MONITOR ionospheric monitoring system: analysis of perturbed days affecting SBAS performance

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BIOGRAPHIES

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Roberto Prieto-Cerdeira is GNSS R&D Engineer in the GNSS Evolutions Programme and Strategy Division of the European Space Agency, where he coordinates technology R&D and scientific activities for the evolution of European GNSS Systems. From 2005 to 2014 he was ESA responsible for the activities related to radiowave propagation for GNSS and Mobile SatCom. He has published over 100 papers in journals and conferences. He conceived and defined the Monitor project and followed it as Technical Officer until end of 2014.

Yannick Béniguel is a senior scientist in electromagnetics. He founded IEEA, an R&D company in antennas, propagation and EMC, in 1987. He has developed the Global Ionospheric Scintillation Model (GISM). He is chairman or coordinator of various national and international activities and leader of research projects. He has over 100 papers published in conferences and journals. He is the Monitor Project Manager.

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Joe Kinrade received his PhD in Electronic Engineering from University of Bath working on Ionospheric Imaging and Scintillation Monitoring in the Antarctic and Arctic. He is a Postdoctoral Researcher at IEEA.

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Andrzej Krankowski is a Full Professor at the Faculty of Geodesy and Land Management of the University of Warmia and Mazury in Olsztyn (UWM), Poland. Since 2007 he is a Chairman of the IGS Ionosphere Working Group and Product Coordinator.

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ABSTRACT

The Monitor project has been designed to monitor ionospheric events that would allow evaluating its impact on European GNSS Systems. It includes a network of ionospheric scintillation monitoring stations in various locations covering different latitude regions and its routine data collection; and, the generation and collection of relevant products that allow understanding ionospheric perturbations from the ionosphere. This paper presents an overview of the project and how it is able to support SBAS systems, including also the analysis of perturbed days during Solar Cycle 24.

INTRODUCTION

Monitor [1, 2] is a project from the European Space Agency's GNSS Evolutions Programme started in 2010, dedicated to the collection, processing and archiving of ionospheric data and products during active periods of solar activity, to the development of improved scintillation monitoring instrumentation and to the establishment of a scintillation monitoring network, in order to build the infrastructure allowing to analyse the impact of the ionosphere on European GNSS (EGNOS and Galileo) system performance.

The second phase of the Monitor project started in 2014, with the objectives: to achieve a simple and robust data collection, processing and access, to implement a flexible data access policy, to enlarge the scintillation monitoring network with new stations, and integrating data from the CNES SAGAIE network [3] and improved monitoring instrumentation, to generate automatic comprehensive reporting; and with main focus to support EGNOS current system and future evolutions.

Monitor Scintillation Network

In the frame of the project, a network of GNSS stations able to record ionospheric scintillation several. Most stations are based on off-the-shelf scintillation receiver and (all the new stations and some of the old ones) includes also bitgrabbers in order to be able to record IF data beyond the tracking capability of GNSS receivers for later analysis on laboratory environment. The stations at mid-latitudes in Noordwijk, The Netherlands and Rome, Italy are mainly targeted for troubleshooting purposes for the equipment installed at remote locations. All the other stations are located at high and low latitudes. For high latitudes, there are 3 stations: Kevo and Sodankylä in Finland and Kiruna in Sweden. There are two other sites under consideration. See Figure 1 for the high latitude stations.

For low latitudes, the first phase deployed 7 stations: Tahiti in the Pacific; Lima, Cayenne and Kourou in South America; and, Cap Verde, Libreville and Malindi in Africa. The second phase focuses in new stations in Africa first of all integrating the five stations from SAGAIE network and deploying five additional stations, planned to be in Benin, Ivory Coast, Mali, Namibia and Togo. All the Monitor stations in Africa are presented in Figure 2.

Figure 1. Monitor network at higher latitudes (in green existing stations, in yellow sites under investigation).

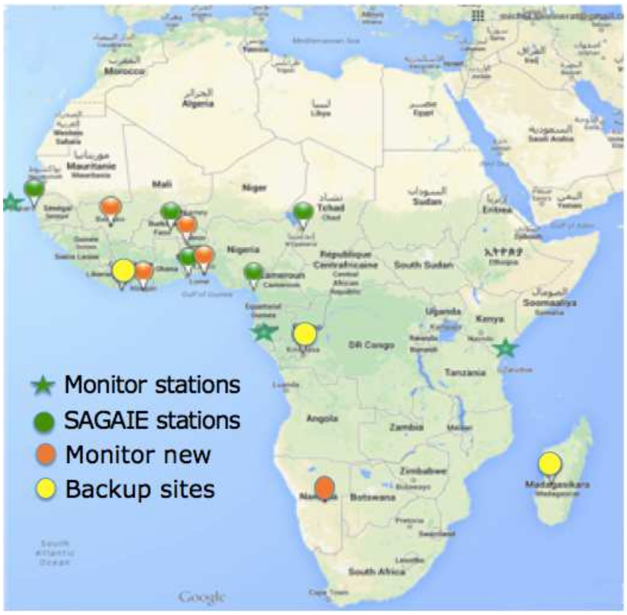


Figure 2. Monitor network in Africa, showing also stations from CNES SAGAIE network [3].

Data and Products

The Monitor project includes a centralised facility that is in charge of collecting and archiving data and products, processing some of them for generating products or reports, and being an interface for data provision with partners and third parties. In addition, this facility collects products from processors hosted at external institutions but providing data routinely.

