The User Domain Integrity Assessment Technique

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INTRODUCTION

This paper presents a study performed for the detailed analysis of user domain and pseudorange integrity on Satellite Based Augmentation Systems. Experimental data of EGNOS pre-operational service was used for some specific tests, aiming at identifying for instance the good reaction of the EGNOS check-set subsystem and the way pseudorange errors are translated into the user domain. From this analysis, a new technique for *User Domain Integrity Assessment (UDIA)* was developed.

With the UDIA technique, the integrity is checked for all possible geometries from 4 to all satellites in view from a network of stations. When no MI is found (from a wide and sufficiently dense stations network), it can be assured that the system is safe, and it becomes the best experimental guarantee at the User Domain Level. If a NMI/MI appears from any geometry of satellites from the stations in the network, thence a search algorithm is applied to identify the satellite, or combinations of satellites, responsible of such NMI/MIs (i.e., their exclusion leads to the disappearance of the NMI/MIs). After identifying such satellites, the reaction of the EGNOS Check Set (CS) is evaluated by checking if they were set as DU or NM within a predefined time interval after the NMI/MI is detected.

Three main graphic displays are used to help the exploratory integrity analysis: The Stanford-ESA Integrity Diagram [4], the Time-Integrity Plot and the Worst-Integrity-Ratio Map, which become three useful tools for the integrity assessment in the position domain. The last two plots are also based on considering all the possible geometries, as in the Stanford-ESA diagram, but they provide complementary information to it.

THE PROPOSED APPROACH

As commented before, the UDIA technique is based on considering all the possible geometries of satellites from 4 to all-in-view from the stations network, to compute the Horizontal and Vertical Position Error (XPE) and Protection Levels (XPL) for each site with sampling rate data at 1-second available.

This technique is based in the following three main concepts:

1) *An exploratory User Domain Integrity Analysis* to identify the possible User Domain NMI or MI (i.e, 0.75<XPE/XPL<1 or XPE/XPL> 1), if any, and to evaluate the System Integrity in terms of the integrity ratio *XPE/XPL*. It involves the above-mentioned three displays, which provide a global view of the system integrity and allow easily identifying the occurrence of eventual NMI/MIs: The Stanford-ESA integrity Diagram, the Time Integrity Plot and the Worst Integrity Ratio Map.

2) *An User Domain Integrity Search* algorithm designed to find the satellites or combinations of satellites responsible of the eventual User Domain NMI/MIs (i.e., which exclusion leads to the disappearance of the NMI/MIs). The output of this algorithm (for each epoch having NMI/MIs) is the Satellite Exclusion and Integrity table (*SEI-Table*) that provides the worst integrity ratios at the worst analyzed location for each possible combination of satellites to exclude. The EGNOS CS reaction is also included in the table as the elapsed time up to setting the fault satellite/s as DU/NM.

3) *The User Domain Integrity Assessment Table (UDIA-Table)* summarizing the SEI-Tables associated with the different epochs having NMI/MIs. This table has been designed as a "visual table" (code-colored) to provide an overall view of the User Domain Integrity, EGNOS CS reaction under NMI/MIs and SREW-Potential UDRE MIs assessment.

It must be pointed out that this is not a simulation. This technique works with real data and explores "all possible geometries" of satellites in view from the station network. Thence, in case of a NMI/MI occurrence, it allows to assess the EGNOS Check Set reaction by comparing with the actual User Domain Integrity (when excluding satellites). In fact, this strategy can provide the true final validation of the System Integrity performance at the User Domain level, if a proper coverage of monitoring stations is assured.

Exploratory User Domain Integrity Analysis: Graphic Tools

The Stanford-ESA Integrity Diagram

The Stanford-ESA integrity Diagram, as the name itself indicates is a modification of the well known Stanford Plot, where all (*XPE,XPL*) pairs for all the combinations from 4 to all-in-view satellites are represented at each second instead of representing only the pair (*XPE,XPL*) for the all-in-view solution (see Figure 1 and find further details in [4]).

This diagram has been showing its capabilities as a powerful tool for safety analysis, since the unsafe system performances are amplified by running over all geometries. Indeed, showing that at user level domain there is no situation for any possible geometry in which the error overcomes the protection level, then this would be the best experimental guarantee that at the position domain, for a specific location and epoch, no over-bounding is incurred.

