

## ESTB PERFORMANCE AGAINST LOSSING SATELLITES (FIRST RESULTS)

Jaume Sanz (1), Xavier Prats (1), Richard Farnworth (2), Santiago Soley (2)

- (1) Research group of Astronomy and Geomatics, Universitat Politècnica de Catalunya (gAGE/UPC), Barcelona, Spain.
- (2) EUROCONTROL Experimental Centre, Bretigny, France.

**Key words:** Augmentation Systems, EGNOS, ESTB

### Abstract

The EGNOS System Test Bed (ESTB) is the EGNOS prototype which has been broadcasting a Signal in Space since February 2000. Accuracy, integrity, continuity and availability are the main concepts in this European component of the Satellite Based Augmentation System which is designed to support en route through precision approach aircraft navigation.

In this work, for the first half of the year of 2002, we study the ESTB performance in fixed sites in Barcelona, and we analyze how this performance is affected when losing a single ESTB monitored satellite. The data set involves a 24 hours weekly measurements collected in two fixed sites (UPC1 and UPC2), from January to August 2002. In particular, the number of Loss of Integrity events (LOI) and the degradation of the Vertical Position Error percentile and the APV-II availability are analyzed.

As the main results, two satellites have been identified which loss could have produced a large number of LOIs (up to hundreds) in two particular days before the ESTB update of April 16th 2002. The improvement in the ESTB performance after such update is also reported.

### 1. Introduction

In the recent years, Global Navigation Satellite Systems (GNSS), have experienced a considerable growth of new applications and users. Safe critical applications, such as civil air radionavigation, require high levels of accuracy and integrity (system's ability to bound its own accuracy) that are not met in standalone GNSS positioning. Satellite Based Augmentation Systems (SBAS) provide differential GNSS corrections and integrity information to single frequency users. These corrections are combined with receiver measurements, and other local information, to obtain the final navigation solution and integrity protection bounds.

Since February 2000 the EGNOS System Test Bed (ESTB), a prototype of EGNOS, has become operational. This has resulted in the initiation of various activities using the ESTB in preparation for the time when the real EGNOS Signal-in-Space validation needs to begin. Prototype data collection tools have been developed, notably the Pegasus tool [1], for processing data collected with the ESTB and various data collection efforts have already taken place.

Based on the experience collected with the ESTB data collection, Eurocontrol has developed documents standardising the way data should be collected and the way the results should be displayed.

With these tools, receivers and associated documents available, a need was identified to perform data collection on a more regular basis to establish a good understanding of the performance of an SBAS Signal-in-Space over a longer time interval over an area with a good geographical distribution. With this objective in mind, Eurocontrol established a small network of data collection sites composed of four European universities, among them UPC Research Group of Astronomy and Geomatics (gAGE/UPC).

Since January of 2002, gAGE/UPC, has been collecting ESTB data in Barcelona as a part of the above mentioned 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, are also processed with BRUS (Basic Research Utilities for

SBAS) [2], which is a software tool developed by gAGE/UPC. One of the targets of this small working group is to analyze the ESTB performance for the different operation modes and to identify and study potential anomalies in both, the Signal-in-Space and user domains.

As a result of this effort, a huge data base is created allowing several studies about the ESTB performance, such as the presented in this work, where the ESTB robustness against loosing a single monitored satellite is analyzed during the first six months of 2002. This period includes the ESTB update of April 2002, after which a clear improvement of the ESTB results is observed.

Before starting with the main topic of this work, a general background about the ESTB System is given in next section 2.

## 2. ESTB general background

### 2.1 The ESTB system

The ESTB is a complete prototype of the EGNOS system. It implements the main functions (ranging, GPS differential corrections and integrity) with real time elements enabling different user experiments or tests. Of course, the ESTB functions, complexity and performance are reduced by an order of magnitude with respect to the EGNOS system, principally concerning the availability, the robustness and redundancy of facilities.

