MONITOR 2: ionospheric monitoring network in support to SBAS and other GNSS and scientific purposes

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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.

1. 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.

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.

Products 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.

2. 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).

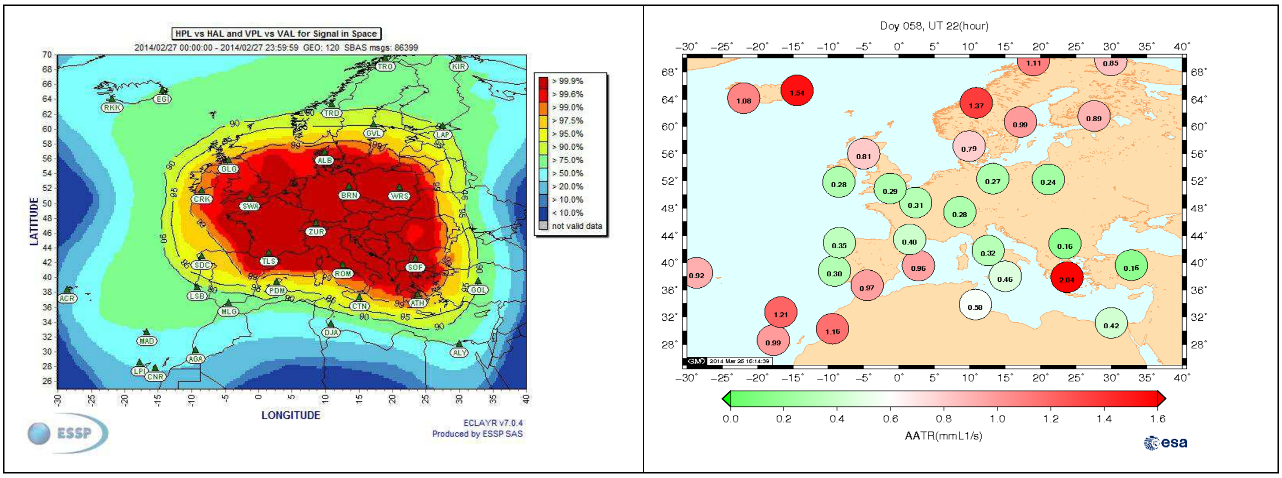

Figure 3. EGNOS APV-1 availability (top) and AATR index computed for EGNOS RIMS on the same day (27/02/2014) at hour 22-23 UT.

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).

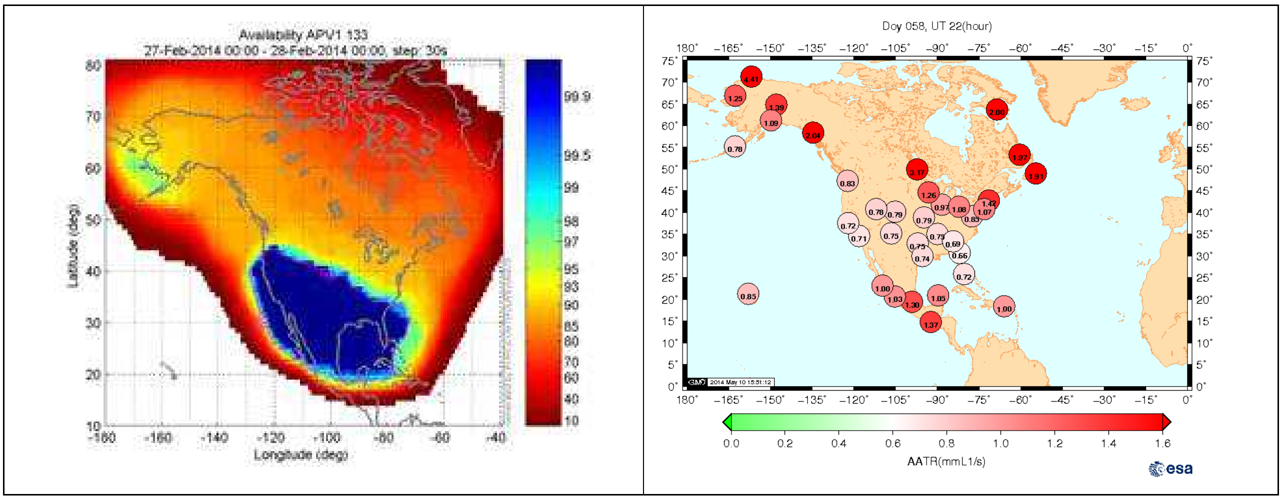

Figure 4. WAAS APV-1 availability (top) and AATR index computed for WAAS Reference Stations on the same day (27/02/2014) at hour 22-23 UT.

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 6-), 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).