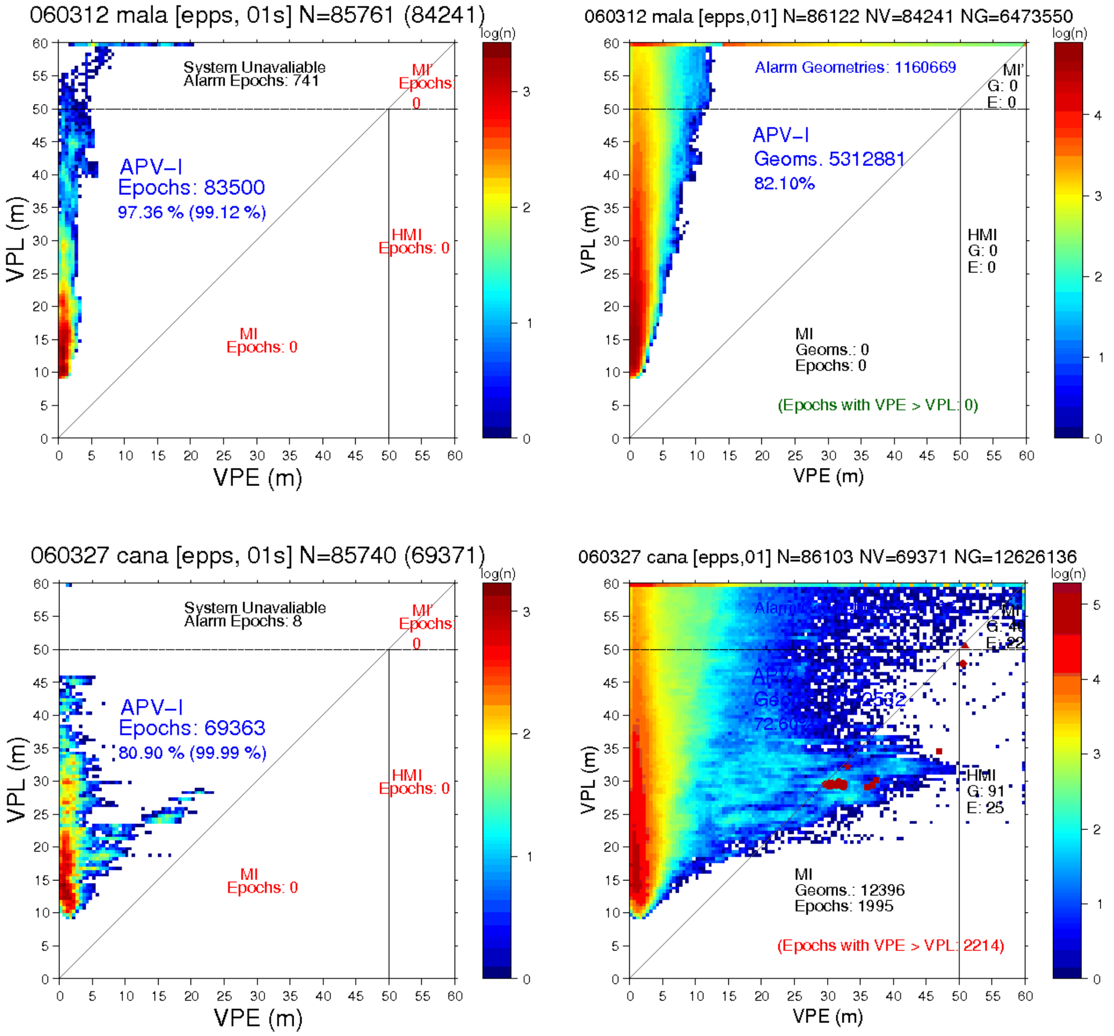

Figure 1. Two examples comparing the classical Stanford Plot (left) and the Stanford-ESA Integrity Diagram (right). The figures in the first row show results for nominal performances. They have been computed with actual EGNOS signal (June 3rd 2006). The figures in the second row correspond to the non-safety-of-life EGNOS Test Bed (ESTB) system and show the displays for unsafe conditions. Notice that thousands of geometries with MIs appear in the Stanford-ESA Integrity Diagram although not appearing MIs in the (all-in-view) Stanford Plot.

The Time Integrity Plot (TI-Plot)

The integrity ratio *XPE/XPL* for all the possible combinations from 4 to all-in-view satellites is computed each second and is represented in function of time in the plot, with a configurable pixel size. The color of each pixel indicates the *XPE* in a logarithmic scale. The largest XPE at each pixel overlaps the values from other possible geometries falling in the same pixel (see Figure 2).

This kind of representation complements the Stanford-ESA Integrity Diagram in the following aspects:

- It shows the evolution of the integrity through time, providing time information of eventual sudden changes or violations of integrity. It allows to identify, easily, CPF switches or other effects producing trends of points in the Stanford-ESA Diagram.
- It overcomes the limitation of the Stanford-ESA diagram to show the integrity for large *XPE/XPL* values (greater than *50m*, as well). Which are very frequent when considering the worst geometries by scanning all the possible combinations of satellites.

