project of EUROCONTROL to process and analyze weekly data sets collected since January 2002. To illustrate an application of BRUS, the ESTB performance during 2002, as well as some examples of anomalies analyzed with this tool will be presented in section 2.

Finally, a Global SBAS Performance Monitoring Prototype using public domain GPS networks data will be presented in section 3 as an extension of BRUS. One of the main features is to allow a wide SBAS performance monitoring with a very low cost, because it is not necessary to build a specific dedicated network.

2. BRUS

BRUS (Basic Research Utilities for SBAS) is a software package, designed to be in compliance with RTCA/MOPS Do 229A/B/C [1], that is being developed by gAGE/UPC. One of the main characteristics is the ability to provide wide information about the applied SBAS messages and how the corrections are internally processed.

The BRUS package consist of three software modules: B2Aconv, BNAV and BNAL (see figure 1).

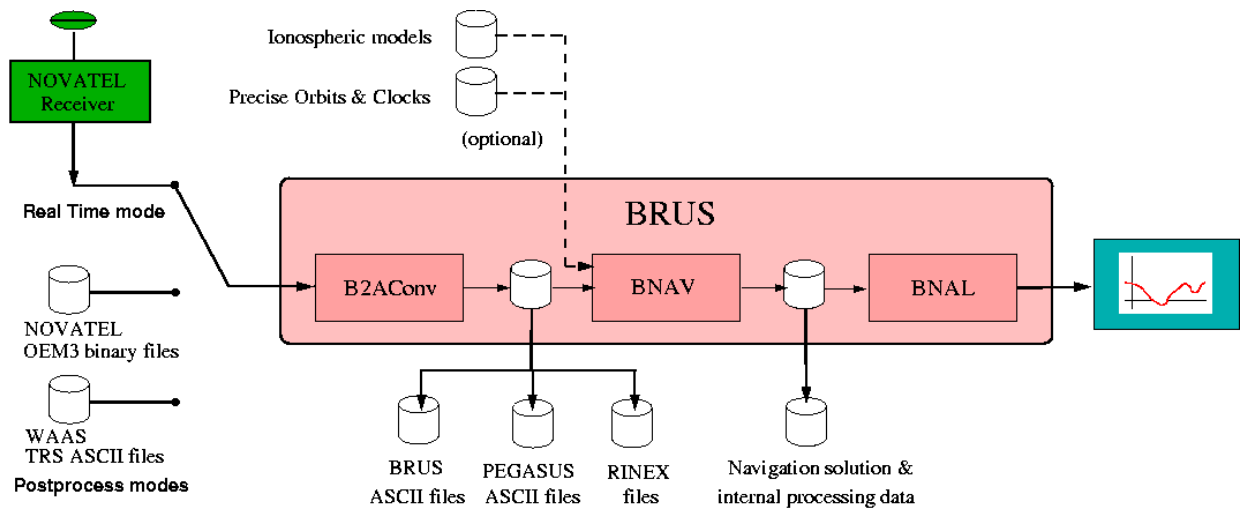


Figure 1. BRUS architecture, with the B2Aconv, BNAV, BNAL.

B2Aconv (Binary to ASCII converter) translates the binary files into a generic format. At present, it can work with NovAtel WAAS/Millennium OEM3 files as well as the Test Bed Reference Stations data files provided by the NSTB for WAAS (<http://www.raytheon.com/waas/> or ftp://ftp.nstb.tc.faa.gov/pub/NSTB_data/). The output ASCII data can be injected into the navigation module (BNAV) for a real-time processing or stored in several data files (GPS measurements and navigation files and GEO messages files), for a postprocessing. Many formats are available for the measurements: RINEX [4], PEGASUS [5], BRUS native. The GPS and GEO navigation data are stored in RINEX 2.10 format and the GEO messages, in the PEGASUS format.

BNAV (BRUS-NAVIGATOR) is the main program. It uses the output of B2Aconv program to compute the navigation solution, either in real-time or in post-process mode. It can compute the solution in the different SBAS navigation modes (Precision Approach, Non Precision approach and En Route and Terminal) as request.

BRUS is designed as a SBAS Analysis and Research Utilities Tool, for this reason, it provides wide information about the SBAS messages applied and about how the corrections are internally processed. Thence, besides the Navigation System Error and the Protection Levels, the confidences of the different corrections and the degradation terms and the pre-fit and post-fit residuals or the design matrix are provided as required.

Moreover, BNAV incorporates other functionalities for SBAS post-processing (besides the real-time mode) such as the possibility to import externally collected data such as RINEX measurements or ephemeris files, as well as the capability to navigate with precise orbits and clocks and/or any ionospheric corrections or Interfrequency Biases (TGDs) provided in a generic format file. Also, it can use the C1 pseudorange measurements or the ionospheric free combination when working with precise orbits and clocks.

Its architecture design and functionalities allow to obtain huge information for the different error source components (satellite coordinates, clocks, ionospheric corrections,...) providing wide possibilities for the SBAS performance analysis in both, SIS and position domain.

BNAL (BRUS-NAVIGATION-ANALYZER) is the data analysis module. It contains different statistics and graphic tools to support the data processing results analysis. The data viewer scripts (plots, images and movies) run over the free software packages gnuplot [6] and Generic Mapping Tools (GMT) [7]. Some examples of the images and movies provided by BNAL are shown in figure 2

BRUS is being used in the ESTB Data Collection and Evaluation project of EUROCONTROL to perform an ESTB data processing independent of the PEGASUS*PLUS (the software provided by Eurocontrol), allowing to check the processing results and the performance of both softwares. For this reason, although the internal architecture and functionality are different from PEGASUS, some effort has been devoted to provide compatibility between the input files and processing modes. In particular, the current version of BRUS v0.0 is able to process the ASCII output files generated by the PEGASUS Converter in the three different modes of the WinGPSAll (the