The data collected from Monitor stations is:

- 1-minute ionospheric scintillation indices
- RINEX files at 1 Hz
- 50 Hz raw data
- Bitgrabber IF data.

Product are categorized by various types:

- Space weather: solar and geomagnetic indices obtained from third parties.
- Station-based: re-computed 1-minute ionospheric scintillation indices, multipath and cycle slips, delay code biases and ionospheric truths.
- Electron Content: Global Electron Content, Slant TEC, VTEC global maps, EGNOS VTEC maps, EGNOS accuracy and integrity.
- Perturbations: AATR parameter (see next section) for EGNOS and WAAS reference stations and for SAGAIE network, Rate of TEC, Solar Flares and TIDs.
- Reporting: automatic and manual reports.

As an example, VTEC is high quality and provided at a rate of 15 minutes (for comparison, IGS VTEC maps provides 1 or 2 hours maps).

ANALYSIS OF PERTURBATIONS AFFECTING SBAS

This section addresses Monitor's ability to support the assessment of the relationship of an SBAS system (EGNOS, WAAS) to the ionosphere's variability, analysing in detail the ionospheric a number of perturbations cases degraded SBAS system performance. For this, assessment, the most relevant events with certain EGNOS availability degradation in the period 2011 to 2014 have been identified. They are about 20 days, with significant events for instance on 1st October 2012 and 27-28 February 2014.

The Along Arc TEC Rate (AATR index) has proven to be an effective independent indicator of ionospheric activity that degrades SBAS system performance [4]. For example, doy 58 of 2014 presented a degraded availability in high and low latitudes of the EGNOS coverage and this was confirmed by high AATR values on high and low latitude RIMS during several hours as presented in Figure 3. On the same day, WAAS availability was also affected showing increased AATR levels in stations in Alaska, Canada, North East US, and the stations in and South of Mexico (see Figure 4).

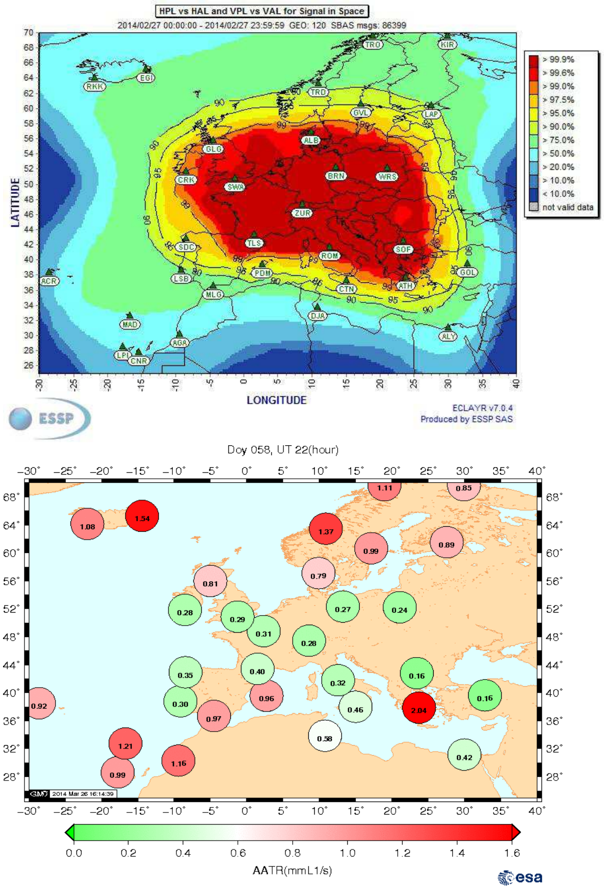


Figure 3. EGNOS APV-1 availability (top) and AATR index computed for EGNOS RIMS on the same day (27/02/2014) at hour 22-23 UT.

Moreover the Ionospheric EGNOS Warning System (IEWAS) has been developed to assess the accuracy and integrity of EGNOS ionospheric model against independent and external truths. Indeed IEWAS (see Figure 5) systematically download the ionospheric messages of EGNOS and transform them in IONEX format at high rate (15 minutes or higher, see example in Figure 6). In this way, the EGNOS VTEC model can be assessed against altimeter (JASON2) VTEC measurements gathered on the European seas (accurate at the level of few TECU, see for instance [5]), and against direct STEC difference (dSTEC) observations provided by GNSS receivers, with accuracies better than 0.1 TECU [6]. The corresponding assessments (relative error, in %) for 2014 can be seen in Figure 6 for VTEC on the seas surrounding Europe and in Figure 7 for dSTEC over two representative high and mid latitude receivers (ONSA and EBRE, respectively). It can be seen that during 2014, the relative error of the EGNOS ionospheric models goes between 10 to 25% in dSTEC, and up to higher values for VTEC. In particular, the period with a declared degraded availability in EGNOS (days 50,51 and 58, 59 of year 2014) are clearly coinciding with an increase of the relative error, when the VTEC is assessed with JASON2 measurements (Fig. 7).