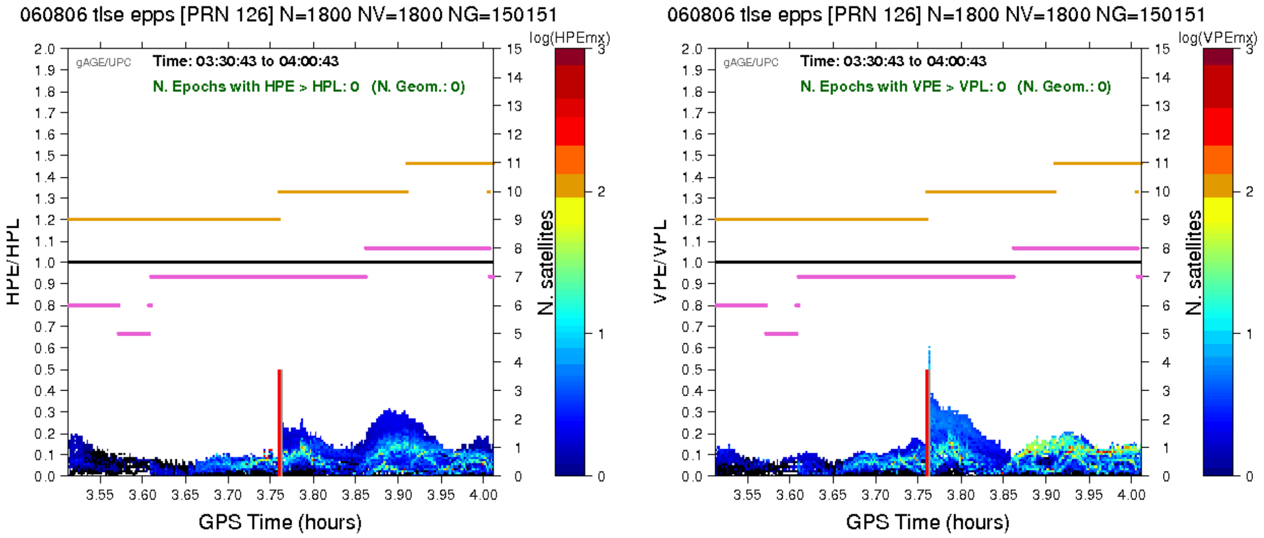

Figure 2. Time Integrity Plot for the Horizontal (left) and Vertical (right) components, for a receiver in Toulouse (France) in August 8th 2006, between 03:30:43 to 04:30:43. The pixels in red indicate XPE values over 100 meters, being the integrity always well maintained. These large errors are related to geometries close to singularity. The number of tracked satellites and the number of satellites used in the all-in-view solution are shown in the plot, in brown and magenta colors, respectively. The number of epochs with XPE<XPL together with the number of geometries involved are also written in the plot at top, summarizing the pass/fail criterion: no pints over the threshold 1 (i.e., always XPE<XPL), for any geometry at any epoch. The vertical red line indicates the CPF switch time.

The Worst Integrity Ratio Map (WIR-Map)

The previous plots (Stanford-ESA and Time Integrity plot) show the performance for a single site. A global view of the integrity (the worst integrity) for all the sites is provided by the Worst Integrity Ratio Map.

The worst integrity Ratio (WIR), i.e. *max(XPE/XPL)*, for all the possible combinations from 4 to all-in-view satellites is computed every second and for each one of the sites over a predefined time interval. When these values are less than *1* for all the sites, it can be assured that no integrity violation occurs for any geometry at any site.

The WIRs are displayed for each site as color circles in a color scale ranging from blue to magenta, with *0.25* units of resolution. Blue or green colors mean that the system is safe for all possible combinations of satellites in such site. Yellow color indicates, at least, one combination producing a NMI. Red o magenta means a real MI for at least one combination of satellites. The information about time when the WIR occurs is also written in the map. It allows identifying geographical-time-correlations between such events (see Figure 3).

A black to white colored corona surrounding the WIR color circle also provides the number of MIs when using all-in-view satellites (with available corrections and integrity data). White means no MIs in the position domain when using all-in-view combination of satellites. Information about the *PRN* of GEO used and the day as *YYMMDD* is also provided in the header. Finally, the time interval within the day is also shown at the top of the map (from *hh:mm:ss* to *hh:mm:ss*).

