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Assessment of EGNOS performance in worst ionosphere conditions (October and November 2003 storm)

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1. Abstract

This paper presents the results of an assessment on EGNOS performance during a severe solar storm occurred at the end of October 2003 and affecting the propagation of radio waves through the ionosphere. The relevance of this assessment is that this storm is one of the largest occurred during the last solar cycle, and one of the worst ionospheric storms ever recorded. This paper will show that EGNOS is able to provide a reliable service over the whole service region with reasonable degradations, as well as vertical guidance capability (APV) over most of Europe during this abnormal ionosphere conditions. These are extremely encouraging result that reinforces the confidence on the EGNOS safety design and algorithmic conception

2. Introduction

One of the system requirements of the EGNOS system is to provide the users with frequent and reliable data to correct the pseudo-range measurements affected by the delay introduced in the propagation of radio waves through the ionized layers of the atmosphere.

This function is accomplished by the EGNOS central processing facility through the use of a model of the ionosphere behaviour dynamically driven by real time measurements carried out in the EGNOS reference stations (RIMS –Ranging and Integrity Monitoring Station.)

In some circumstances, sudden variations in the solar activity may lead the ionosphere to behave in a way far different from the nominal behaviour. This happens during severe ionosphere storms. In these cases, it is essential for a safety system like EGNOS, to confirm that the integrity of the computed corrections and the continuity of service are still maintained. Qualification of EGNOS performance (both at computing platform and at user level) is done assessing if the system is able to compute the corrections and estimate reliably the residual errors even in the unusual or extremely perturbed propagation conditions of radio waves though the ionosphere.

It has been found in the historical recordings of the ionosphere parameters that an exceptional event occurred the period Oct 28 to Nov 1, 2003.
This event has been classified by international ionospheric experts as one of the most severe storms ever recorded. During this period of time EGNOS was not yet transmitting, so we can not derive from direct measurements what was or what should have been the behaviour of the EGNOS system in such circumstances.

However, there was enough collected ionosphere information to generate an equivalent realistic (based on real data collected by the International GPS Service network) simulation scenario, against which EGNOS performances could have been tested. The equivalent scenario IET-5 was generated by the ESA-lead Ionosphere Expert Team (IET), and a detailed performance analysis on the days of interest (30th and 31st October 2003, D3 and D4 respectively) has been carried out by EGNOS industry using the ionosphere scenario IET-5 to run real EGNOS operational algorithms and asses the output of the computing platform and performance at user level [RD1].

3. The solar storm occurred in October 2003

According to the records, the geomagnetic storm of the 30th and 31st October 2003 was one of the largest occurred in this solar cycle. Solar wind conditions produced very large energy transfers into the Earth magnetosphere creating optimal conditions for auroral precipitations and visible displays at latitudes lower than usual. However, in that period, the orientation of the Earth magnetic field was such that the low coupling with the solar wind attenuated a little bit the storm intensity.

Severe storm conditions were observed (Fig.1 – Kp index vs. time) from 16:00 UTC of 30th to the first hours of 31st October 2003. In North America starting from the 29th October unusual auroras appeared in southern regions like California, New Mexico, Texas and Oklahoma before the storm began to decrease the intensity. In Europe unusual auroras appeared later in regions south Germany, Slovenia and even Greece.

From the observations (Fig.2 – vTEC snapshots) a strong ionization (positive storm) occurred over the western American coast (vTEC units of $10^{16}/m^2$) and a strong depression of ionization (negative storm effect) over Europe (vTEC units of $10^{15}/m^2$).

The spatial and temporal gradients occurring after sudden ions accumulation or drag make very difficult the computation of timely and reliable corrections for the ionospheric delay.

4. The IET-5 scenario and processing steps

The scenario consists in a set of data called “AZ grid” describing the effective ionization level of the atmosphere. AZ grids are computed from grids of vertical electron content produced by means of GPS observations. The steps for the production of the AZ grids are essentially the following:

1. Produce hourly vTEC maps (La Plata Map model) from GPS data (IGS network) for the days 28-31 Oct 2003;
2. Convert vTEC maps into "AZ grids";
3. Perturb the data to contrast the smoothing of vTEC maps;
4. Compute sTEC data for every station (RIMS and USER) to satellite (GPS and GLONASS) link;
5. Compute vTEC for the grid points (they include the IGPs);
6. Format the data for the use with EETES-HS.