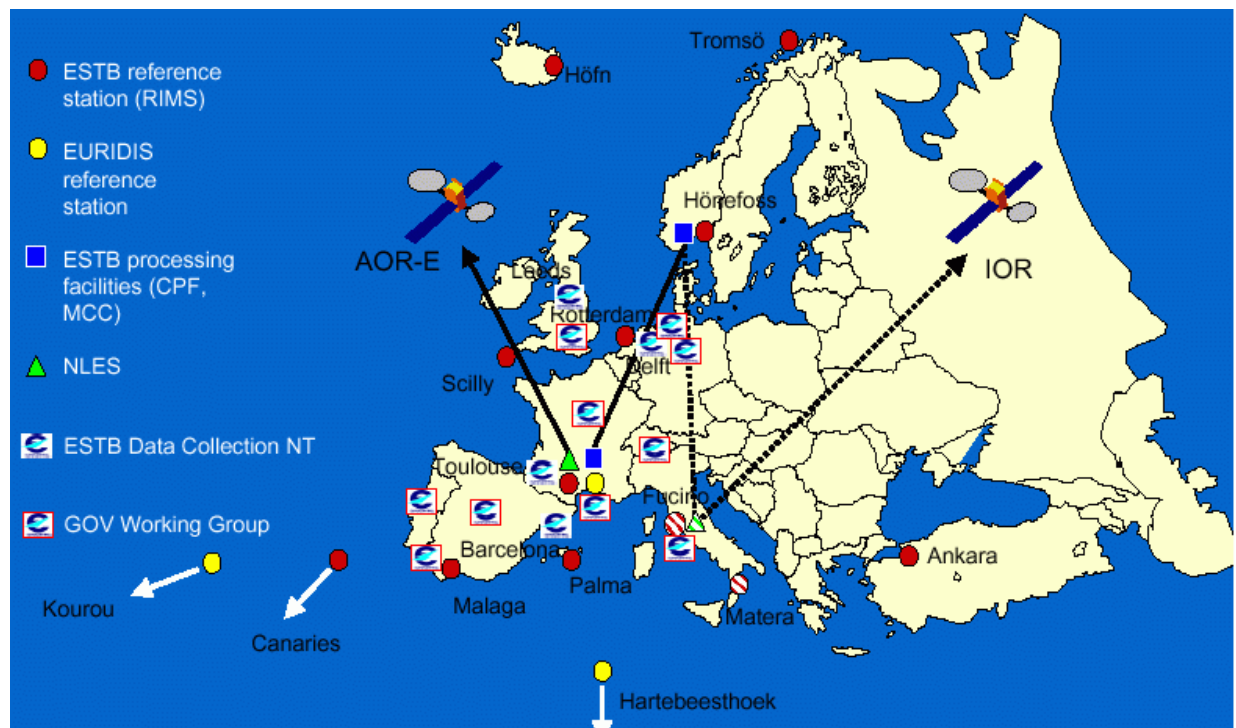


Figure 1. ESTB System Architecture

The ESTB system is illustrated in figure 1. It is composed of:

- Remote Integrity Monitoring Stations (RIMS) gathering data for the purpose of generating corrections and integrity messages deployed over Europe at hosting sites,
- Central Processing Facility (CPF) to compute on-line differential corrections and integrity data, based at Hönefoss in Norway (NMA premises),
- three EURIDIS Reference Stations implementing a wide triangular observation base for ranging purposes with the stations located in Aussaguel (France), Kourou (French Guyana) and Hartebeeshoek (South Africa),
- a Mission Control Centre (MCC) located in Toulouse, France, (CNES premises), to compute ranging messages and prepare navigation messages for transmission through the AOR-E payload,
- Two Navigation Land Earth Station (NLES) based on existing stations of the INMARSAT network, one located in Aussaguel (France) implementing the broadcast link to the AOR-E Navigation payload, the

other located at Fucino (Italy) implementing the broadcast link to the IOR Navigation Payload. Each NLES is compliant with requirements from the INMARSAT SDM

- a ground network composed of sub-networks to transmit data from reference stations to central processing facilities, to the mission control centre and to the appropriate geostationary uplink stations.

Through the GEO satellite, the ESTB provides messages containing corrections to the user for position and integrity computation.

## 2.2 *The ESTB signal in Space*

The ESTB system transmits its differential corrections and integrity information to users in a 250 bit messages. The corrections for individual satellites must be combined with receiver measurements and other local information to form the navigation solution and the protection bounds. The main components of the ESTB message are described as follows [3]:

### *Fast Corrections*

They are necessary to correct the fast changing errors – usually the satellite clock error. The fast corrections, provided as range correction values, are applied directly to the range measurements.

Together with the fast corrections, integrity indicators in the form of UDRE estimates are broadcast. These UDRE are an upper bound on the error of the pseudorange after the application of fast corrections, including the possibility that the user misses any messages. The UDRE are used to compute protection levels and also warning flags indicating that an individual PRN should not be used in the position solution.

### *Slow Corrections*

Slow corrections are used to remove the slowly varying errors such as the satellite position errors caused by errors in the ephemeris transmissions and the degradation of the satellite position calculations with the time.

The satellite clock error is also corrected by the slow correction.

### *Ionospheric Corrections*

In contrast to the calculation of the fast and slow corrections (which are very straight forward), the determination of the ionospheric error corrections is more complex. The slant delay and the slant residual ionospheric error caused by the ionosphere are calculated using several steps.

The SBAS ionospheric correction messages are related to an interpolation grid above the earth's surface at an altitude of the ionosphere. For each satellite, the pierce point of the direct line-of-sight from the satellite to the user's position through the ionosphere is determined. This pierce point is then used to determine the appropriate grid points for the interpolation.

The interpolation uses a weighting scheme for all four neighbouring grid points to determine an estimation of the vertical delay of the pseudorange at the ionospheric pierce point. This vertical delay is finally modified to take the elevation of a particular satellite into account. Thus, a slant delay for the ionospheric error model and an estimation about its residual error are calculated.

## 2.3 *The performance*

The Minimum Operational Performance Standards (MOPS) [4] for SBAS specify the computation of the Vertical and Horizontal Protection Levels (VPL, HPL) of the differentially corrected navigation solution which must be met at a probability of 99.99999%. Thus the true error must not exceed the protection level more than once in  $10^7$  seconds.