The Worst-Integrity-Ratio Map provides a geographical view of the user domain integrity performances and its spatial correlation. It is a very conservative and exigent display, because only the worst integrity event of each site is shown. This map is very sensitive to any integrity anomaly (also, when it involves just one geometry in a single epoch).

Figure 3 shows the WIR-Maps for the Horizontal and Vertical components, computed for a 1-hour time interval (between 09:30:00 to 10:30:00 of August 9th 2006) using the EGNOS RIMS and other permanent sites with 1-second sampling rate measurements available. The messages broadcasted by the GEO PRN126 were used. As it can be seen, neither MIs nor NMIs appear for the Horizontal component at any site. The Vertical component, on the other hand, shows one station with a red circle (in Berlin) which means that "at least" one combination of satellites has an MI. In spite of that, no MIs occur when using all-in-view satellites (the circle is surrounded by a white corona). Finally, three stations (in the East of Europe) show yellow circles that means Near MIs. All these MIs and NMIs are simultaneous, as it is shown by the time-stamp (t=09:53:03), and were produced by a CPF switch.

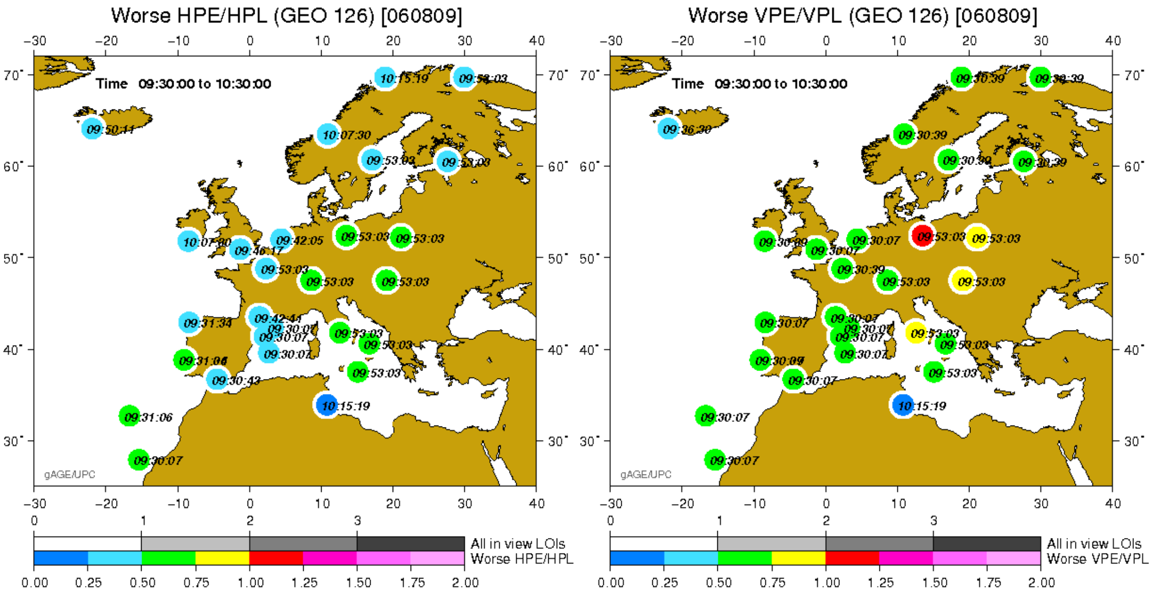

Figure 3. The Worst Integrity Ratio Maps for the Horizontal (left) and Vertical (right) components for August 9th 2006 between 09:30:00 to 10:30:00 GPS time for GEO PRN 126. The WIR for each site is shown by a colored circle in the color scale from blue to magenta. The MIs for All-in-View satellites are shown in the white to black scale. The red circle means that, at least, one combination of satellites in view has a MI (i.e., VPE/VPL>1). The yellow circles mean Near MIs (i.e., 0.75< VPE/VPL<1). The white coronas around the color circles indicate that no MIs occurred when using all-in-view satellites. The time-stamps in the circles indicate the epochs associated to the WIRs.