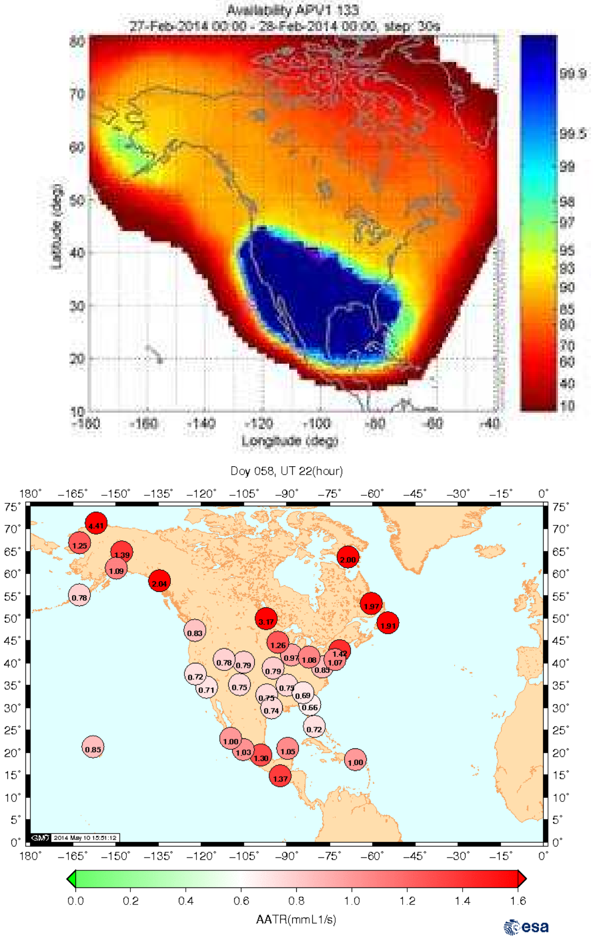


Figure 4. WAAS APV-1 availability (top) and AATR index computed for WAAS Reference Stations on the same day (27/02/2014) at hour 22-23 UT.

However, looking at the dSTEC relative error, compared with the direct observed precise values, from high to low latitude receivers (from ONSA, at Scandinavia, to MATE, at South of Italy, passing by EBRE, at NE Iberian Peninsula –see Figure 7-), only EBRE shown a certain increase of relative error during these days. This result of the EGNOS model, coming directly from external ionospheric truths, is in agreement and supports the distribution of AATR indicator found during these days (see Figure 2).

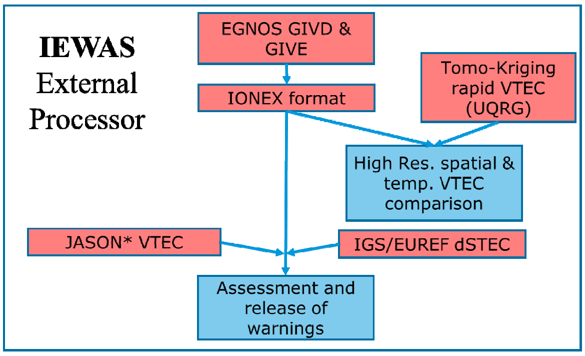


Figure 5: Layout of the Ionospheric EGNOS Warning System (IEWAS).

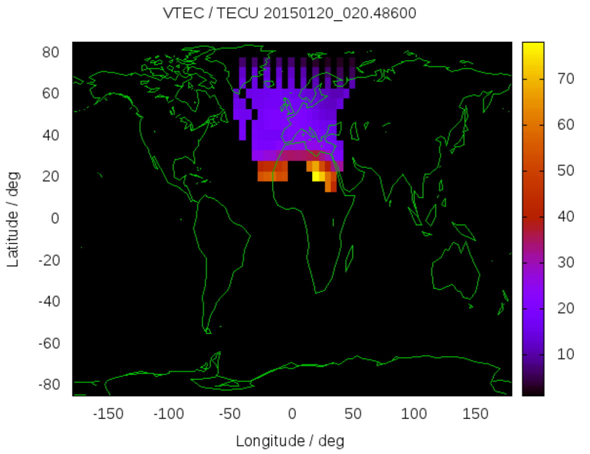


Figure 6: Example of the Ionospheric EGNOS VTEC directly decoded by IEWAS from EDAS messages (13:30 GPS time, day 20, 2015)

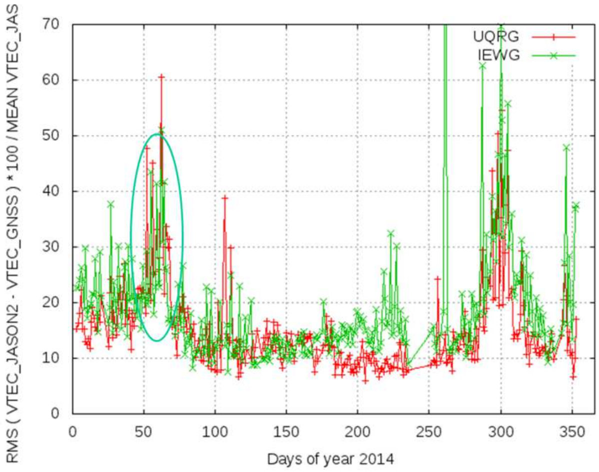


Figure 7: EGNOS VTEC Relative Error, taking direct JASON2 measurements as reference, during 2014 (green), compared with the same magnitude for the “UQRG” UPC global VTEC maps (red).

For high latitude North, analysis during days containing remarkable EGNOS events since 2011 to 2014 indicates a coincidence with high values of some ionospheric indices: (1) variations of horizontal magnetic field component exceptionally strong for high latitude stations (Nurmijärvi and Sodankylä in Finland); and (2) Rate of TEC index (ROTI) over Europe, typically at high latitude (Scandinavia peninsula), but sometimes at mid or low latitude (Iberian Peninsula and Canary Island ECAC sub-regions, respectively). But the reversal condition is not always fulfilled: there are periods with high magnetic field variability but not coinciding with remarkable EGNOS events. Moreover, selected days of degraded availability were compared against the AE geomagnetic index, suggesting that most days exhibiting reduction of service range at high latitudes corresponded with peak responses in the mean daily AE index, however no evident relation with significantly high Geomagnetic Auroral Electrojet (AE) index have been found for this index to be used as event discriminator (see Figure 8 for years 2012 and 2013).