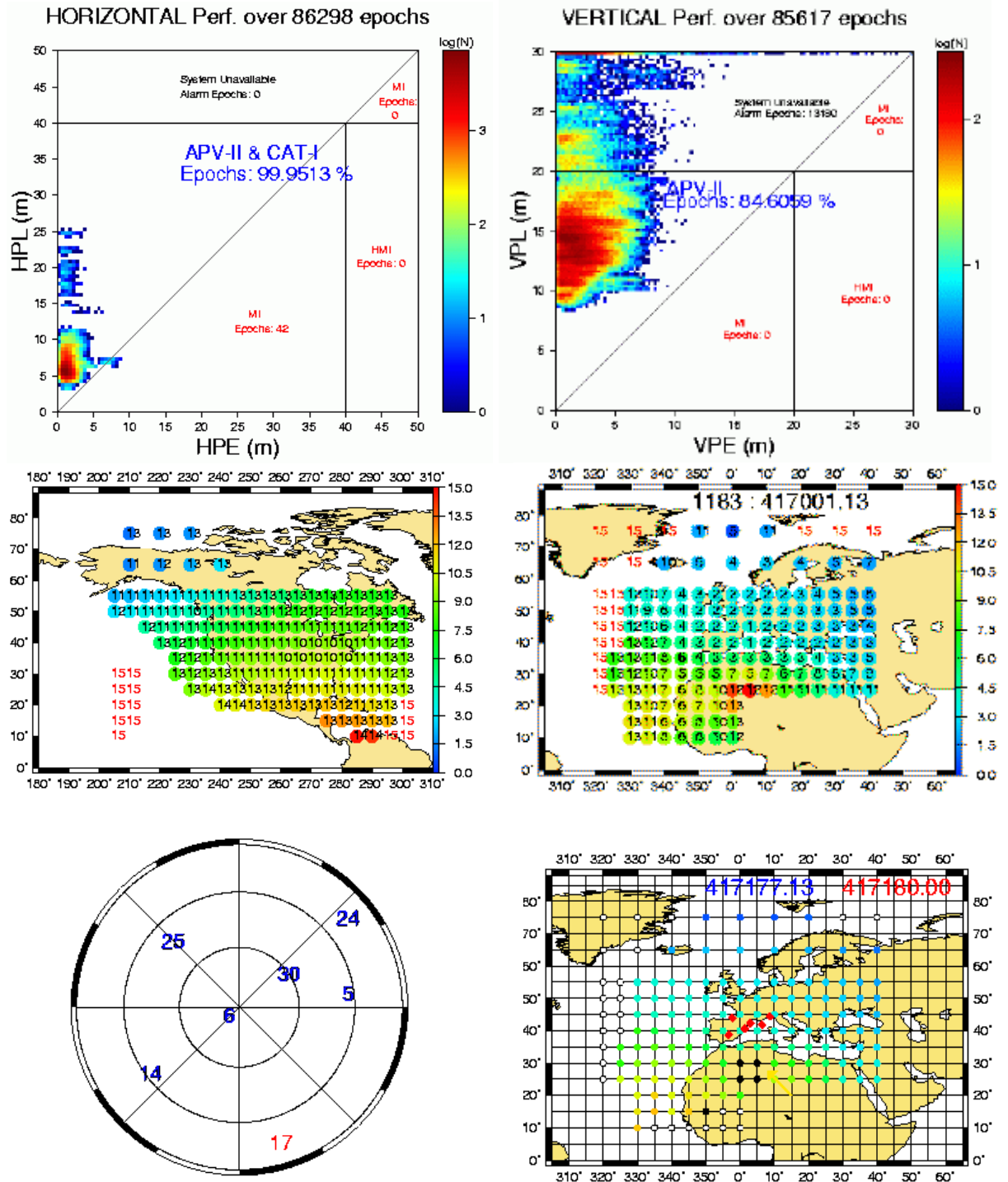


Figure 2. Some examples of images and movies provided by the BNAL module of BRUS. First row: Stanford plots for the Horizontal and Vertical performances (left and right respectively). Second row: Ionospheric corrections movie frames. The Vertical Ionospheric Corrections are given at the Ionospheric Grid Points (IGPs) by the circles in a colour scale. The numbers inside the circles are the confidence values indicators (GIVEI) values. The GPS week and TOW are indicated in the top of the movie. The figure at the left is extracted from a NSTB (WAAS) data movie. The figure at the right comes from the ESTB (EGNOS) movie. Last row: Frame of sky plot at the left, and frame of Ionospheric Pierce Points (in red) and Vertical delays in the IGPs at left.

Navigation module of PEGASUS): Precise Wide Area (PWA), Basic Wide Area (BWA), and GPS Standalone (SAL). The B2Aconv module of BRUS is similar to the PEGASUS*PLUS Converter. The BNAV can emulate the WinGPSAll PEGASUS*PLUS module to compute the navigation solution from range measurements, and GPS and SBAS messages in the PWA, BWA and the SAL modes. Finally, BNAL can generate the statistics and plots contained in the reports generated by PEGASUS*PLUS.

Some Technical Specifications are:

Source code:

B2Aconv: Coded in C

BNAV: Coded in FORTRAN 77

BNAL: Several C-shell scripts using awk, perl and the Generic Mapping Tools (GMT).

Platform: LINUX (B2Aconv and BNAV can be also compiled in DOS).

2. Applications: ESTB Data Collection Analysis

Since January of 2002, gAGE/UPC, is being collecting ESTB data in Barcelona as a part of the ESTB Data Collection network of Eurocontrol. The data sets are processed using the Pegasus*Plus tool provided by Eurocontrol and, in the case of the UPC sites, they are also processed with BRUS. One of the targets of the working group is to analyze the ESTB performance for the different operation modes and to identify potential anomalies in both, the Signal-in-Space and position domains. The ESTB performance results from weekly 24h measurements along the year 2002 in UPC, as well as some examples of the analysis of SIS anomalies detected in the collected data sets are provided as follows.

2.1 ESTB performance in 2002

The ESTB accuracy, integrity and availability for different navigation modes during 2002 are shown in this section, using 24h weekly measurements starting at 10UT Tuesday up to 10UT of Friday. The data sets were collected in a fixed site, in the Engineering Aeronautics School building of the Universitat Politècnica de Catalunya in Castelldefels, close to the final approach area of the Barcelona Airport. The Data Campaign Performances details are given in table 1.