Figure 2 shows the Stanford plot [4] reporting the Vertical Performance of the navigation solution. 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 horizontal and vertical lines at 20m indicates the Vertical Alarm Limit (VAL) for the operation mode APV-II defined by ICAO's GNSS SARPS. The system is declared unavailable when  $VPL > VAL$ .

Points with error greater than the protection level ( $VPE > VPL$ ) indicates Loss-Of-Integrity failures (LOI). It includes the Misleading Information (MI) and the Hazardously Misleading Information (HMI) events.

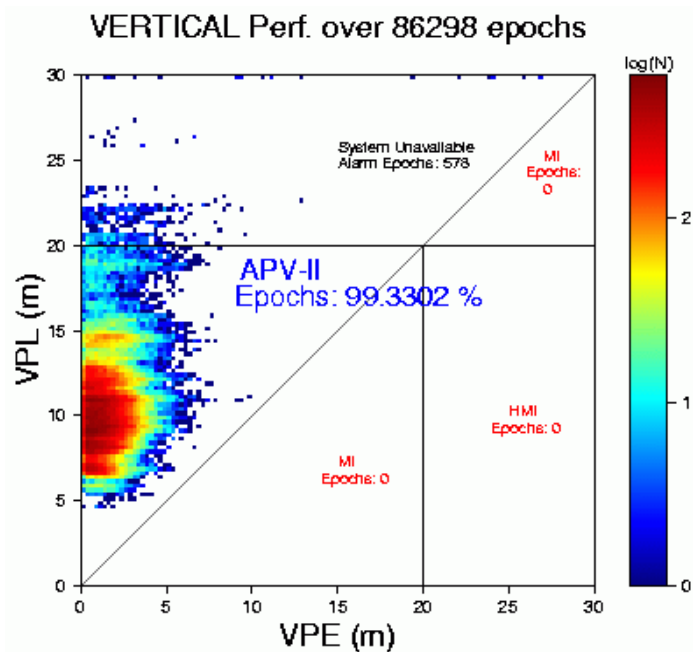


Figure 2. Vertical System Performance

The Normal Operation Region is the left upper triangle defined by the conditions:  $VPL > VPE$  and  $VPL < VAL$ . The availability requirements defined by SARPS specify a minimum of 99% of the system in this normal operation region for every phase of flight. In figure 2, such requirement is fulfilled 99.33% of the time.

Similar metrics and plots are defined for the Horizontal performance (see [5]).

### 3. ESTB performance analysis against losing satellites

The integrity requirements defined in previous section must be fulfilled whenever the set, or subset, of  $n \geq 4$  satellites used in the navigation solution with valid differential corrections available for the navigation mode. And the loss of a single or multiple valid satellites due, for instance, to space-craft maneuvers, should not produce LOIs. Indeed, the degradation in the navigation solution accuracy, due to the loss of satellites, must be followed by an increase of the protection levels in such a way that the integrity be guarantee.

As we are going to show in the next section, it was identified two days, before the ESTB updating of April 16<sup>th</sup>, in which the losing of a single satellite could produce a large number of LOIs. From hereafter, we are going to call these satellites as "critical satellites" in the sense that their losses produce integrity failures.

#### 3.1 Computations

The ESTB performance against losing a single satellite has been analyzed during the first half of the year 2002, using the ESTB data sets collected at the UPC1 and UPC2 sites, located in Barcelona and Castelldefels, Spain, with 16 Km of baseline.

The data sets involve 24h weekly measurements starting on 10UT Tuesday up to 10UT of Friday, from January to August of 2002. In total, it has been analyzed 29 days, with about 28 satellites in view per day, which suppose more than  $70 \cdot 10^6$  processed epochs for each site.

The data processing algorithm consisted of computing the navigation solution after excluding a single satellite in view and iterating this computation for all of the satellites, and for all of the data collecting days. The algorithm is summarized in the following scheme:

```

for each $DAY
  for each satellite in view $PRN

    compute the navigation solution with BRUS
    "excluding the satellite $PRN"

  endfor
endfor

```

This algorithm has been easily implemented in a very straightforward script using BRUS under LINUX operative system.

### 3 Results

The ESTB performance results obtained from the previous computations are given as follows, where integrity, accuracy and availability are analyzed for both sites UPC1 and UPC2, before and after the ESTB update in April 16<sup>th</sup>.

#### 3.1 Integrity: LOIs when losing a single satellite

The results for UPC1 are shown in figure 3, where the LOI failures are given for the different data collecting days. As it is shown, in general, the loss of a single satellite does not produce a significant increment of the LOIs, except for the DOY 87 (March 28<sup>th</sup>) and DOY 101 (April 11<sup>th</sup>). The integrity failures on both days are related with the exclusion of satellites PRN20 and PRN01. The most critical day was March 28<sup>th</sup>, where more than 250 LOIs appears after excluding the PRN20. Notice that both days are previous to the ESTB updating of April 16<sup>th</sup>, and no significant increasing of LOIs appears when deselecting a single satellite after such time.

Similar results as in UPC1 were obtained for UPC2 site, but with a number of LOIs quite greater, i.e., with more than 350 events when excluding PRN20 in March 28<sup>th</sup> (see fig 4).