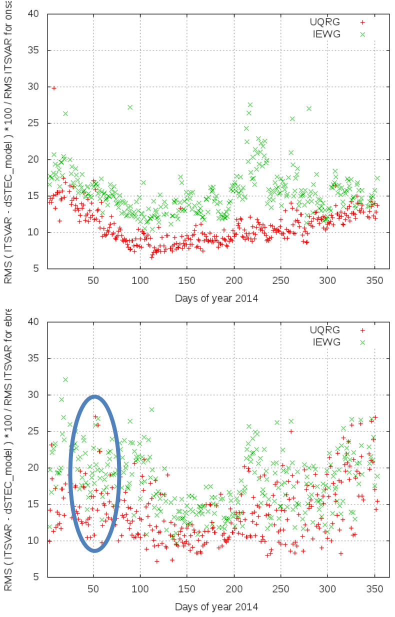


Figure 7: dSTEC relative assessment during 2014, of EGNOS-IEWAS (green) and UPC-UQRG (red) VTEC models, for one high-latitude and one mid-latitude IGS European GNSS receivers: ONSA (E11.9º,N57.2º) –top- and EBRE(E0.5º,N40.6º) –bottom-

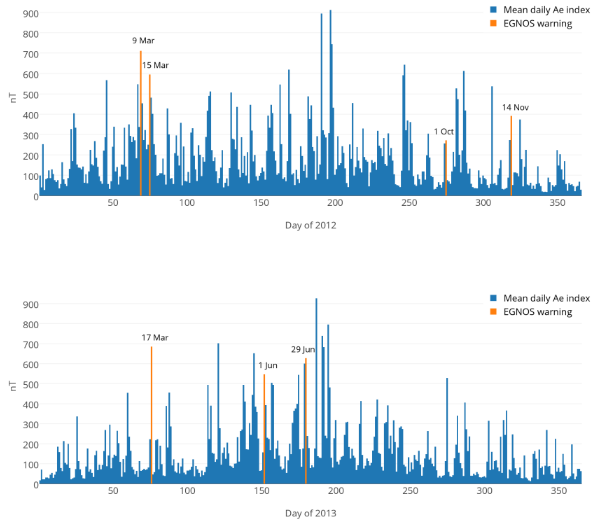


Figure 8. Mean daily Ae index in nT. Days coinciding with degradations observed in EGNOS, presented in orange. (top is 2012, bottom is 2013).

Similar analysis has been performed with ROTI in an Scandinavian site showing some peak correspondence with flagged EGNOS days (see Figure 9), but still not conclusive. Further analysis and multi-instrument comparisons are required.

ROTI Polar maps are generated within Monitor allowing to estimate the overall fluctuation activity and auroral oval evolutions. They are based on the classical approach when Rate of TEC (ROT) is detrended rate of line-of-sight TEC change and ROTI – index calculated on 5 min interval with 30 sec sampling rate. Due to strong connections between the Earth's magnetic field and the ionosphere, the behavior of the fluctuation occurrence is represented as a function of the magnetic local time (MLT) and of the corrected magnetic latitude. ROTI maps are constructed with the grid of 2 deg x 2 deg resolution. An example in 2015 is presented in Figure 10.

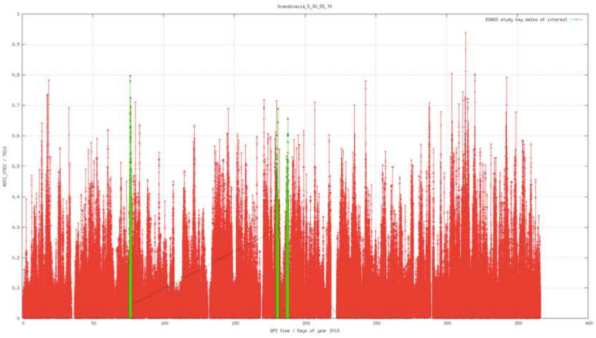


Figure 9. An example of the ROTI data from UPC for a site in Scandinavia, during 2013. Days when EGNOS experienced reduced service availability due to ionospheric activity are highlighted in green.