Data Campaign Performance	
Receiver	NovAtel™ WAAS Millennium (OEM3)
Antenna	L1/L2 Antenna NovAtel 600 (Pinwheel)
Receiver Software	SW Version 4.52 S9
Measurement Type	Static
Data collecting Period	From January 10 th to December 26 th of 2002
Time Start	Every Tuesday at 10:00 UTC
Time End	Friday at 10:00 UTC
Latitude	41.275371448 degrees
Longitude	1.986838444 degrees
Altitude	76.7445 meters
Recorded Data	UTCB, IONB, RGEb, ALMB, REPB, FRMB, POSB,SATB
ESTB Message Types	00, 01, 02, 03, 04, 07, 09, 12, 18, 25, 26

Table 1: Data Campaign and measurement environment

Regarding the ESTB signal, the following changes, among others, happened during the data collection period (see the history of ESTB signal status in [8]):

- MT10 update at 22/01/2002: Change of some values of the fixed parameters about the message type 10, namely *Iltc_v1*, *Iltc_v0*, *Igeo*, *Iiono*.
- MT07 update at 14/02/2002: Change of the values of the "UDRE degradation factor indicators" in the message type 7 for all the GPS (new value 13 instead of 15).
- From February 21st to March 20th, no ESTB data sets were collected due to the following reasons:
 - 21/02/2002 09h47 up to 15/03/2002 11h36 UT: no broadcasting due to a technical problem.
 - 15/03/2002 11h36 up to 25/03/2002 15h07 UT: Period dedicated to testing, and therefore, an important number of broadcast interruptions occurred.
- ESTB update at April 16th. Update the geo-coordinates of RIMS and the computation of TGDs.
- ESTB message contents are consistent with RTCA/DO-229B from August 28th.

Horizontal and Vertical Accuracy

The Horizontal and Vertical Position Errors (HPE and VPE) have been obtained applying all the available differential corrections from the ESTB signal (in mode 2, i.e. fast corrections and ionospheric corrections), where the slow corrections (satellite orbit corrections) were not available. The ranging function of the geostationary satellite was not taken into account in the navigation solution, because it was set as unmonitored by ESTB.

The 95th percentiles for the Horizontal and Vertical Position errors accuracy are given in figure 3. As it is shown, before the ESTB update of April 16th, such percentiles was typically between 4 to 6 meters for the horizontal component and between 5 to 7 meters for the vertical one. After ESTB update, the accuracy was clearly improved, being the horizontal and vertical 95th percentiles typically lower than 3 and 4 meters, respectively, except on April 25th which was an anomalous day. Thence, taking into account the accuracy requirements derived from ICAO's GNSS Standards and Recommended Practices (SARPS) given in table 2, it can be concluded that after April 16th the horizontal and vertical accuracy requirements were fulfilled up to CAT-I in the UPC site.

Operation	Horizontal Accuracy 95%	Vertical Accuracy 95%
NPA	220 m	N/A
APV-I	220 m	20 m
APV-II	16 m	8 m
CAT-I	16 m	6-4 m

Table 2. Accuracy requirements derived from ICAO's GNSS Standards and Recommended Practices (SARPS).

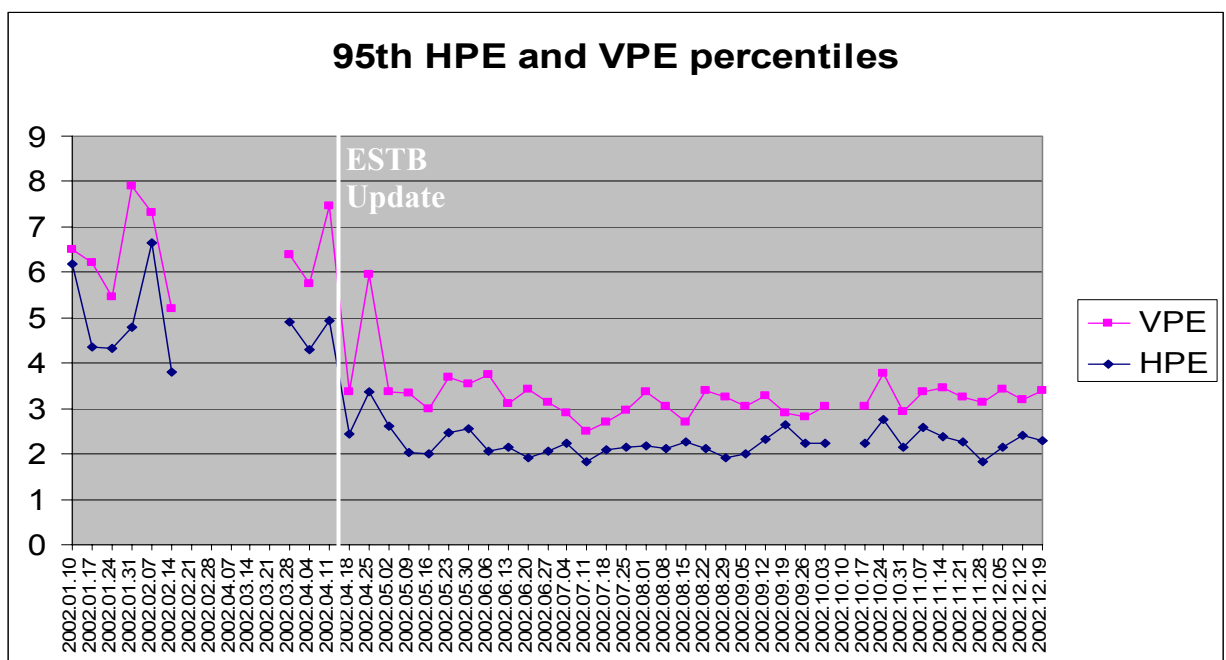


Figure 3. 95th Horizontal and Vertical Position Error percentiles at the UPC site.

System Integrity and Availability:

Integrity is the system’s ability to provide warning to the user when the system is unavailable for a specific operation. The user computes its protection levels (Horizontal and Vertical Protection Levels, HPL and VPL), which represent an upper bound on its position error.

The alarm limits against which a user has to compare its protection levels are defined in the ICAO’s GNSS SARPS as:

Operation	Horizontal Alarm Limit	Vertical Alarm Limit
NPA	556 m	N/A
APV-I	556 m	50 m
APV-II	40 m	20 m
CAT-I	40 m	15-10 m

Table 3. Alarm limits defined in the ICAO’s GNSS SARPS.

The 95th percentiles for the Horizontal and Vertical Protection Levels are given in figure 4. As in previous case (XPE), the XPL percentiles are reduced after the ESTB update of April 16th, its values seems to increase at the end of the year. The typical Protection Level values are about 10 meters for the horizontal component and about 15 meters for the vertical one. Thence, according to table 3, the 95th percentiles for the horizontal protection level are always under the alarm limits for all of the operation modes. The 95th percentiles for the vertical protection level are typically under the alarm limits up to APV-II mode. And, many days, also for the vertical guidance CAT-I.