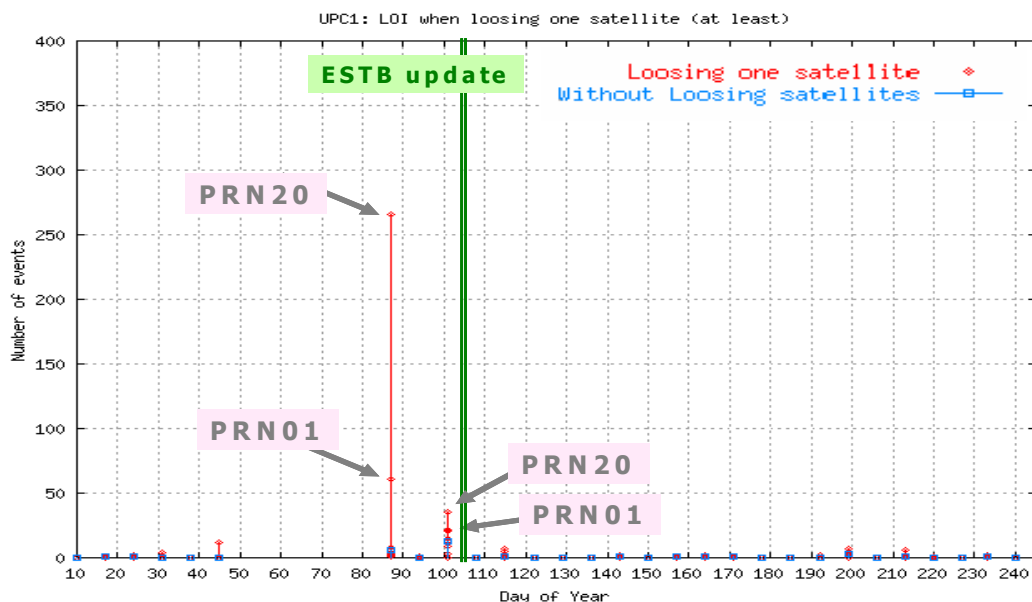


Figure 3. LOI failures when losing a single satellite in UPC1 site. The horizontal axis is the Day of the Year (DOY) ranging on January 10th (DOY=10) to August 28<sup>th</sup> (DOY=240) of 2002. The vertical axis is the number of LOI failures obtained without excluding satellites (squares) or, after excluding a single satellite (diamonds). The day corresponding to the ESTB update, April 16<sup>th</sup> (DOY= 106), is also indicated by a vertical line.

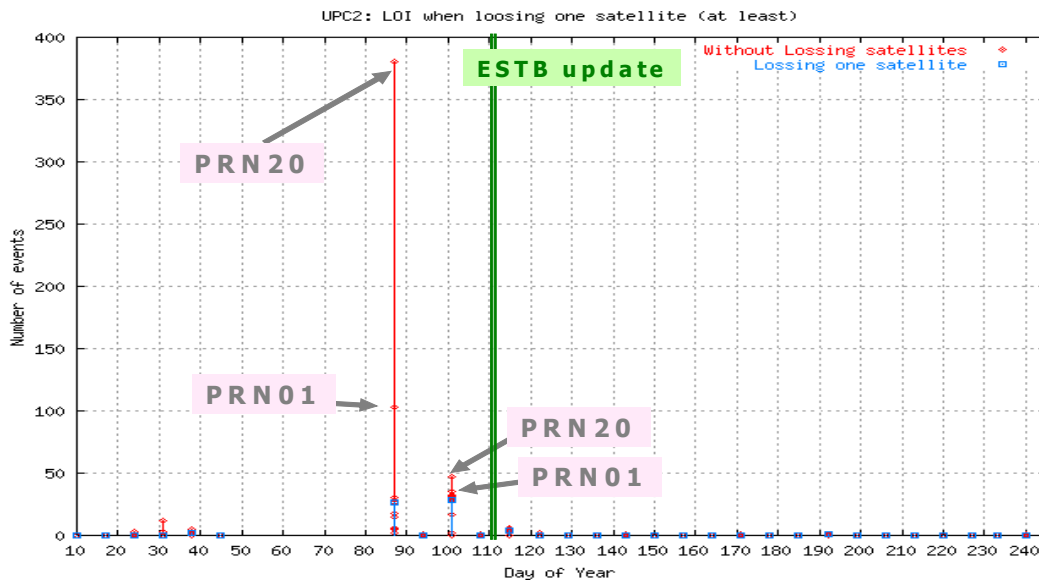


Figure 4. Same plot as in previous figure 3, but for UPC2 site

The number of LOIs in function of the PRN satellite for all of the analyzed days in UPC1 is given in figure 5. This plot allows to easily identify the critical satellites, which exclusion produce large number of integrity failures. As it is shown, and accordingly, it has been commented in the previous figures, only the satellites PRN01 and PRN20 can be identified as a critical ones.