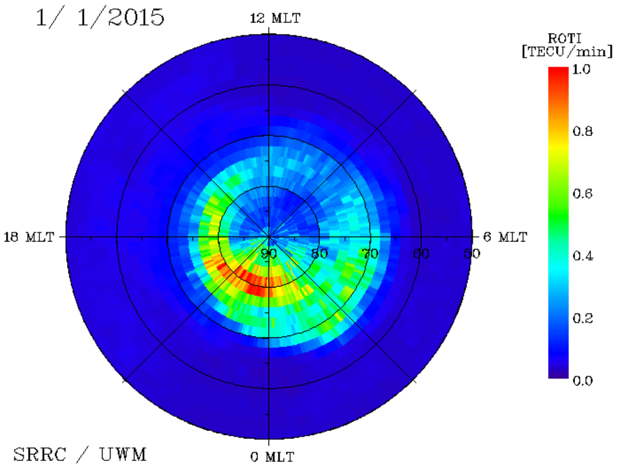


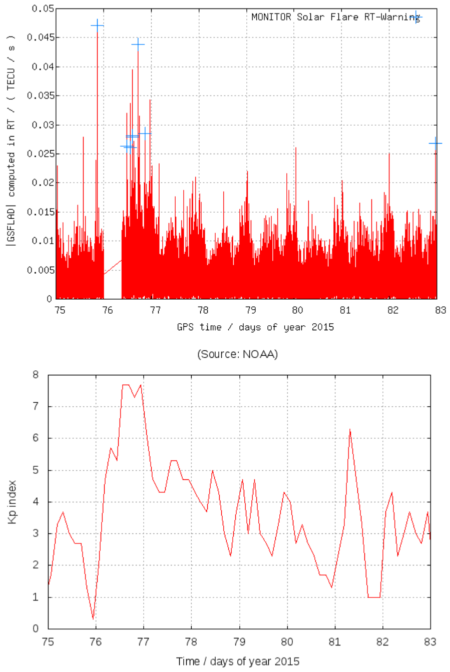
Figure 10. ROTI polar map from 1/1/2015

During the previous Monitor campaign, several GNSS scintillation receivers were deployed in the high latitude Scandinavian region. The analysis performed so far has shown that significant systematic differences were observed in the measurements provided by these receivers, showing the importance of the detrending filter stage and the quality of the oscillator for phase noise.

RECENT CASE STUDY: EGNOS IONOSPHERIC PERFORMANCE DURING THE ST. PATRICK'S GEOMAGNETIC STORM (17 March 2015)

Several geoeffective solar flares that occurred during days 75 and 76, 2015 (16 and 17 March), were detected and notified in RT by the MONITOR system by means of

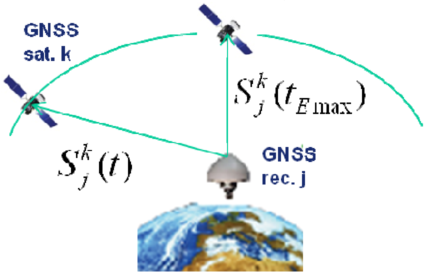
GNSS Solar Flare Indicator, (GSFLAI, see top plot in Figure 11 and [7] for details). Several hours after the beginning of such Solar Flare activity, a major geomagnetic storm (*St. Patrick's storm*) started (Kp reached a value close to 8 within day 76, March 17, 2015, see Figure 11, bottom plot).



(Source: NOAA)

Figure 11. Evolution vs time, during days 75 to 82, 2015 of: (top plot) GNSS Solar Flare Indicator (GSFLAI , with blue crosses representing the RT Solar Flare warnings) and (bottom plot) the Kp geomagnetic activity index.

In order to characterize the impact of this geomagnetic storm on the EGNOS ionospheric model, the error of such model, provided in high resolution by the MONITOR IEWAS system, has been assessed in order to reproduce: very well known differences of Slant Total Electron Content (dSTEC) measured in few representative permanent GNSS receivers over Europe (and bellowing to International GNSS Service, IGS).



$$\Delta S_O \equiv S_j^k(t) - S_j^k(t_{E\max}) =$$

$$= [(L_I)_j^k(t) - (L_I)_j^k(t_{E\max})] / \alpha \equiv \Delta L_I / \alpha$$

Figure 12. Layout and equation showing the derivation of ITSVAR (dSTEC) ionospheric truth (S represents the STEC, from a satellite k and receiver j and at different times t, and t_{Emax}, being Emax the maximum elevation of the observed satellite above the receiver horizon).

Indeed, in order to characterize the error of any model of ionospheric electron content, a simple and very precise GNSS truth can be used (the Ionospheric Truth based on STEC variation, dSTEC –ITSVAR-). ITSVAR is directly given, for a phase-continuous arch GNSS satellite-receiver- by the difference of the geometric-free (ionospheric) phase at any time minus the value when the satellite attained its maximum elevation above the horizon, providing directly the STEC difference, ΔS≡dSTEC (see Figure 12). Considering that the STEC at the highest elevation used to be close to the Vertical Total Electron Content, VTEC, dSTEC constitutes an excellent way of testing any ionospheric model (both VTEC, and mapping function) vs. observed values with precisions better than 0.1 TECU (i.e. less than 1 cm due to carrier phase noise and multipath, see an example of its application for assessing four different ionospheric models in [6]).

Looking at dSTEC daily bias during days 75-82 for three European GNSS permanent receivers (at latitudes of 57º, ONSA, 47º, ZIMM, and 40º, MATE), it is seen that EGNOS model underestimates very significantly the TEC on days 75, 76 and overestimates it on days 77 and 78 (see left column in Figure 13), coinciding with positive and negative phase of geomagnetic storm, with respectively more and less TEC than expected (see right column in same Figure 13). This is not the case (as expected) for rapid global UPC VTEC maps (UQRG), computed with one day of latency with a tomographic-kriging model and involving IGS receivers.