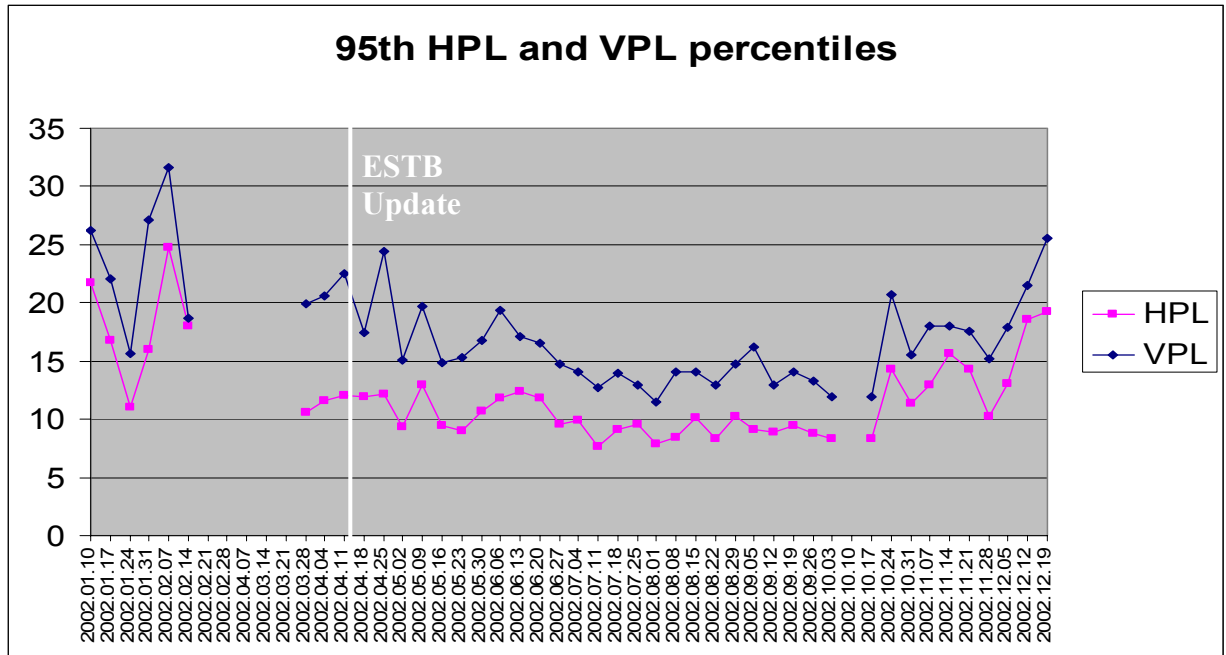


Figure 4: 95th Horizontal and Vertical Protection Levels percentiles at the UPC site.

The availability is defined as the percentage of time during which the system fulfils the accuracy, integrity and continuity requirements for the intended operation. In this case, the position error is bounded by the protection level and the protection level is less than the alarm limit. Thence, the integrity is assured and the system is “available”. If the protection level is greater than the alarm limit, the requirements for the approach can not be met and the system is declared as “unavailable”.

The availability results for the different operation modes are given in figures 5 and 6. As it is shown, the availability for the horizontal component and the vertical APV-I are most of the time close to 100%. The APV-II and Vertical CAT-I availability was improved after the ESTB updating, being the APV-II many times greater than the 99% between June and October. The CAT-I also reached values greater than 90% in such period.

The availability requirements specify a minimum of 99% for every phase of flight. Thence, the system fulfils such requirement for the horizontal guidance and the vertical APV-I, and looks like almost fulfilling APV-II. Nevertheless, this objective is currently not met for the vertical guidance of CAT-I.

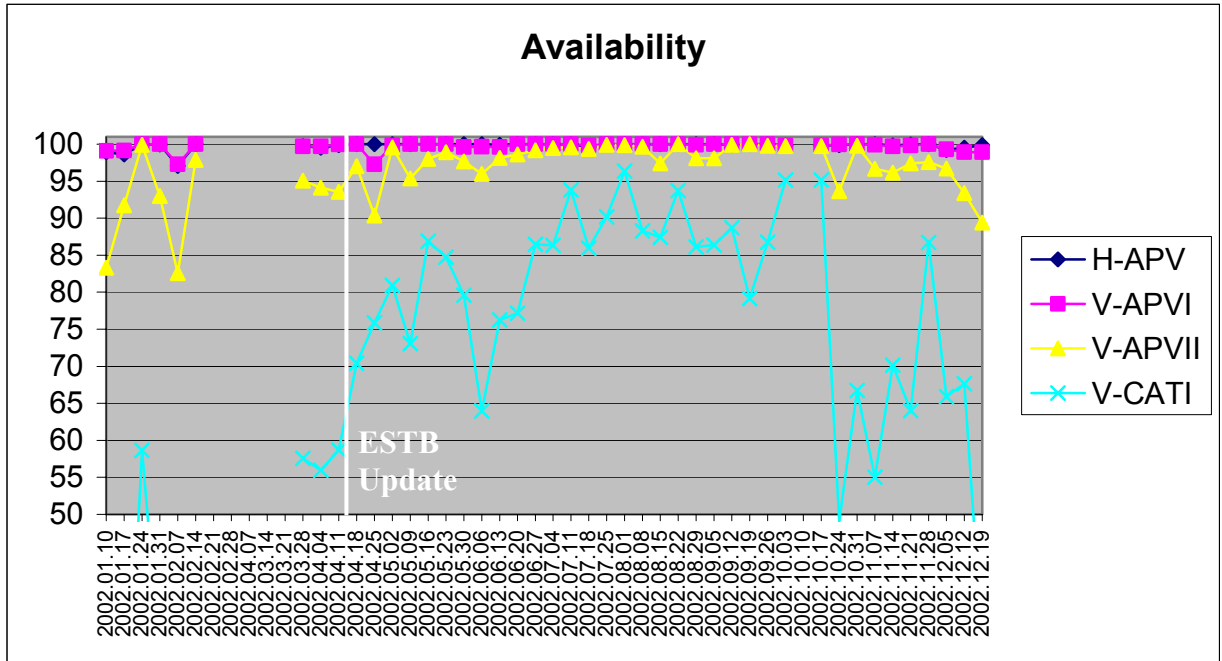


Figure 5: Availability at the UPC site for the different operation modes.