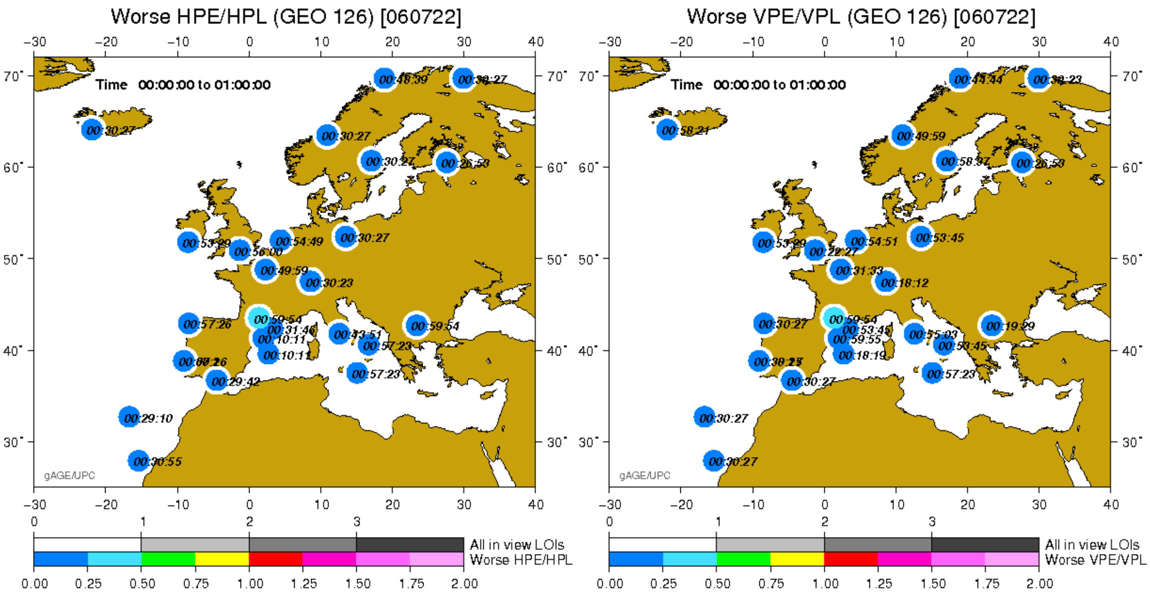

Figure 4: The same maps as in figure 5 but for July 22nd 2006 (GEO PRN 126), between 00:00:00 to 01:00:00. An excellent integrity ratio (XPE/XLP< 0.25) is found in all the sites, except in Toulouse where the ratio was 0.27 for the horizontal and vertical domain.

The Figure 4 shows a typical situation where the integrity is well maintained, with Worst Integrity Ratios under 0.25 for most of the sites in both, Horizontal and Vertical components. Only the site in Toulouse shows a ratio over this threshold (with a value of *0.27*, for the horizontal and vertical domain), which could be related by local effects. This map has been computed for a period containing a potential UDRE MI for the satellite PRN 19. Nevertheless, these high integrity results strongly suggest that it was a false UDRE MI (notice that the Worst-Integrity Ratio is displayed for each site), being the integrity guaranteed, so far, at the user level.

As it is known, ionospheric integrity anomalies can affect to a reduced or a wide region of the service area, depending on the location of the anomalous Ionospheric Grid Point/s (IGP/s) involved. On the other hand, the anomalies related with orbits and clocks will affect to a wide range of locations. Thence, EGNOS like reference station networks (with typical baselines of *1000 km*) should be enough to detect any anomaly producing MIs at the position domain, especially for those related with orbits and clocks. That is, WIR-Maps without MIs or NMIs (i.e., *max (XPE/XPL) <0.5* in for the entire network) would be the best experimental guarantee at the user domain that no over-bounding is incurred for any geometry from 4 to all-satellites-in view from any site in the network.

The User Domain Integrity Search (UDIS) algorithm

This algorithm is applied in case of User Domain NMI/MI detection. It runs over all geometries of satellites from 4 to all-in-view from the stations network and computes the Worst Integrity Ratio for each possible combination of satellites to exclude. In this way, it allows identifying which satellite/s must be excluded in order to remove the detected User Domain NMI/MI.

The output of this algorithm is the Satellite Exclusion and Integrity Table (SEI-Table) that provides the worst integrity ratios at the worst analyzed location, for each one of the combinations of satellites to exclude. The EGNOS CS reaction is also included in this table as the time delay up to setting the satellites involved in the combination to exclude as DU/NM.

The algorithm is described as follows (see a layout in Figure 5).

For each time with Position Domain MIs

For each combination of satellites to exclude among the satellites in view (from 1 to N-4)

For each station in the network

- Exclude the combination of satellites *[*]* and compute the *HWIR* and *VWIR* for all possible geometries for the given station.
- From previous results:
  - Sort the geometries by *HWIR* (first) and *VWIR* (second) and select the Worst Horizontal Geometry for the given station.
  - Sort the geometries by *VWIR* (first) and *HWIR* (second) and select the Worst Vertical Geometry for the given station.
  - Merge the selected values in the common file (the `WG-file`).

```
The WG-file contains the following fields:
[station:name, WSEC, HWIR, VWIR, sat:used, sat:not:used, comb:excluded]

Note:
     sat:used:      Satellites used to compute the navigation solution.
     sat:not:used:  Satellites in view with valid corrections, but not
                     used to compute the navigation solution (for the
                     selected geometry).
     Comb:excluded: Combination of satellites excluded (some of these
                     satellites can not be in view from this station.
```

End

- From previous `WG` file, select the station with the maximum *WIR* (whatever horizontal or vertical). If two stations have the same maximum value (horizontal or vertical), thence, select the station with the highest value for the other component (vertical or horizontal).
- Merge selected values a common file.