Additional information on the production scheme of the AZ grids is available in the reference documentation [RD2].

Once the scenario IET-5 was ready, it was given in input to the EETES-HS to generate the measures (RINEX files) that the RIMS and the users would have performed in the period analysed.
In addition, information on the real clock synchronization, real ephemeris data and real GIVD was computed by EETES-HS.
The RIMS data were then given in input to the EGNOS computing platform: CPF-AIV to generate the augmentation messages.
The augmentation messages generated by the CPF-AIV, together with real clock, ephemeris and GIVD data were (with some format changes and combinations) given in input to the analysis tools (ESVS, PATAC-S and AE-User Tool) to assess respectively the EGNOS system performance at CPF and user level. In particular the analysis was carried out for the most significant days: D3 and D4.

5. EGNOS CPF performance during the storm

The assessment of the EGNOS computing platform during the geomagnetic storm basically consisted in the measurement of the system ability to generate reliable data to correct for the ionospheric delay for as much time as possible.

This analysis on the data reliability was carried out by comparing, for each IGP monitored within the service area, the value of the real residual error on the correction for the ionospheric delay, the $GIVD_{err}$, with the corresponding estimated residual error computed by the system, the GIVE, and broadcast to the users. Indeed, as part of the EGNOS System requirements, a part from the condition that no MI/HMI should occur at the user domain level, it is also required that no MI/HMIs occur neither at the level of pseudorange UDRE and GIVE/UISE domain for all identified/defined possible feared event conditions. For the specific case of the GIVE, this condition has been mathematically expressed in EGNOS as follows: the measured residual error on the correction for the ionospheric delay, the $GIVD_{err}$, has to be, for any sample and during the whole storm (for which no a priori probability is accepted), less than 5.33σ multiplied by the GIVE (1σ).

We can say then we have no GIVE MI if it is always verified that:

$$GIVD_{err} < GIVE\ (1\sigma) * 5.33 \qquad (1)$$

or, in other words, the maximum ratio between $GIVD_{err}$ and GIVE(1σ) shall be less than 5.33 for each monitored IGP.

To verify the equation (1) it has been first computed the $GIVD_{err}$ with the EETES simulator (on the basis of the information provided by the scenario IET-5) and assumed these data as true, later it has been generated the GIVE with the EGNOS CPF and finally compared the $GIVD_{err}$ and GIVE with the analysis tools.

As a general result it has been found for the days D3 and D4 that:

- **No GIVE integrity problem** has been found;
- For day D3 the maximum ratio between $GIVD_{err}$ and GIVE(1σ) is 3.70 (Fig.3 – Broadcast GIVE integrity analysis for D3); in other words 3.70 times the GIVE (1σ) value bounds with 100% probability the $GIVD_{err}$ during D3.
- For day D4 the maximum ratio between $GIVD_{err}$ and GIVE(1σ) is 3.04 (Fig.4 – Broadcast GIVE integrity analysis for D4); in other words 3.04 times the GIVE (1σ) value bounds with 100% probability the $GIVD_{err}$ during D4.

For a central IGP (Band 4; Bit 174: close to the border of Italy, France and Switzerland) during D3 and D4, we obtained the following results:

- Low $GIVD_{err}$ (roughly 1m max);
- Low GIVE (around 2.5m) but with peaks up to 8m;
- GIVE integrity margin assured (2.2 margin factor);
- Near 100% IGP monitoring availability.

For a border IGP (Band 3; Bit 198: close to Madeira Island-Portugal) during D3 and D4, we obtained the following results:

- Low $GIVD_{err}$ (less than 2m);
- High GIVE (not more than 8m);
- GIVE integrity margin assured (2.2 margin factor);
- Less than 50 % IGP monitoring availability.

The analysis on the time availability of data to correct for the ionospheric delay was carried out by measuring the time percentage during which reliable information was available for each IGP within the service area or, in other words, the percentage of time in which the IGP were monitored.