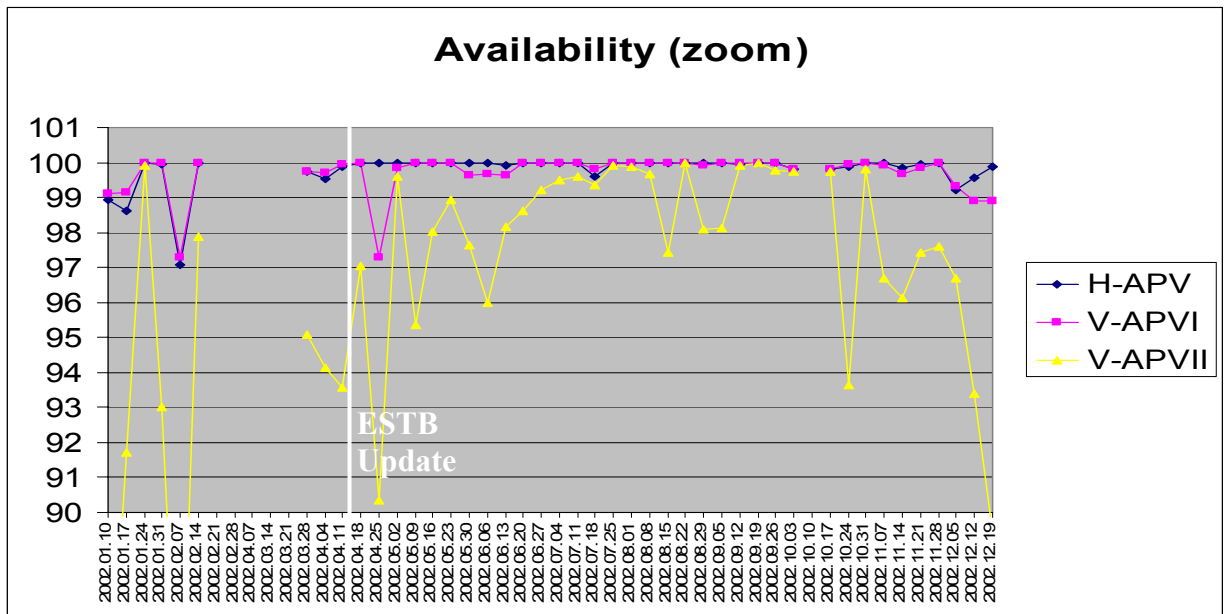


Figure 6: Zoom of previous plot.

If, being the system available, the Position error exceeds the protection level, i.e., the position error is not bounded by the protection level, thence there exist a Loss-Of- Integrity (LOI) failure, since the protection level is always supposed to be an upper bound of the position error. In such case, the event is declared as Hazardously Misleading Information (HMI) if the position error exceeds the alarm limit (which suppose an integrity risk), or as Misleading Information (MI) if the alarm limit is not exceeded.

The LOIs events for the UPC site are given in figure 6. As it is shown, the LOIs basically disappears after the ESTB update of April 16th. An exception was September 12th where many tens of LOIs were found in the horizontal component. This case will be analyzed in next section 2.2.

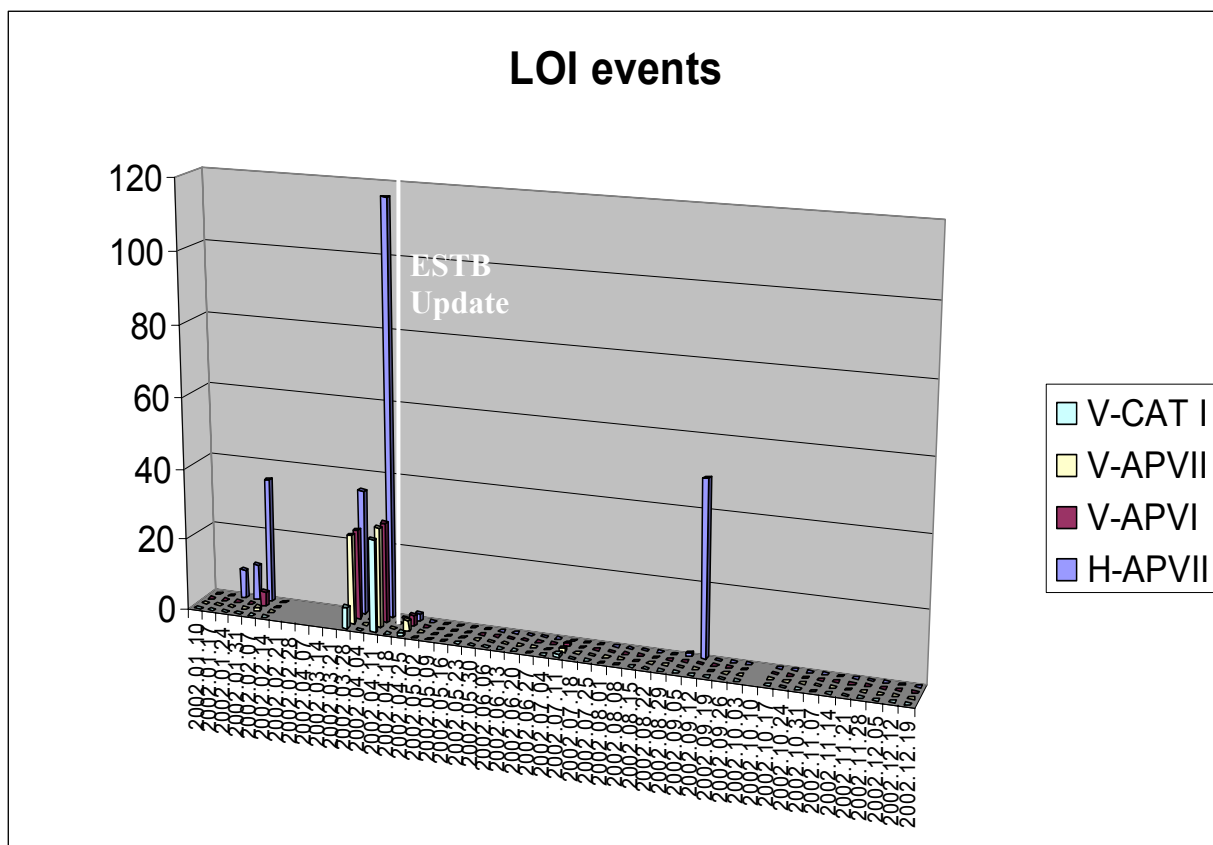


Figure 7: Loss-Of-Integrity in UPC for the Horizontal and Vertical guidance operation modes .

2.2 Analysis of SIS anomalies

As it was mentioned above, BRUS has been designed as a SBAS data processing and analysis tool, and one of the main features is the ability to provide wide information about the applied SBAS messages and how the corrections are internally processed. Such kind of internal information is very useful for analysing the SIS performances. Two examples of detected ESTB SIS anomalies are shown in this section.

Example 1: Analysis of a lack of the navigation solution. Data set of February 14th 2002.