End

End

[*]: Combinations up to only 2 satellites were excluded in [3], in order to reduce the computational load. The exclusion up to 2 satellites was enough to remove the integrity overbounding conditions.

The obtained file provides what we call the *Satellite Exclusion and Integrity Table* (*SEI-Table*). A different SEI-Table is built for each one of the epochs having a NMI or MI. This table provides, for each combination of satellites to exclude, the worst integrity ratio for the worst possible geometry of satellites in view at the worst location (from the stations in the analyzed network). This information is combined in the same table with the UDRE values changes to assess the EGNOS CS reaction in terms of time delays setting the fault satellites as DU/NM since the NMI/MIs appearing.

The SEI-Table allows easily identifying which satellites have to be excluded in order to remove the NMI/MIs and to check the EGNOS CS reaction on such satellites. It must be pointed out that in many cases, the solution is not unique, that is, there is more than one possible combination of satellites which exclusion leads to the NMI/MIs disappearance. The algorithm explores and provides all these possible solutions.

The User Domain Integrity Assessment (UDIA) Table

The previous SEI-Tables, for the different epochs having NMI/MIs are summarized in the UDIA-Table. This table is a "visual" (code-colored) panel designed to provide an overall view of the User Domain Integrity, EGNOS CS reaction under NMI/MIs and SREW-Potential UDRE MIs assessment.

The generation of this table can be summarized as follows (see Figure 5): First the Worst Geometry file (WG-file) with the Horizontal and vertical Worst Integrity ratios (HWIR, VWIR), computed after excluding the different combination of satellites from 1 to N-4 is generated for each station and at each epoch. Thence, a SEI-Table for each epoch is generated selecting in the WG-file the station with the maximum WIR (WIRws), whatever horizontal or vertical. Finally, the UDIA-Table is compiled from the SEI-Tables for the different epochs having at least one geometry with NMIs/MIs. The following information is picked-up from the SEI-Tables: 1) The BEST and WORST combination of satellites to exclude (i.e., providing the short/larger WIR at the worst location. 2) The best combination of satellites to exclude among those set as DU/NM by the CS, within the first 6 seconds after the NMI/MI.

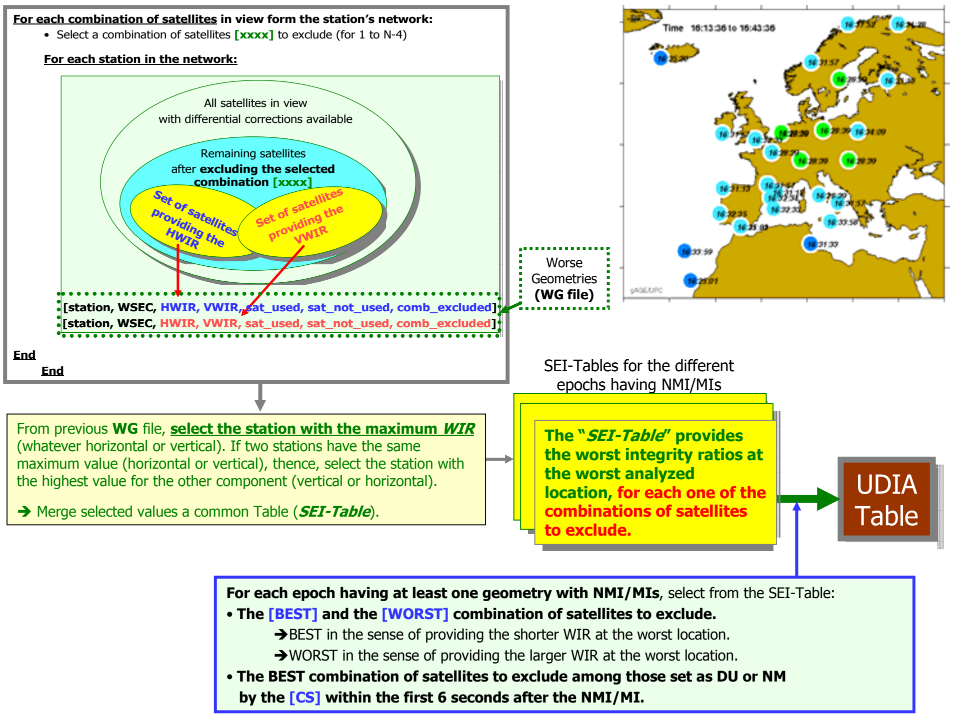

Figure 5: Layout illustrating the generation of the UDIA-Table. See explanation in the text.