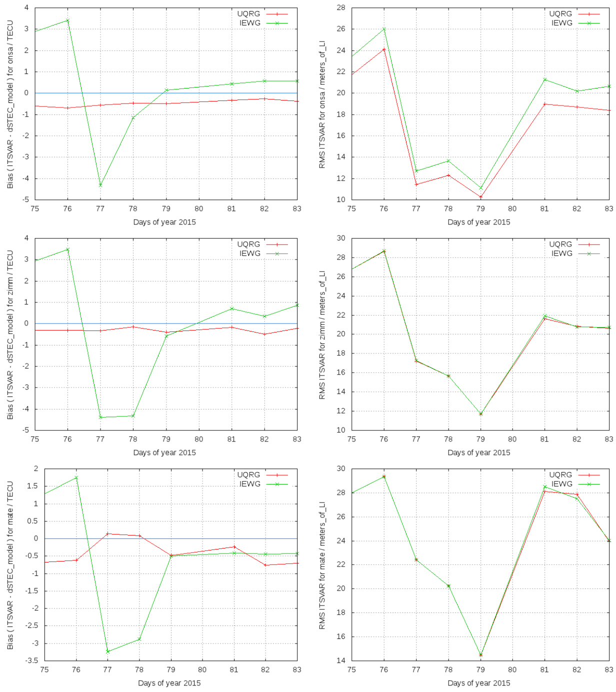


Figure 13. Daily modeled dSTEC error bias (left) and daily observed dSTEC RMS (right) for EGNOS and UPC ionospheric models (green and red, respectively), in TECUs, during days 75-83, 2015. The first, second and third rows corresponding to ONSA, ZIMM and MATE IGS GNSS receivers at (E12º,N57º), (E07º,N47º) and (E17º,N40º) respectively.

Indeed, the positive phase peak at European latitudes can be clearly seen on day 76, 2015, on global rapid UPC VTEC maps (top-left plot of Figure 14), and the strong decrease of electron content over Europe (coinciding with the almost disappearance of the equatorial anomaly) can be also seen during next day, 77, 2015, compared with the VTEC for the next days, after finishing the geomagnetic storm effects (see as example day 082 VTEC, at lower-left plot, and the corresponding EGNOS modeled values at the right column of same Figure 14).

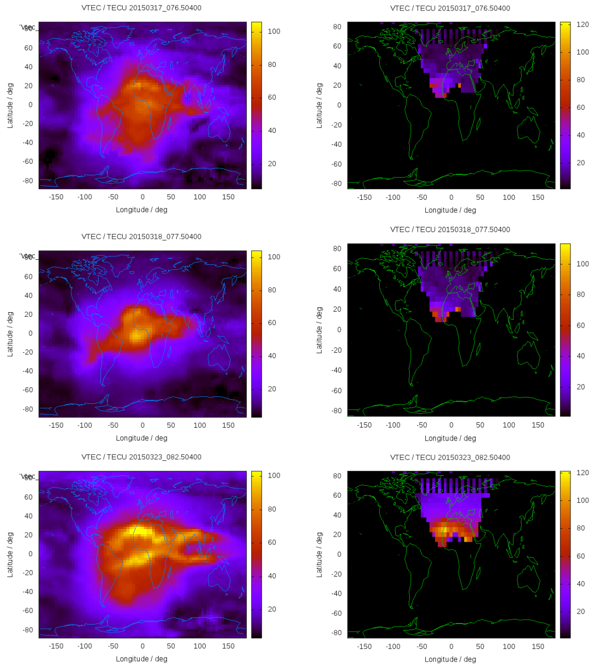


Figure 14. VTEC total electron content maps, in TECUs, at 14h GPS time during days 76 (first row), 77 (second row) and 82 (third row) provided by rapid global UPC VTEC model (left column) and RT EGNOS VTEC model (right column).

On the other hand, the dual-frequency altimeter measurements provide an excellent and independent source for assessing GNSS-based VTEC models (see [5] for instance). They allow a very clear evaluation and comparison of the errors of the different ionospheric models (considering for instance the daily statistics), typically much larger and systematic than the errors of the altimeter VTEC data.

During the same period of days 75-83, 2015, it can be seen a remarkable agreement between the daily VTEC relative error of EGNOS model (IEWG, among rapid and RT UPC models, UQRG and URTG respectively) over same JASON2 altimeter observations in the European Seas (top plot of Figure 15), and the daily dSTEC relative error regarding observed values over GNSS receivers (like ZIMM in central Europe, central plot). The derived performances are summarized in Table 1, which clearly show that dSTEC over selected European receiver and JASON2 VTEC (over European seas) give a similar result: A high degradation of EGNOS VTEC model (errors above 100%, days 75-79), in front of RT-UPC model (< 40%), and different from Rapid UPC VTEC model (<20%). Such degradation in ionospheric domain – its first part- is coinciding with the EGNOS APV-I Performance Degradation (< 80% of Service Area, since 17/03/2015 14:59:59 UTC until 19/03/2015 7:14:59 UTC, see as well Figure 15, top plot).