Some periods without navigation solution were found when processing the February 14th data sets. A detailed analysis of the ESTB broadcasted messages showed that it was a SIS anomaly related with the Message Type 26 (MT26: Ionospheric Corrections) repetitions, due to an IONO alarm condition. Due to the MT26 repetitions, the Fast corrections were not updated up to 21 seconds, producing the deselection of the associated satellites because of the UDRE Time-Out, which is established as 12 seconds for Precision Approach mode.

The broadcasted ESTB messages between 413846 and 413870 seconds of GPS week (TOW), as well as the satellites with differential corrections available for the Precision Approach navigation mode, are given in figure 8, which summarizes this SIS anomaly analysis. Notice that (due to the UDRE time out) from TOW=413860 up to TOW=413868 there were less than four satellites with differential corrections available for the selected mode and, hence, no navigation solution could be computed. After TOW=413867 new Fast correction messages (MT02-04) were received and the satellites were being incorporated to the navigation solution.

Such SIS anomalies can be avoided by broadcasting the Message Type 6, as it is usually done after August 28th.

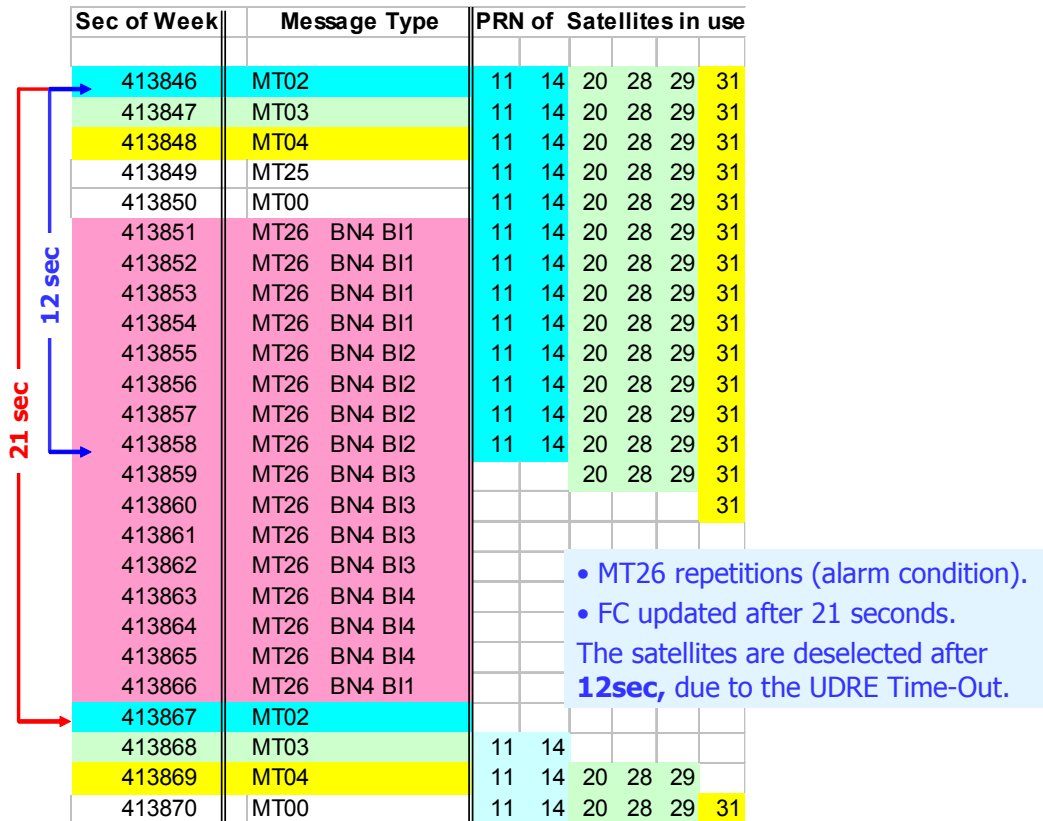


Figure 8: SIS anomaly analysis. ESTB messages broadcasted and satellites used in the navigation solution.

Example 2: Analysis of large number of LOIs in the Horizontal component. Data set of September 12th 2002.

A large number of LOI events (MI) appear when processing the data set of September 12th. Similar results were obtained in an other fixed site, in Barcelona, with 16km of baseline. Such integrity failures were done only for the horizontal component, that is, no LOIs appears in the Vertical one (see figure 9).

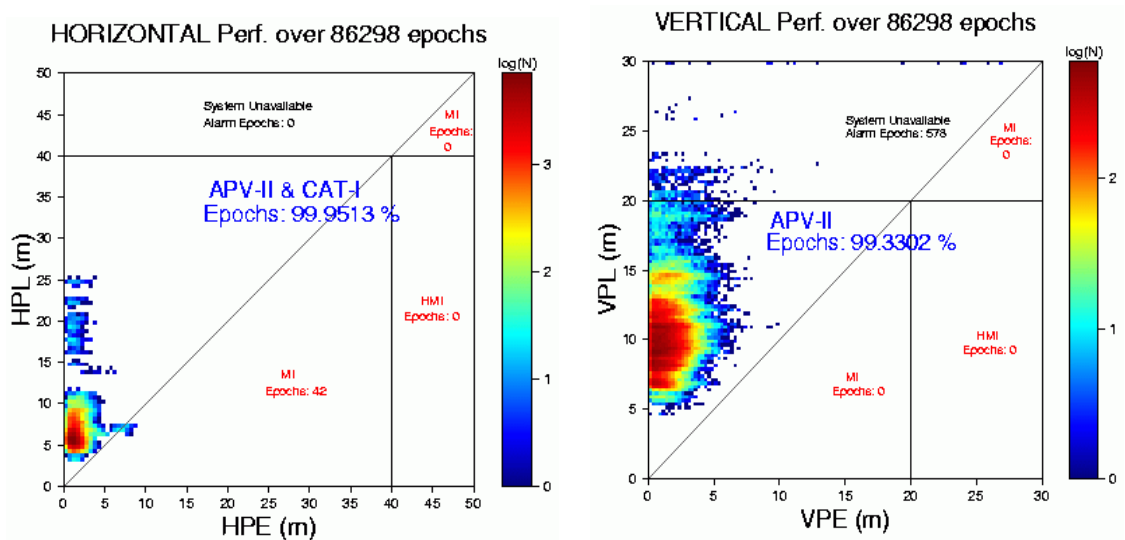


Figure 9: Stanford plots for the horizontal (left) and Vertical (right) performances. The horizontal axis is the true error of the EGNOS navigation solution regarding the true position. The vertical axis corresponds to the protection level computed for the navigation solution. Each bin specifies the number of occurrences in a logarithmic color scale. The Alarm Limits, as well as the MI and HMI regions are also indicated in the figures. The percentage corresponds to the Normal Operation Region which is the left upper triangle defined by the conditions $VPL > VPE$ and $VPL < VAL$.