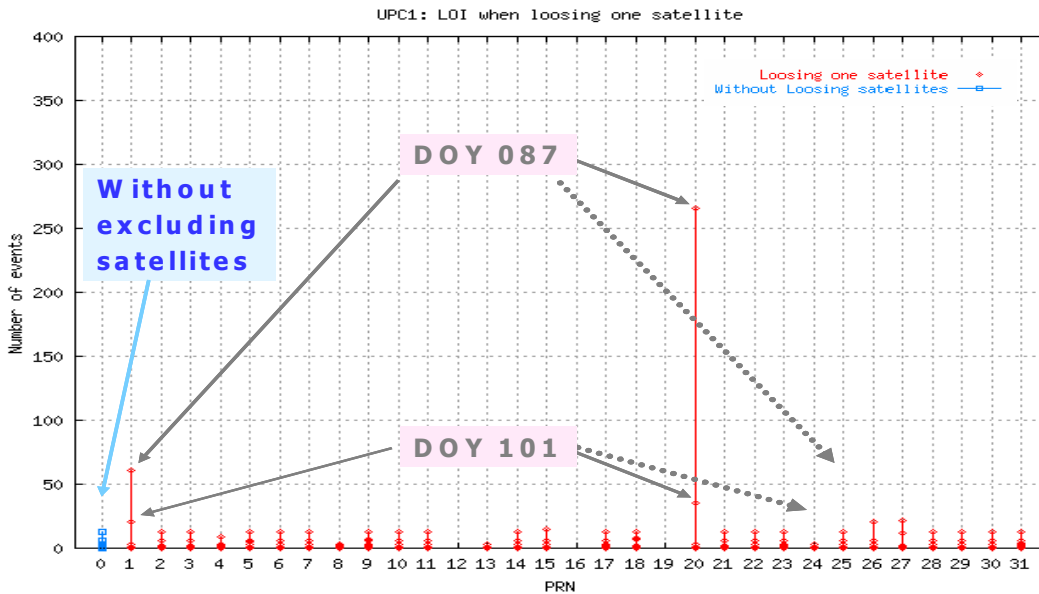


Figure 5. LOI failures when losing a single satellite in UPC1 site for all of the data collecting days (from January 10<sup>th</sup> to August 28<sup>th</sup>). The horizontal axis is the PRN number of the excluded satellite in the computation. The “0” stands for the solution computed without excluding satellites. The vertical axis is the number of LOI failures events. The days in which the large LOIs appears are also indicated in the figure. Similar plot has been obtained for UPC2.

A comparison between the LOIs when deselecting a single satellite, before and after the ESTB update of April 16<sup>th</sup>, is given for UPC1 in figure 6. As it can be seen, the system shows a shorter number of integrity failures after such update, being clearly more robust against losing satellites.

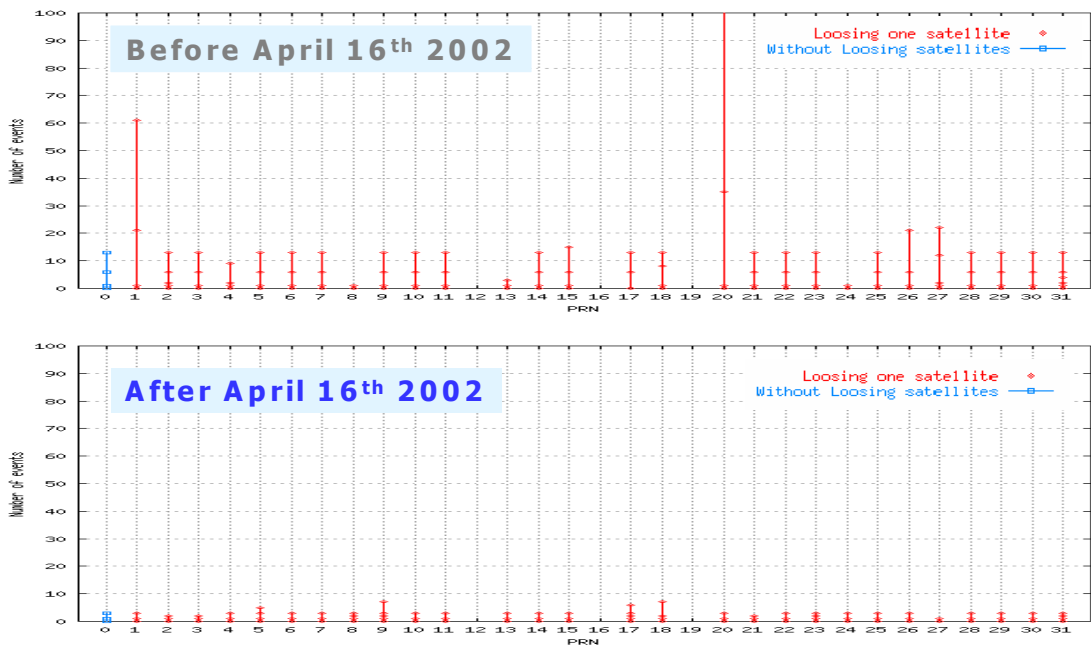


Figure 6. Same plot as in previous figure 5, but distinguishing the results before the ESTB update (upper) and after (lower).