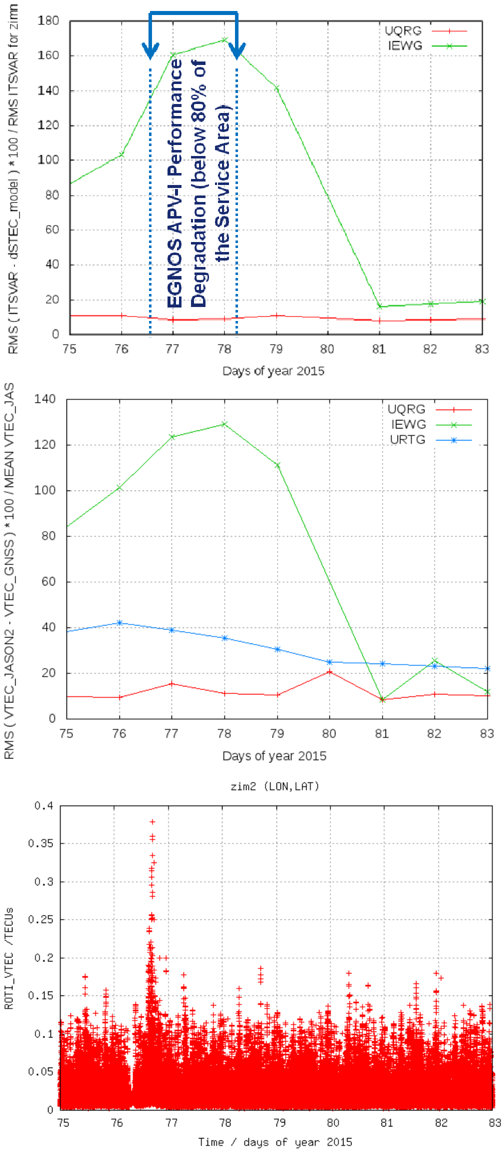


Figure 15. From top to bottom: (1) Daily relative error modeling the dSTEC observations of GNSS receiver ZIMM, at Switzerland, for EGNOS (green) and rapid UPC (red) models, during days 75-83, 2015 (in TECU). (2) Daily relative error modeling the JASON2 VTEC observations over European seas, for EGNOS (green), rapid UPC (red) and RT UPC (blue) models, during days 75-83, 2015 (in TECU). (3) Rate Of TEC Index (ROTI) for days 75-83, 2015, over ZIM2 receiver, collocated with ZIMM.

On the other hand the comparison of significant values of ROTI and dSTEC relative error of EGNOS ionospheric model, over the same site at Switzerland (GNSS receivers ZIM2 and ZIMM respectively, see top and bottom plot of

Figure 15), are coincident in this period during the afternoon of day 76. The high-ROTI period is coincident with the starting of EGNOS APV-I Performance Degradation (and change from positive to negative phase in the geomagnetic storm over Europe, discussed above).

VTEC rel.error	**(RT) EGNOS**	**(RT) UPC**	**(Rapid) UPC**
Disturbed (d.75-79)	82%-130%	30%-42%	10%-17%
Quite (d.80-83)	10%-23%	21%-23%	8%-12%

Table 1. Summary of relative errors in VTEC, experienced by EGNOS (RT), UPC (RT) and UPC (rapid) VTEC models in order to approximate the directly observed JASON2 VTEC values, distinguishing between Space Weather disturbed (75-79, 2015) and quite days (80-83, 2015).

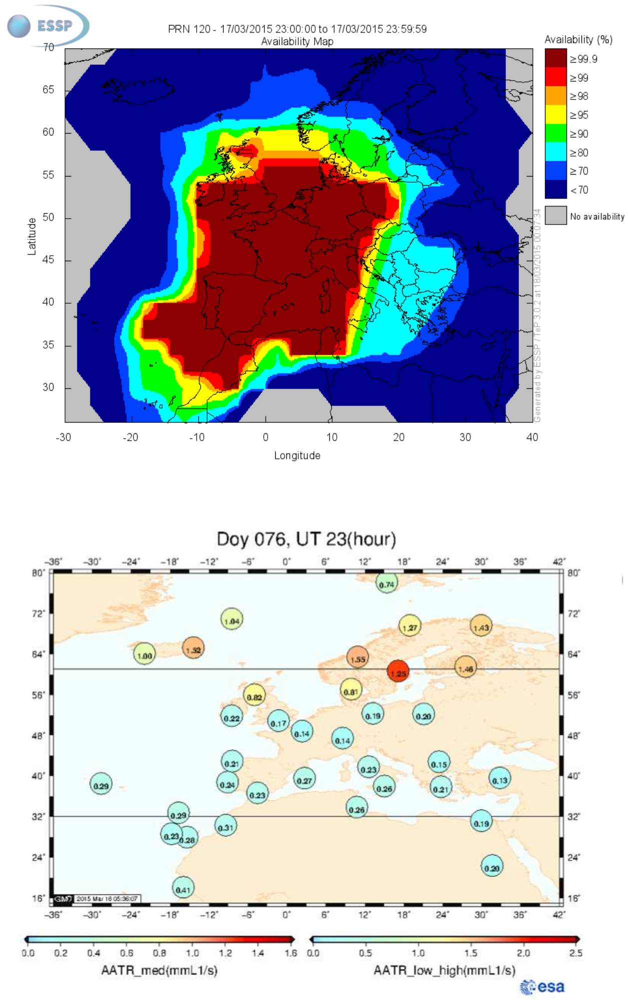


Figure 16. EGNOS APV-I Performance Service Area at 23:59 of St.Patrick's storm day 17/03/2015 (top plot) versus the AATR distribution over a set of European GNSS receivers (same day, at 23:00, bottom plot).

A first glance of the contribution of the ionospheric modeling to potential integrity problems is shown in Figure 17, in a zoom of *Pseudo-Stanford Plots (hereinafter PSP)*. The PSP represents the estimated error vs. actual error, but in ionospheric delay domain (instead of in positioning domain, as usual) and after transforming to IONEX format. The ground truth is taken again as the JASON2 VTEC (see above), and the PSP are shown in Figure 17 during (left column) and after (right column) the geomagnetically disturbed days, for the EGNOS (IEWG), rapid UPC (UQRG) and RT-UPC (URTG) VTEC maps.