It shall be noted that, in the case of a geomagnetic storm, the number of monitored IGP can be less than the nominal value. This is due to the fact that, in case of large spatial and temporal TEC gradients, EGNOS algorithms tend to elaborate the more conservative error estimation. This means that in some cases the IGP with high GIVEI may become “not monitored[1]” for safety reasons.

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[1] GIVEI=15 means IGP “not monitored”

From the IGP monitoring analysis it was found that:

- The average number of IGP monitored (mainly in the core area) during D3 was 69 out of 147 needed (Fig. 5 – IGP monitoring availability for D3);
- The average number of IGP monitored (mainly in the core area) during D4 was 72 out of 147 needed (Fig. 6 – IGP monitoring availability for D4).

It was also noticed for both D3 and D4 that when the number of surrounding IPP was greater than 10 the percentage of IGP monitoring availability was above 80% of the time, with 15-17 surrounding IPP the requirement was fully met.

6. EGNOS performance at user level during the storm

The analysis of EGNOS performance at user level mainly consisted in the assessment of accuracy, integrity and service availability requirement over the service area for APV-1 operations.

APV-1 operational requirements			
Accuracy		Integrity	
HNSE	VNSE	HPL	VPL
16m	8m	40m	50m

In particular, 17 locations (Fig.7 – Users locations) were carefully analysed with the following results:

- No MI or HMI event occurred for any user; i.e. at all times and for all assessed 17 locations, the xPL bounded the xNSE error with no exception.
- For D3 many users, particularly at the borders of ECAC, were found slightly above the requirement for most part of the day with a reduction of the average service availability (Fig.8 – Average service availability for D3) down to 80% of the time, excepted over South of France, North of Spain and Italy where the system performed almost as if there were no storm. West and south-west of ECAC area suffered of a significant reduction of service availability compared to nominal conditions (Fig.9 – Impact on average service availability for D3);
- For D4 many users were found below the requirement for most part of the day improving the average service availability (Fig.10 – Average service availability for D4) up to 95% of the time even if the ionosphere was still perturbed by the solar storm.
- Impact of the degraded ionosphere conditions is weak over main part of ECAC, more important at the edges. The location where the system provided the best performance during D3 was Rome-Italy (Fig.11 – Horizontal Stanford Diagram for a user in Rome). To be noted that WAAS Precision Approach with Vertical Guidance Service was totally unavailable in the same time period [RD3].

7. Conclusions

The paper has shown that EGNOS is able to provide a reliable service over the whole service region with reasonable degradations, as well as vertical guidance capability

(APV-1) over most of Europe during abnormal ionosphere conditions affecting the propagation of radio waves.

Assessments at CPF level have indicated that no GIVE or UDRE integrity problem has been detected during the storm, no MI or HMI has been found at user level, while APV vertical guidance was maintained over most of ECAC with reasonable availability values.

This is an extremely encouraging result that reinforces the confidence on the EGNOS safety design and algorithmic conception

8. Acknowledgements

The authors with to thank all those colleagues of the following organizations: European Space Agency, Alcatel Space, GMV, International Centre of Theoretical Physics and the University of Graz, who have contributed to this study and have not been directly mentioned.

9. Acronyms

AIV – Assembly Integration and Validation
CPF – Central Processing Facility
ECAC – European Civil Aviation Conference
EGNOS – European Geostationary Navigation Overlay Service
EETES-HS – EGNOS End To End Simulator-Hosting Site
ESVS – EGNOS Service Volume Simulator
GIVD – Grid Ionospheric Vertical Delay
$GIVD_{err}$ – Grid Ionospheric Vertical Delay Error
GIVE – Grid Ionospheric Vertical Error
GIVEI – Grid Ionospheric Error Indicator
HMI – Hazardous Misleading Information
IGP – Ionospheric Grid Point
IGS – International GPS Service
Kp index – Index of geomagnetic activity at planetary level
MI – Misleading Information
RIMS – Receiver Integrity Monitoring Station
sTEC – Slant Total Electron Content
UDRE – User Differential Range Error
vTEC – Vertical Total Electron Content