### 3.2 Accuracy: 95<sup>th</sup> Percentile of the VPE

The 95<sup>th</sup> percentile of the Vertical Position Error is given in figure 7 for the UPC1 site. As it is shown, the accuracy could be significantly affected when losing a single satellite, before the ESTB update, which error could be degraded up to two times the original values. Moreover, in some cases the accuracy is improved when deselecting a single satellite. Such improvement could exhibit a potential anomaly in the differential corrections broadcasted for such satellite, because when losing satellites, a degradation of the accuracy should be expected due to the more poor geometry.

After the ESTB update, the 95<sup>th</sup> vertical percentile is reduced up to two times regarding the previous periods with typical values of about 3 meters. And the loss of a single satellite has a small impact over the 95<sup>th</sup> percentile, except for April 25<sup>th</sup> (DOY 115). The DOY 115 was an anomalous day showing VPEs clearly greater than the typical ones after April 16th. Similar behavior was obtained in the other ESTB Data Collecting sites for such a day.

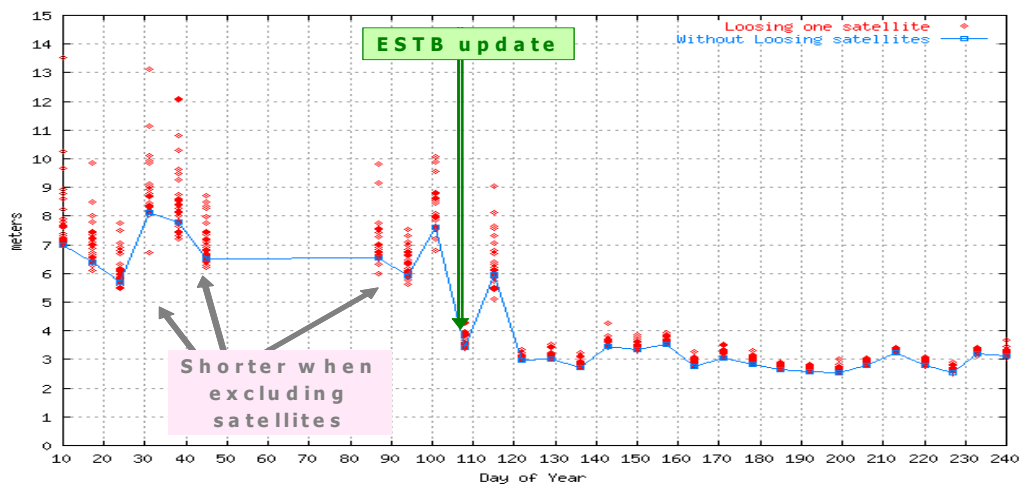


Figure 7. Accuracy: 95<sup>th</sup> percentile of Vertical Position Error for UPC1. The horizontal axis is the Day of the Year (DOY) ranging on January 10<sup>th</sup> (DOY=10) to August 28<sup>th</sup> (DOY=240) of 2002. The vertical axis is the 95<sup>th</sup> percentile in meters. The solid line indicates the results without excluding satellites. The diamonds indicate the values when excluding a single satellite.

The results for the UPC2 site are compared with those of UPC1 (with 16 Km of baseline) in figure 8, showing similar performances, as expected. Notice also the abnormal behavior for DOY 115 in both sites as such has been previously mentioned.

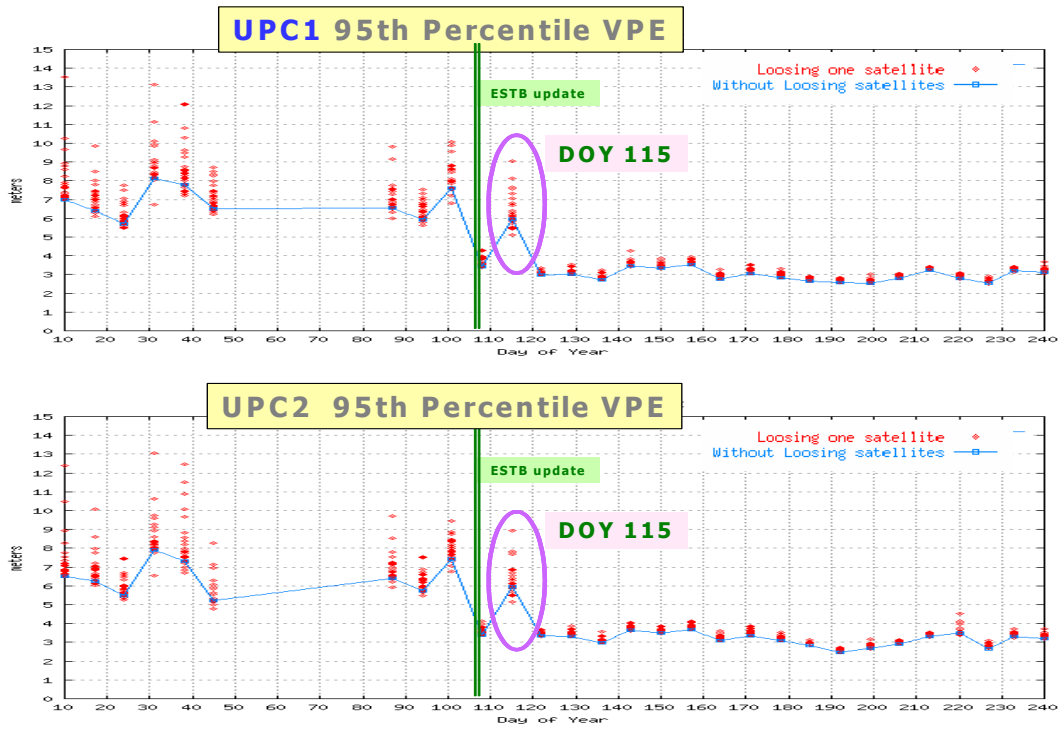


Figure 8. The same plot such as in previous figure 7, but comparing the results for UPC1 (top) and UPC2 (bottom).