It can be seen that no Miss of Integrity events in ionospheric domain are found, after applying multiplicative (inflation) factors of χ = 30, 5 &12, to the estimated standard deviation of the model errors for IEWG, UQRG and URTG, respectively. Significantly larger errors of EGNOS model appear during stormy days when compared with the quite period.

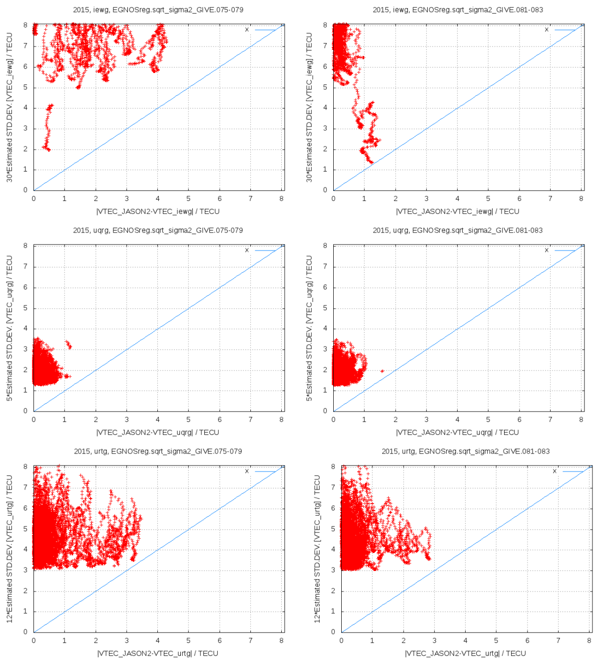


Figure 17. Estimated Standard Deviation of vertical ionospheric (VTEC) model error (in TECU), multiplied by and empirically- adjusted inflation factor χ (Y-axis) vs. actual VTEC error when compared with JASON2 VTEC measurements (X-axis), in TECU: Stormy (days 75-79, 2015) are represented in first column, quite days (81-83) in second column, and the results for RT EGNOS model, rapid UPC and RT UPC models are shown in first, second and third row (being χ=30, 5 and 12, respectively).

Finally in Figure 18 the scintillation observations (S4) during the same period (days 75-82 2015) are also shown, but measured from Dakar (Senegal) GNSS receiver, in the African-equatorial region, performing with a different pattern than ROTI over Europe as it could be expected.

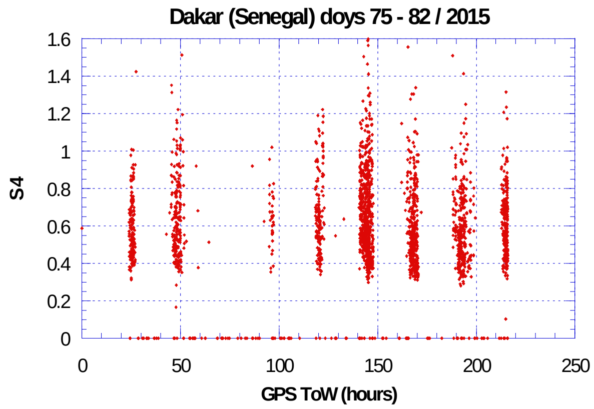


Figure 18. It can be seen the scintillation observations (S4) versus time during the studied period (days 75-82 2015) but close to the equator in the African sector (GNSS receiver at Dakar, Senegal).

SYNTHETIC SCENARIOS FOR SBAS ASSESSMENT

For system design and architecture assessment, the capability to generate synthetic ionospheric scenarios based on realistic data but not linked to a pre-defined set of stations is required. For EGNOS this has been performed using a data-assimilated version of NeQuick model through a grid of vertical Effective Ionisation Parameters Az from a VTEC grid map. For very disturbed cases, the modeled electron density profiles from NeQuick may reach their validity limit and therefore, enhancements on the assimilation process or alternative approaches needs to be considered. On this respect, various investigations has been considered:

- To assimilate ionosonde-derived peak parameters like foF2 or hmF2
- To assimilate Slant TEC where available
- To consider Radio-Occultation data.
- To vary Az along the ray-path.
- To simplify the NeQuick formulation in the optimization process.

For the moment, the assimilation of Slant TEC appears to provide improved results with respect to VTEC assimilation.

SUMMARY AND CONCLUSIONS

This paper has presented the Monitor Ionospheric Monitoring Network and demonstrated some of the potential of its data and products to support the analysis of SBAS systems exemplified with a number of days with EGNOS performance degradation in solar cycle 24.

Moreover the MONITOR system has allowed a comprehensive analysis of EGNOS ionospheric model performance during days 75-82, 2015 (comprising the St. Patrick's major geomagnetic storm during March 17th, 2015), after broadcasting RT warnings on Solar Flares preceding the major geomagnetic storm.

Indeed, a detailed assessment has been done versus two sources of ionospheric truths in terms of STEC (against GNSS dSTEC observations) and VTEC (versus direct VTEC measurements from JASON2 altimeter). The main result is that the EGNOS VTEC appeared clearly underestimated during the positive storm phase and overestimated during the negative phase, with associated relative errors which reached up to more than 100%. Such degradation in ionospheric domain included the EGNOS APV-I Performance Degradation (< 80% of Service Area).

These particular results suggest the possibility of improving the EGNOS RT VTEC model by implementing a Kalman filter (or equivalent) with increased process noise (as it is done in the RT UPC ionospheric model for instance), possibility which should be confirmed by an analysis of a larger number of Space Weather events affecting Europe.

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