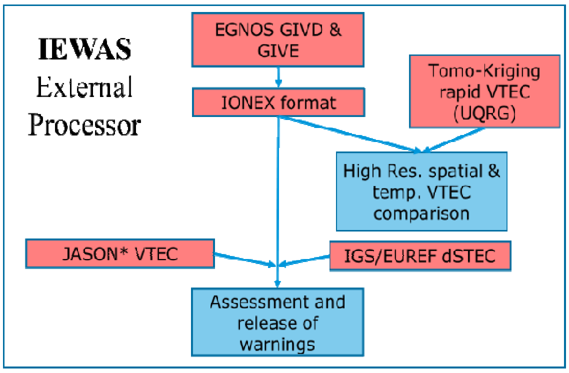

Figure 5: Layout of the Ionospheric EGNOS Warning System (IEWAS).

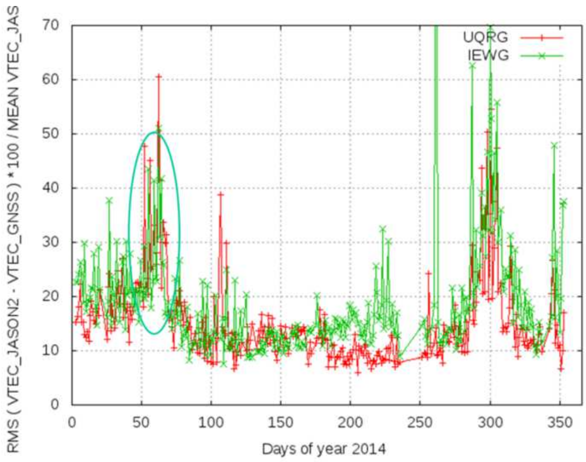

Figure 6: EGNOS VTEC Relative Error, taking direct JASON2 measurements as reference, during 2014 (green), compared with the same magnitude for the "UQRG" UPC global VTEC maps (red).

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.

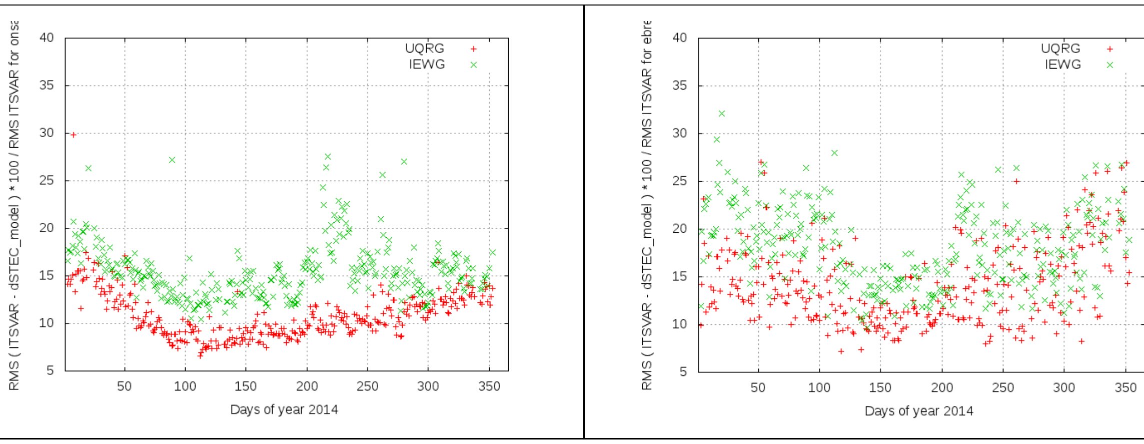

Figure 7: dSTEC relative assessment during 2014, of EGNOS-IEWAS (green) and UPC-UQRG (red) VTEC models, for one high-latitude and one mid-latitude IGS European GNSS receivers: ONSA (E11.9º,N57.2º) –left- and EBRE(E0.5º,N40.6º) –right-

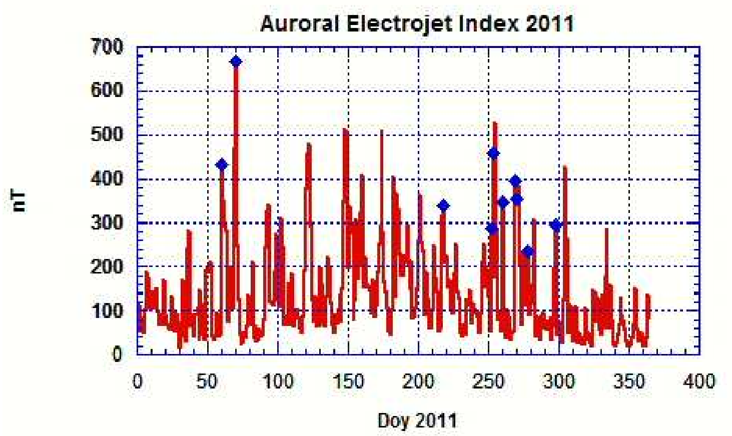

Figure 8. Mean daily Ae index in nT. Days coinciding with degradations observed in EGNOS, corresponding to the blue squares (year 2011).

Selected days of degraded availability have been compared against the AE geomagnetic index, showing that all days of year 2011 exhibiting reduction of service range at high latitudes were corresponding to peak responses in the mean daily AE index. This criterion is under investigation to be used as event discriminator at high latitudes.

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 11.