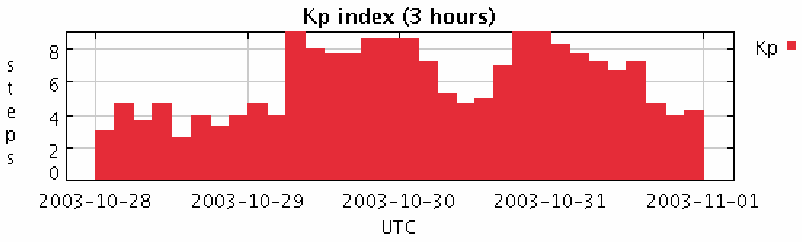
10. References

[RD1] - F. Froment, E. Tapias – *Assessment of EGNOS performance under worst ionospheric conditions observed in October 2003* – EGN-ASP-SYST-TN/0447 -1/A Date: 18/03/05

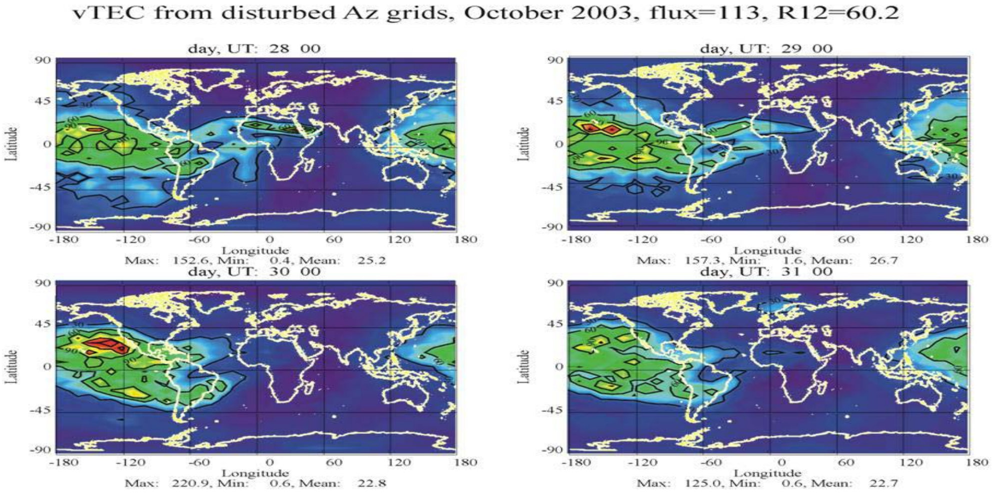
[RD2] - R. Leitinger, S.M. Radicella, P. Coisson, B. Nava - *EGNOS IET Scenario 5 description* – Deliverable of the contract “IET support to ESA” - January 2005

[RD3] – www.ntsb.tc.faa.gov WAAS performance analysis report #7, Date: 30/01/04

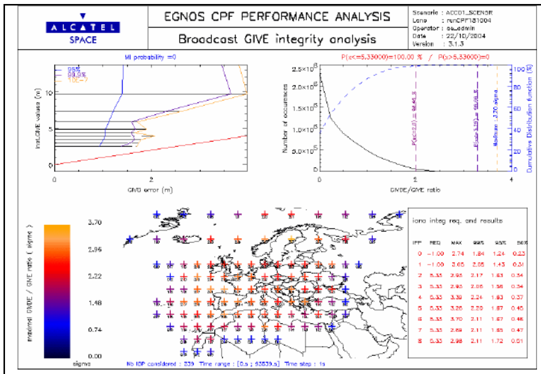
11. Figures



[Fig.1] – Kp index vs. time



[Fig.2] – vTEC snapshots



EGNOS CPF PERFORMANCE ANALYSIS

Broadcast GIVE integrity analysis

Scenario : ACC01_SCENSR
Lane : runCPF181004
Operator : ss_admin
Date : 22/10/2004
Version : 3.1.3