A comparison of the 95th percentile for UPC1 site before and after the ESTB update is given in figure 8 in function of the PRN of deselected satellite. As it is shown, after April 16<sup>th</sup>, all satellites have similar impact over the 95<sup>th</sup> percentile when they are deselected from the navigation solution (excluding the DOY 115). This is not the case before such update, where the accuracy is clearly degraded when excluding some of the satellites PRN20, PRN31, or PRN07, among others.

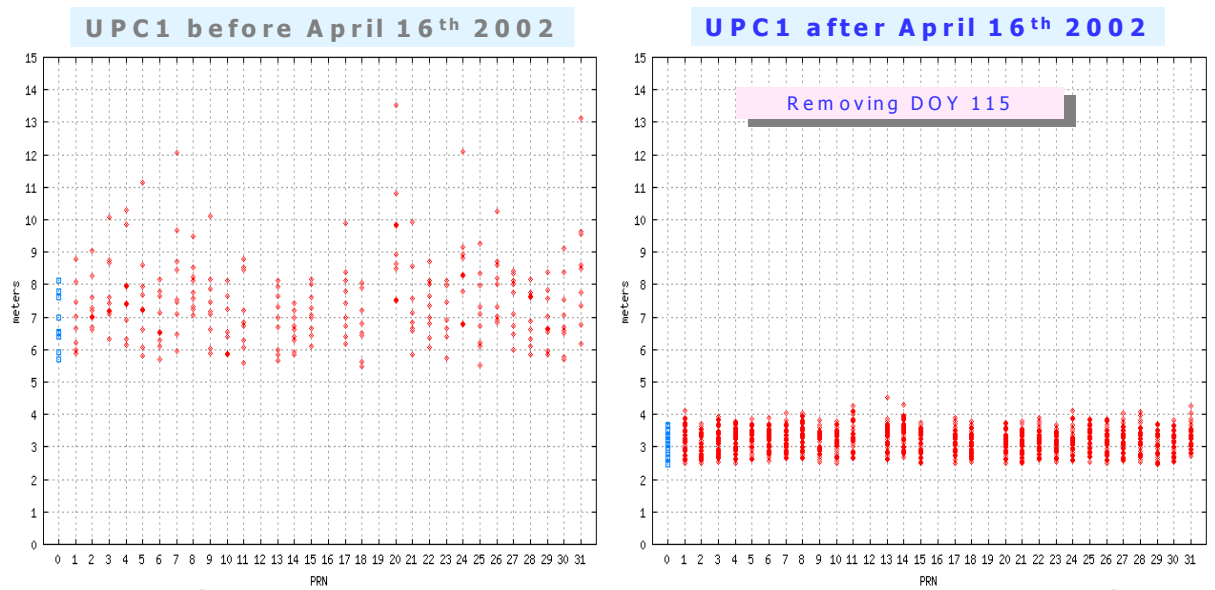


Figure 9. Accuracy: 95<sup>th</sup> percentile when losing a single satellite in UPC1 site for all of the data collecting days from January 10<sup>th</sup> to April 11<sup>th</sup> (left) and from April 18<sup>th</sup> to August 28<sup>th</sup>, but excluding the DOY 115, (right). The horizontal axis is the PRN number of the excluded satellite in the computation. The "0" stands for the solution computed without excluding satellites. The vertical axis is the 95<sup>th</sup> VPE percentile in meters.

### 3.3 APV-II Availability

The results for the APV-II availability in function of the day of the year are given in figure 10. In general it appears a decreasing of the availability when deselecting the satellites, which is produced by the increasing of the protection levels due to the worst geometry. But, on the contrary than in previous cases, the availability results for the periods before and after the ESTB updating are more similar. Nevertheless, after the ESTB update, the APV-II availability seem to be less sensible to losing a single satellite, and could decrease up to 5%.