The main outputs of UDIA-Table can be summarized as follows:

- In case of NMI/MIs detection (isolated or trend or NMI/MIs), it allows to identify the satellites responsible of such events (i.e., their exclusion lets to the disappearance of the NMI/MIs). It also provides the BEST combination of satellites to exclude.
- After identifying such satellites, the reaction of the EGNOS Check Set is assessed from the time delay up to set such satellites as DU or NM (or other sub-optimal combination to remove the NMI/MIs).
- Finally, the table includes the WIR when excluding the satellite/s flagged as having a potential UDRE MI by the SREW-Tool.

Site	GPS Time HH:MM:SS	WSEC	WIRws H	WIRws V	Satellites in view from the site (wvc) Used	Not used	Combin. Excluded	CS Reaction Time Delay up to DU/NM reception		Result
										BEST 0,61
										CS 0,77
										SREW 0,93
a026	09:28:00	293280	0,22	0,82	02 08 10 13	24 27 29 04				WORST
a034	09:28:00	293280	0,16	0,27	04 13 27 28	10 29 02 08	08 10	----	7s DU	BEST
cana	09:28:00	293280	0,69	0,68	02 27 08 10	29	13		5s DU	CS
										SREW
dlf5	09:28:01	293281	0,24	0,98	27 04 13 08 02	10 29				WORST
ist4	09:28:01	293281	0,49	0,20	29 08 10 02 04	13 27	13 27	4s DU	----	BEST
cana	09:28:01	293281	0,68	0,63	02 27 08 10	29	13		4s DU	CS
upc4	09:28:01	293281	0,25	0,93	02 27 13 08	10 04	04		----	SREW
dlf5	09:28:02	293282	0,27	1,08	27 04 13 08 02	10 29				WORST
creu	09:28:02	293282	0,53	0,42	08 04 29 28 10 02 24	27 13	13 27	3s DU	----	BEST
a015	09:28:02	293282	0,34	0,71	02 04 08 27	10 13 29	10 13	5s DU	3s DU	CS
										SREW
dlf5	09:28:03	293283	0,55	1,31	27 10 29 04 13 08	02				WORST
creu	09:28:03	293283	0,61	0,26	04 28 10 02 24 27	13 08 29	08 13	----	2s DU	BEST
a015	09:28:03	293283	0,44	0,77	04 08 27 29	10 13 02	10 13	4s DU	2s DU	CS
										SREW
dlf5	09:28:04	293284	0,31	0,89	27 10 29 04 13 08	02				WORST
a016	09:28:04	293284	0,29	0,23	04 08 27 29	13 02	02 13	----	1s DU	BEST
cana	09:28:04	293284	0,35	0,24	02 27 08 10	29	13 29	1s DU	1s DU	CS
										SREW

Table 1. Example of UDIA-Table for August 9 2006 (GEO PRN 126, potential UDRE MI on PRN 04 at 09:28:01). Each epoch having a NMI or MI is represented in this table by five rows, its left side colored in yellow (when NMI, i.e., 0.75>=WIRws<1) or red (when MI, i.e., WIRws>=1). The first row shows the Worst Integrity Ratio found at the worst site (WIRws) when exploring all geometries from all-in-view to 4 (i.e., without excluding any combination of satellites given "a priory"). This row is labeled as "WORST" in its last column. The second row shows the same results, but when excluding ("a priory") the combination of satellites providing the smallest WIRws (best combination of satellites to exclude --regardless if they are set as DU/NM or not by the EGNOS CS --). This row is labeled as "BEST" in its last column and colored in blue (WIRws<0.5), green (0.5<=WIRws<0,75), yellow (0.75<=WIRws<1) or red (WIRws>=1). The third row, "CS", shows the results when excluding the best combination of satellites (providing the smallest WIRws) set as DU/NM by the EGNOS Check Set (if any) within the next 6 seconds after the NMI/MI. The next row shows WIRws when excluding the satellite/s detected by the SREW-Tool as having the potential UDRE MI ["SREW"]. The same color code is applied to the last column of these rows (Note: these rows are only given when the NMI/MI lies within the target interval). The names of the different columns are self-explanatory: The first column gives the name of the site used to compute the solution. The second and third columns give the GPS time in HH:MM:SS and seconds of GPS week (WSEC). Columns 4 and 5 provide the Horizontal and Vertical Integrity Ratios. The values greater or equal to 1.00 are colored in red to emphasize such events. Column 6 and 7 show the satellites in view used and not used, respectively, to compute the navigation solution. Column 8 shows the combination of satellites excluded (regardless if they are in view or not from all the sites). Columns 9 and 10 show the number of seconds up to setting the satellites of column 8 ("Combin. Excluded") as DU/NM by the CS (up to 30 seconds). The box "RESULTS" at the upper right corner summarizes the table: The "BEST", "CS" and "SREW" colored sub-boxes show the worst WIRws results in the table among the "BEST", "CS" boxes (or the "WORST" when "CS" row is empty) and "SREW" boxes, respectively. *Note: This table is taken from [3] where only combinations up to 2 satellites to exclude were considered.*