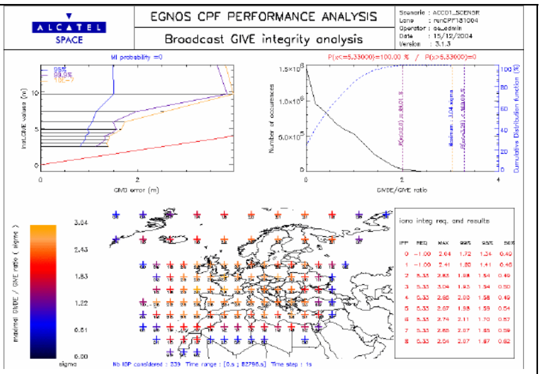
MI probability =0

P(x<=5.33000)=100.00 % / P(x>5.33000)=0

iono integ req. and results

IPP	REQ	MAX	99%	95%	50%
0	−1.00	2.74	1.84	1.24	0.23
1	−1.00	3.05	2.05	1.43	0.31
2	5.33	2.95	2.17	1.63	0.34
3	5.33	2.95	2.06	1.56	0.34
4	5.33	3.39	2.24	1.63	0.37
5	5.33	3.26	2.20	1.67	0.45
6	5.33	3.70	2.11	1.67	0.46
7	5.33	2.89	2.11	1.65	0.47
8	5.33	2.98	2.11	1.72	0.51

[Fig.3] – Broadcast GIVE integrity analysis for D3



EGNOS CPF PERFORMANCE ANALYSIS

Broadcast GIVE integrity analysis

Scenario : ACC01_SCENSR
Lane : runCPF181004
Operator : ss_admin
Date : 15/12/2004
Version : 3.1.3

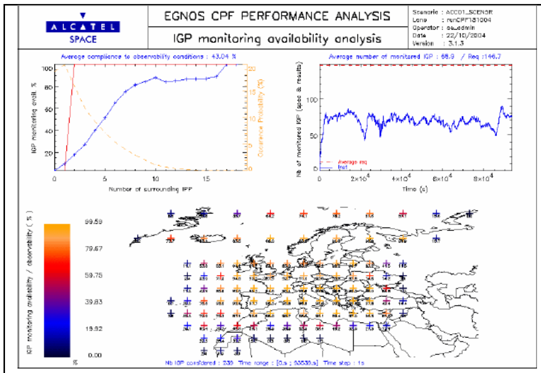
MI probability =0

P(x<=5.33000)=100.00 % / P(x>5.33000)=0

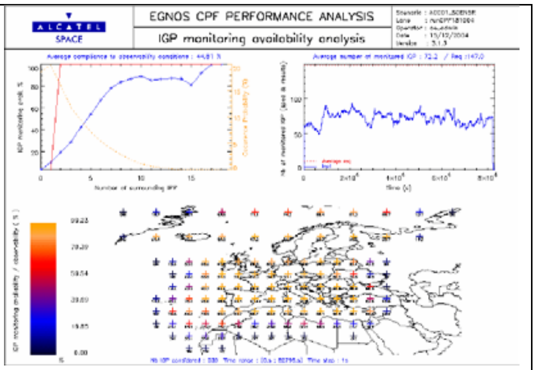
iono integ req. and results

IPP	REQ	MAX	99%	95%	50%
0	−1.00	2.04	1.72	1.34	0.49
1	−1.00	2.41	1.80	1.41	0.46
2	5.33	2.83	1.98	1.54	0.49
3	5.33	3.04	1.93	1.54	0.50
4	5.33	2.66	2.00	1.58	0.49
5	5.33	2.67	1.98	1.59	0.54
6	5.33	2.74	2.11	1.70	0.57
7	5.33	2.65	2.07	1.65	0.59
8	5.33	2.64	2.07	1.67	0.62