The epochs in which the LOIs happen can be identified from figure 10 (left), where the Horizontal Position Error and Protection level are plotted in function of the seconds of the GPS week. As it is shown around TOW=418300 sec, there is a jump in the HPE which exceeds the HPL producing the integrity failures.

After analyzing the different ESTB messages (Fast and Slow Corrections, Integrity Messages and Ionospheric Corrections), it was found that the LOIs were produced by wrong ionospheric corrections values broadcasted for the region in which the satellite PRN17 pierce point was located during such period. In figure 10 (right), the ionospheric correction values computed by BRUS from the ESTB messages for the different satellites in view are given in function of TOW. As it is shown, there is a jump in the IONO values for the satellite PRN17. This jump, which is due to the wrong IONO broadcasted values, is the reason of the LOI failures.

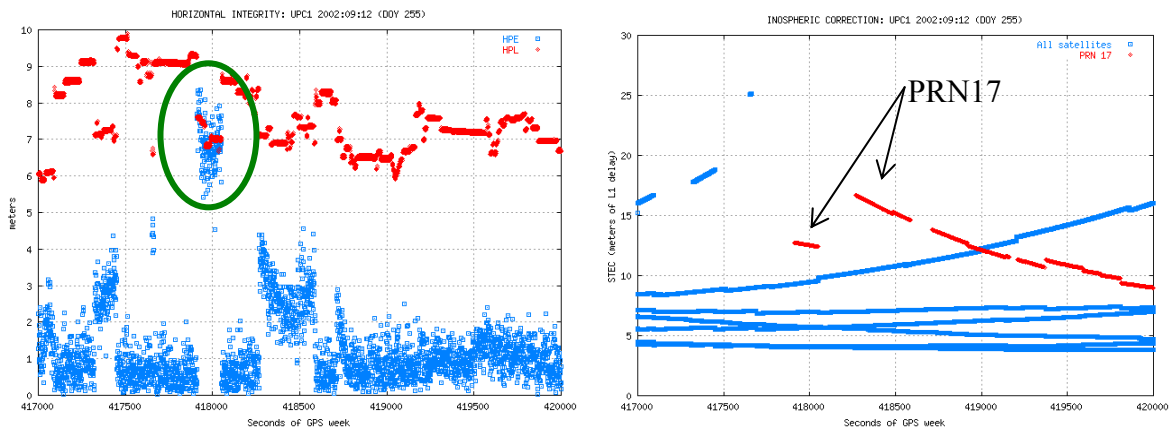


Figure 10: HPE and HPL in function of the Seconds of GPS week (left). Ionospheric corrections computed from the ESTB messages in function of the Seconds of GPS week, for the different satellites in view from UPC. (right).

Other applications: Analysis of the Ionospheric Corrections accuracy

BRUS is being also used to analyze the accuracy of the SIS corrections. An analysis of the ionospheric corrections accuracy is provided in [9].

3. Future developments: GLOBAL Performance Monitoring using public domain GNSS networks

A global (the Service Volume) SBAS (WAAS, EGNOS, MSAS) performance monitoring using the available GPS or GPS/GLONASS data collecting networks (i.e. fixed sites with public data available from the internet) is going to be developed as an extension of BRUS. This system will provide a wide SBAS performance monitoring with a very low cost, because it will not require building a specific dedicated network. Thence, it will also provide an additional use to the existing public domain data collecting networks.

There are several GPS data networks world wide distributed that are collecting data on a daily basis at 1, 5, 15 or 30 seconds, and many of them have the data sets available in a RINEX format from internet. Only in Europe, it can be gathered data from more than 100 permanent stations, most of them at 30 second, but also many at 1sec. Examples of sites are: lox.ucsd.edu, cddisa.gsfc.nasa.gov, lareg.ensg.ign.fr, geodaf.mt.asi.it, among others.

Such networks have been basically developed for geodetic research, orbit determination or other scientific applications and, usually, do not include SBAS receivers (they are double frequency GPS or GPS/GLONASS receivers). Nevertheless, the GEO messages are common for all the Service Volume and, as a consequence, a SBAS receiver can be emulated for each site using the GEO messages collected in any point of the Service Volume (for instance in UPC site for EUROPE) and processing with BRUS (see figure 10). The ESTB message can be also gathered from the internet by means the ESA application SISNeT [10]. Only the GEO ranging is out of the scope of such emulation.

This global monitoring is going to be implemented by means of an automatic system that will get the data files from the ftp sites, on a daily basis, and will compute the navigation solution using the GEO message collected from the SBAS receiver. On the other hand, the automatic processing will have a latency of 1 or 2 days in order to

allow the inclusion, under request, of additional data sets collected from some independent sites (delivered in a ftp server) that would be added to the processing.

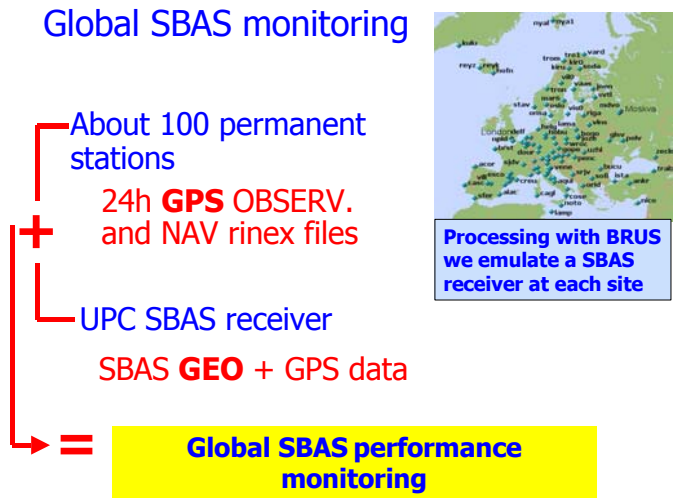


Figure 11: Layout of the SBAS Global Monitoring Concept. Using the GEO message collected in UPC site, a SBAS receiver (except for GEO ranging) can be emulated in each GPS site over EUROPE.