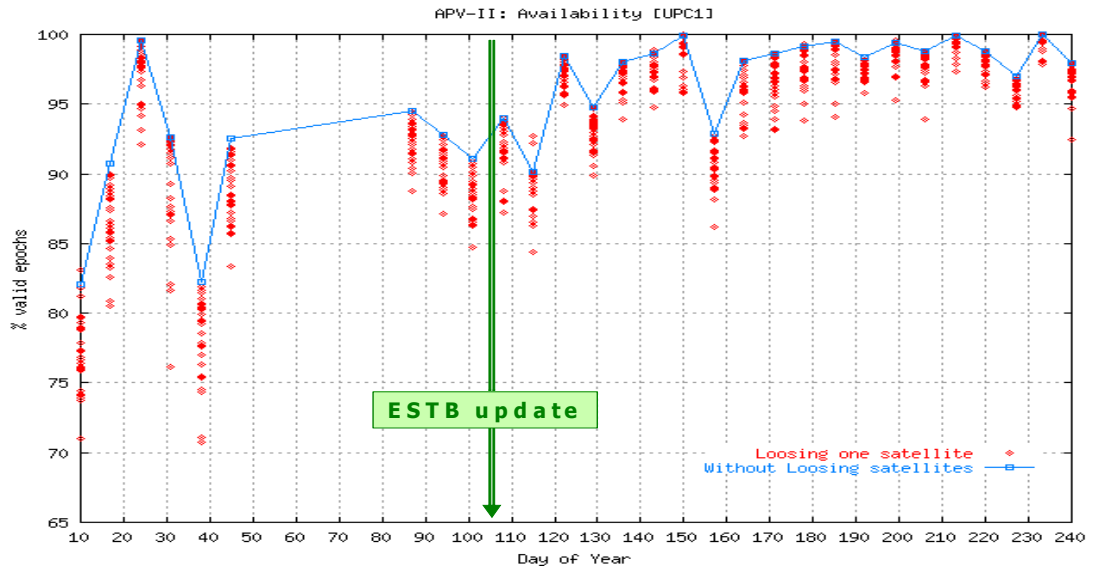


Figure 10. APV-II Availability for UPC1. The horizontal axis is the Day of the Year (DOY) ranging on January 10<sup>th</sup> (DOY=10) to August 28<sup>th</sup> (DOY=240) of 2002. The vertical axis is the percentage of epochs inside the Normal Operation Region. The solid line indicates the results without excluding satellites. The diamonds indicate the values when excluding a single satellite.

The results for the UPC2 site are compared with those of UPC1 (16 Km of baseline) given in figure 11. The same behavior is obtained in both sites, as expected.

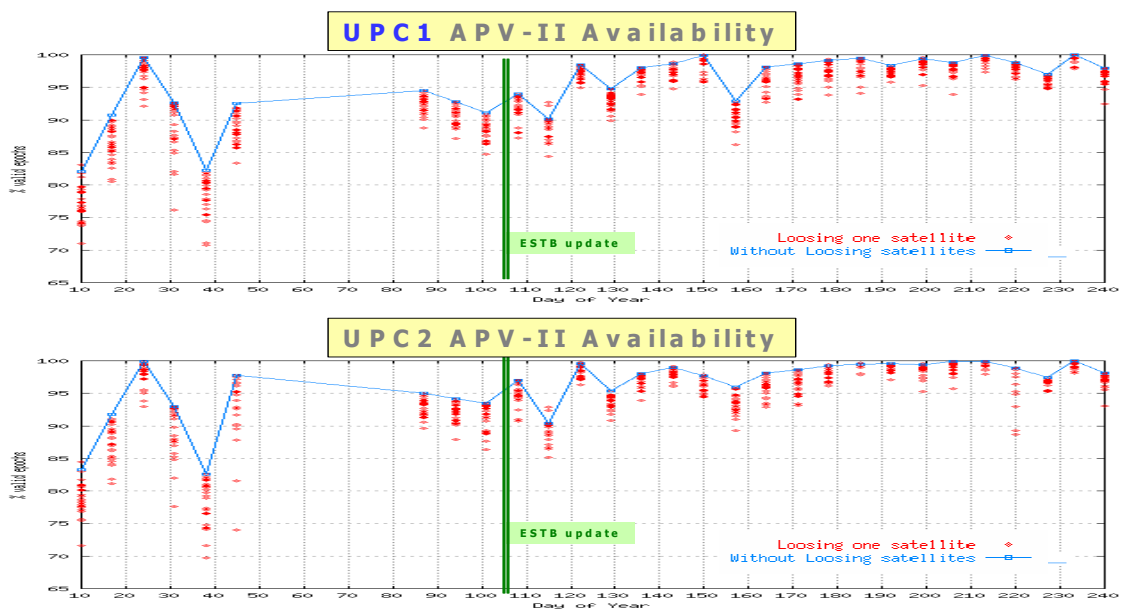


Figure 11. The same plot such as in previous figure 10, but comparing the results for UPC1 (top) and UPC2 (bottom).

## **Acknowledgments**

This work has been carried out under the contract C/1.239/CE/JR/01 of EUROCONTROL

## **References**

- [1]. PEGASUS\*PLUS Software User Manual, 2001, Doc. No. PEG-SUM-01 Issue C.
- [2]. Hernández-Pajares, M., J.M. Juan, J. Sanz, X. Prats and J. Baeta, 2002. Basic Research Utilities for SBAS. V Semana Geomática, Barcelona, Spain.
- [3]. ESTB SIS User Interface Description, ESA, Doc.-No.:E-TN-ITF-E31-0008-ESA, issue 0 revision 0, 20-03-00.
- [4]. RTCA Minimal Operational Performance Standards for GPS/WAAS Airborne Equipment. Doc. No. Do 229A, June 1998.
- [5]. WAAS Precision Approach Metrics. Accuracy, Integrity, Continuity and Availability <http://waas.stanford.edu>.