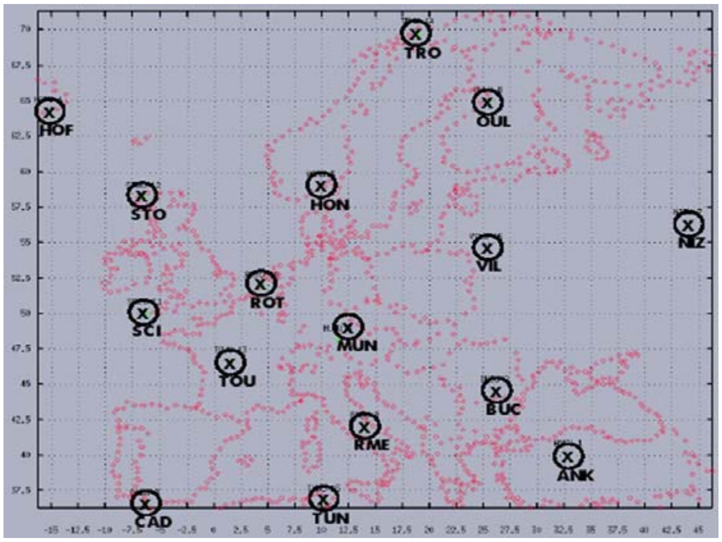
[Fig.4] – Broadcast GIVE integrity analysis for D4



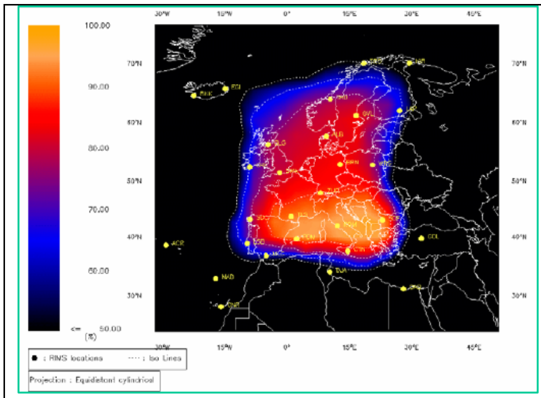
[Fig.5] – IGP monitoring availability for D3



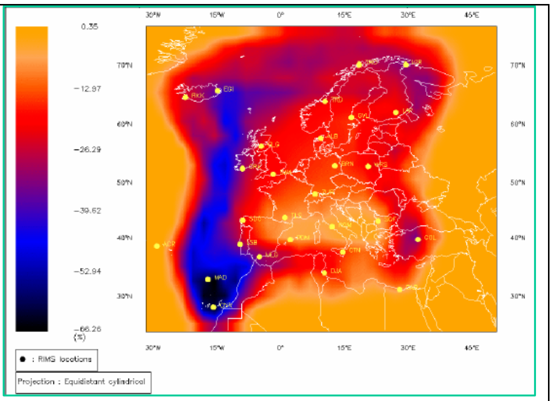
[Fig.6] – IGP monitoring availability for D4



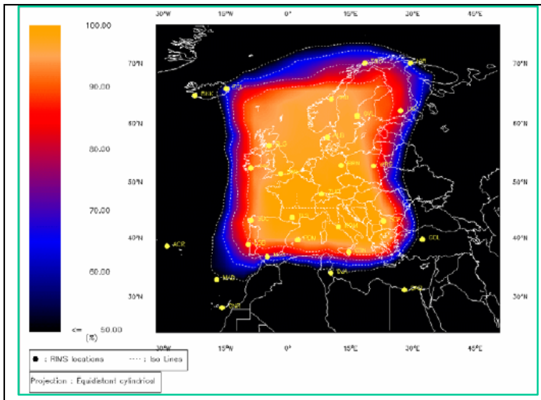
[Fig.7] – Users locations



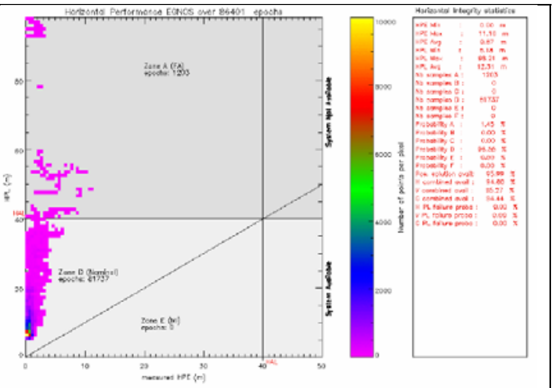
[Fig.8] – Average service availability for D3



[Fig.9] – Impact on average service availability for D3 with respect to nominal conditions



[Fig.10] – Average service availability for D4



[Fig.11] – Horizontal Stanford Diagram for a user in Rome