The automatic system shall provide some statistic analysis and graphic results of the regional performances to help the data analysis. Also, an automatic e-mail with a brief report of the global daily performances and a short historical summary will be broadcasted to a distribution list. Moreover, some results will be saved in a data base to allow the daily evolution monitoring at a regional scale, or to analyze potential local features at the sites, as well. Finally, some relevant data or results will be uploaded to a web server.

The layout of the Automatic Global Monitoring System is illustrated in figure 12. Some examples of possible graphical outputs are shown in figure 13.

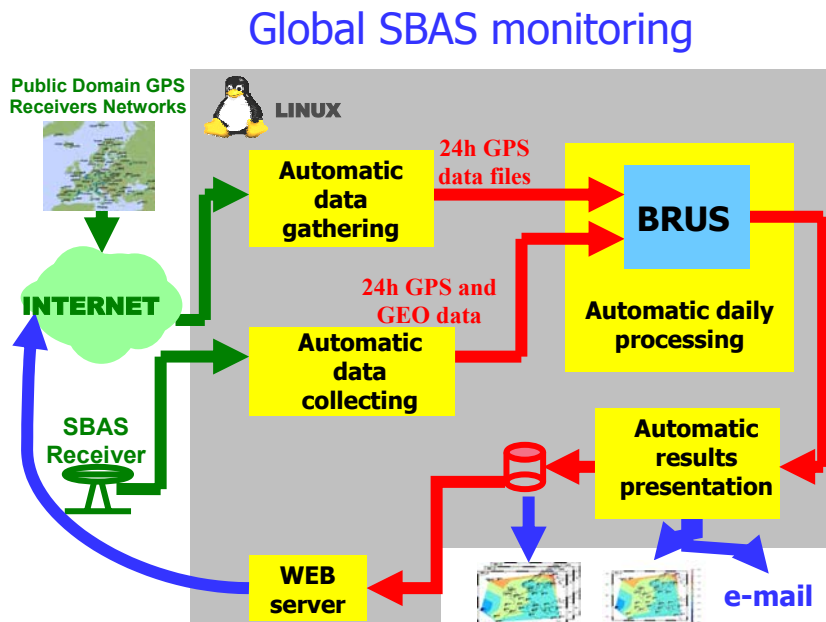


Figure 12: Layout of the Automatic Global Monitoring System. In a daily basis, the data set files from the GNSS receivers networks are gathered from the internet. These files are combined with the collected GEO data form a SBAS receiver and processed with BRUS. After processing, some statistic analysis and graphic results are generated and an automatic e-mail is broadcasted to a distribution list. Moreover, a data base is updated for further analysis and some relevant information is uploaded to a web server.

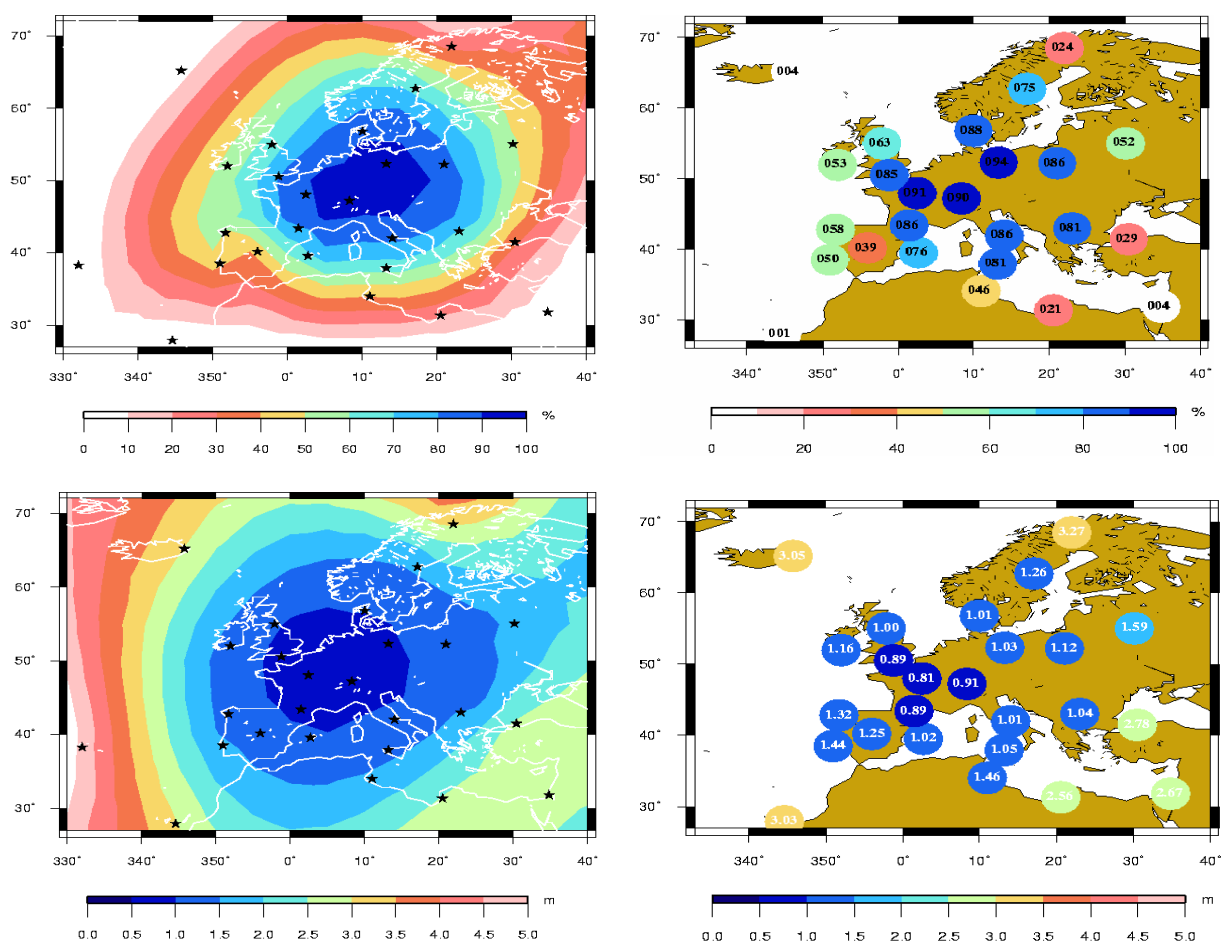


Figure 13: Examples of possible graphical outputs: Availability plots for Vertical guidance CAT-I (first row) and Vertical Position Error (second row). The contour plots (left) are computed by interloping the values provided in the bubble plots (right). The numbers in the bubbles corresponds to values at the site, given in the color scale. The stars in the contour plots indicates the sites used in the computation.

Acknowledgments

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