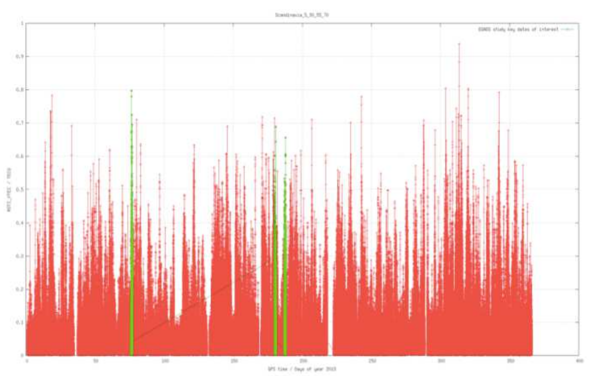

Figure 9. An example of the ROTI data from UPC for a site in Scandinavia, during 2013. Days when EGNOS experienced reduced service availability due to ionospheric activity are highlighted in green.

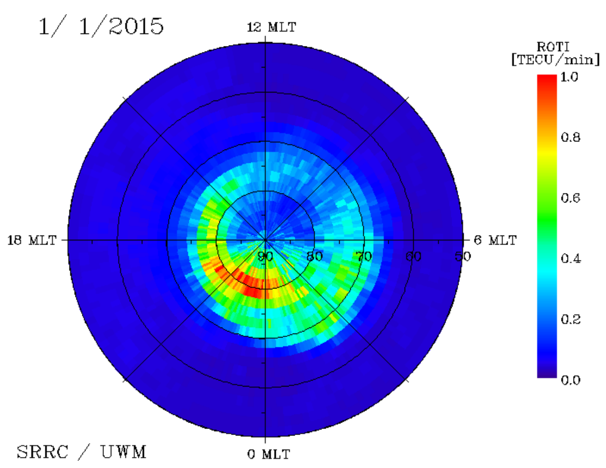

Figure 10. ROTI polar map from 1/1/2015

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.

A new tool for scintillation mapping has in addition been implemented. The algorithm developed is based on a Kriging technique [7]. As a regular product it delivers scintillation maps over West Africa using data recorded both by the Monitor and the Sagaie networks. These are composed of 50 Hz receivers (Novatel and Septentrio) and 1 Hz receivers. The maps are updated every 15 mn. The Kriging technique can be seen as a data assimilation technique. The accuracy of the results depends on the accuracy and quantity of the measurements. The algorithm provides maps and concurrently error maps. The more data it can be available at a given location, the more accurate is the resulting map. It works currently with a reduced number of stations. This will be complemented in the near future with additional stations belonging to the Monitor network. The GISM model [8] is used as a background tool to fill the gaps between the measurements data points providing the algorithm with the "variogram" function which plays a major role in this technique.

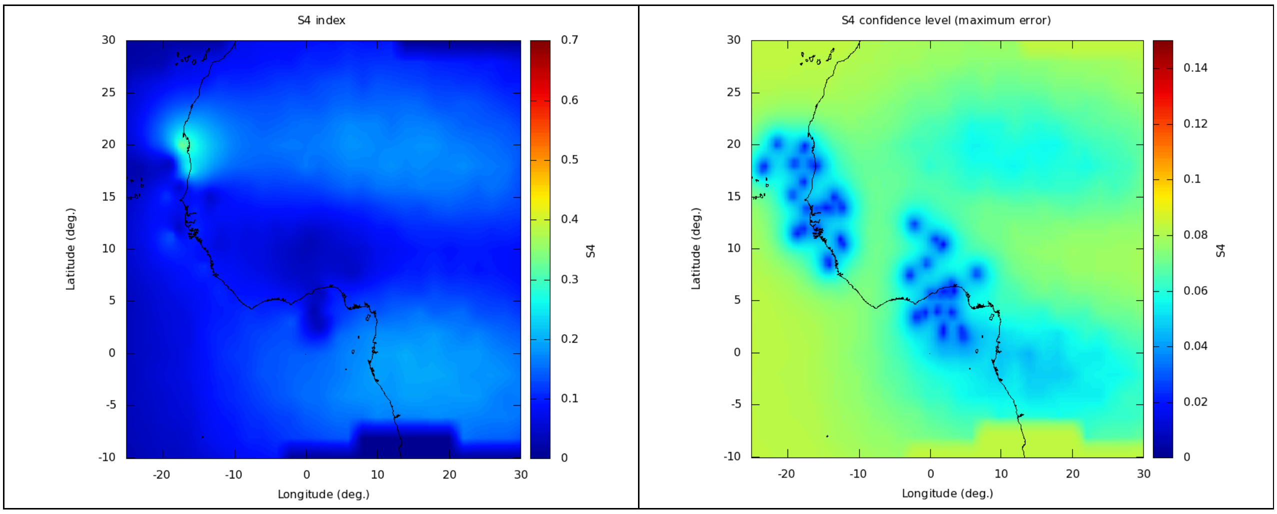

Figure 11 : Scintillation maps (S4 level) and corresponding confidence level over West Africa using data from Dakar and Lomé.

3. 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.

4. CONCLUSION

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.

5. ACKNOWLEDGEMENTS

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