DATA ANALYSIS AND RESULTS

The UDIA technique was been applied to analyze 43 potential UDRE MIs linked to the CPF switch detected between April to October 2006.

The EGNOS RIMS and other permanent stations with 1-second sampling rate were used for the assessment. The GPS measurement files from the stations network were combined with the GEO messages and GPS ephemeris data (compiled and checked by the Global Monitoring System [5]) and navigated by BRUS [6] (a software package developed by gAGE/UPC) in such a way that an EGNOS receiver was emulated at each site according to the MOPS [7]. For the data processing, the strategy applied by the EDCN working group of Eurocontrol, which involves a *100-second* smoothing window and the deselection of satellites during the convergence of the smoothing-filter (*360 seconds*) was applied, and worst case signal reception conditions were also assumed (i.e, $\sigma_{noise,GPS}=0.4m$ and $\sigma_{noise,GEO}=1.8m$) [7].

For all cases analysed, the EGNOS Check Set reacted within the 8 seconds associated Time to Alert to APV-1, when a real MI occurred, setting as Don't use or Not Monitored the necessary satellites in order to remove the MI after the first MI. Further, in all analyzed cases, except one, the reaction time was below 6 seconds. In one case, case of August 14th

at 03:59:25, the reaction time was within the 8 seconds interval instead of 6 seconds. This case, although not a problem for APV-1 performances, was identified in EGNOS as a non-conformance, since while APV-1 requirements ask for 8 seconds TTA, EGNOS specification require all alarms to be sent with an additional margin, within 6 seconds time to alarm (paving the way to future potential evolutions towards APV-2). The study here was linked to the signal broadcasted by the EGNOS release v2.0.2. On December 2006 a new version v2.0.3 was deployed correcting this identified non-conformance. Since December 2006 no a single MIs/TTA problem have been identified neither on the pseudorange or user domains.

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REFERENCES

[1] GNSS-1 Programme Implementation Phase. Technical Note for SREW_tool al analysis Tool Pre-processor. EGN-GMV-CPFPS-DRD 206/70, Is. 3, Rev. A, 19/09/2003. GMV.
[2] Analysis of Potential UDRE MIs Using the Stanford-ESA technique in the position domain. M. Hernández-Pajares, J.M. Juan, J. Sanz, P. Ramos-Bosh, A. Aragón Angel. ESA report, 2006.
[3] The User Domain Integrity Assessment Technique (UDIAT). Application to the analysis of Potential UDRE MIs after EGNOS CPF Switching. M. Hernández-Pajares, J.M. Juan, J. Sanz, P. Ramos-Bosh, A. Aragón Angel. ESA report, 2006.
[4] The Stanford-ESA Integrity Diagram: A new tool for the user domain SBAS integrity assessment. M. Tossaint, J. Samson, F. Toran, J. Ventura-Traveset, M.Hernández-Pajares, J.M. Juan, J. Sanz and P. Ramos-Bosch. Journal of the Institute of Navigation. Vol. 54, No 2, Summer 2007. USA.
[5] GMS Architectural Design and Detailed Design Document, M. Hernández-Pajares, J. M. Juan and Jaume Sanz. gAGE/EEC, 2004. EUROCONTROL.
[6] Basic Research Utilities for SBAS (BRUS), M.l Hernández-Pajares, J.M. Juan, J. Sanz, X. Prats and J. Baeta, Research Group of Astronomy and Geomatics (gAGE/UPC) Univeristat Politècnica de Catalunya, 2003.
[7] Minimum Operational Performance Standards for GPS/WAAS Airborne Equipment, RTCA, Do 229C, Nov. 2001.