Ionospheric Effects on GNSS Performance

Y. Béniguel[1], M. Angling[2], E. Banfi[3], C. Bourga[4], M. Cueto[5], R. Fleury[6], A. Garcia-Rigo[7], P. Hamel[1], R. Hartmann[8], M. Hernández-Pajares[7], N. Jakowski[9], K. Kauristie[10], R. Orus[11], R. Prieto-Cerdeira[11], JJ Valette[12], M. van de Kamp[10]

[1]IEEA, [2]QinetiQ UK, [3]Thales Alenia Space Italy, [4]Thales Alenia Space France, [5]GMV, [6]Télécom Bretagne, [7]gAGE/UPC, [8]Jena Optronik, [9]DLR Neustrelitz, [10]FMI, [11]ESA/ESTEC, [12]CLS,

Abstract— **This paper presents the features of the MONITOR project. This project initiated by ESA / ESTEC aims to increase the knowledge of the ionospheric effects and its impact on GNSS systems during active periods of solar activity. It includes the deployment of a set of GNSS-based ionospheric monitoring receivers worldwide distributed, the development of specific analysis software tools some of them integrated on a common platform, others distributed providing products routinely and a measurement campaign which will last beyond the peak of the current solar cycle.**

Keywords—ionosphere, GNSS, receivers, TEC, scintillation, solar Flare

I. INTRODUCTION

The performance of Global Navigation Satellite Systems (GNSS) is impacted by signal propagation impairments due to the ionosphere. The understanding of climatology of ionospheric propagation behaviour is well established under nominal conditons. Ionospheric effects follow variations depending on time-of-day, season, location and solar condition. The Sun activity exhibits a long-term variation following approximately an 11-year cycle, and after a long solar minimum it is expected that the coming years will be active, increasing the likelihood to see abnormal effects affecting GNSS systems.

Ionospheric modelling is a challenging domain, depending on solar activity and its interactions with geomagnetic field; the ionosphere may deviate from its nominal behaviour. This happens, for instance, during severe geomagnetic storms. In those cases, it is essential for a safety of life system to confirm that the integrity of the computed ionospheric corrections is still maintained while minimising the impact on availability and continuity of service. For this reason, accurate models or realistic synthetic/measured data of a disturbed ionosphere is needed for a complete system qualification.

Ionospheric amplitude and phase scintillations are important ionospheric impairments on GNSS signals affecting system performance for user receivers, but also for Sensor Stations in the ground segment of the GNSS system. Strong scintillations can induce cycle slips and loss-of-lock in GNSS receivers. Scintillations depend on location, time-of-day and solar activity. Also large spatial and temporal gradients of electron density are observed in low latitude regions and they may impact the performance of safety-of-life carrier smoothing receivers.

Specific developments of semi-codeless tracking GPS receivers for ionospheric scintillation monitoring have been done in the past, which can provide very useful information for nominal scintillation levels, however they are far from robust under strong scintillation activity, not being able to derive enough statistics under extreme cases, which is needed for stringent Integrity and Continuity GNSS requirements. Those receivers have very specific characteristics regarding sampling rate and loops filter bandwidth in order to cope with scintillation without altering the results. The possibility to use codes on signals at various frequencies in Galileo, together with other signal characteristics (C/No, bandwidth, code length, pilot signals ...) will allow designing a robust receiver for ionospheric monitoring.

II. MONITOR OVERVIEW

MONITOR [1] is a project from the European Space Agency's GNSS Evolutions Programme, dedicated to collection of data and products during active periods of solar activity for later understanding of the impact of ionospheric effects on EGNOS and Galileo system performance. Those systems include certain requirements on availability and continuity of service. Requirements driven by safety-of-life applications such as civil aviation, requiring a complete knowledge of the effects of severe ionospheric events in the performance of the system.

The Total electron content (TEC) is the most important quantity for correcting first and higher order ionospheric range errors. Global and regional TEC products are required for verification of ionospheric error correction capabilities, or for directly correcting or accelerating the GNSS positioning convergence, for single and double-frequency services. TEC gradients may also impact the performance of smoothing filters in single-frequency systems, therefore, proper characterisation of gradients is required. The measurements of ionospheric gradients may be used to derive probability density functions of horizontal gradients of ionospheric ionization under different geophysical conditions.

In addition to TEC and TEC gradients, amplitude and phase scintillations pose a problem to GNSS systems. Indeed, most of the time and in particular during the recent and long solar activity minimum, low-level ionospheric behaviour has been observed (and in particular no or few scintillations). This prevents direct experimentation of GNSS performance and robustness, whereas it is well known that significant disruption of service can be induced especially by ionosphere amplitude and phase scintillations. Besides, past observations (e.g. for the last peak around year 2000) do not allow to fill the gap, because of the lack of observations. The few GPS receivers monitoring the scintillation did not allow a full characterisation of the phenomenon. Also the boreal area was scarcely covered.

These facts have led to base GNSS performance assessment on synthetic state-of-the-art models, such as GISM [2], with known limitations in the modelling, in particular for:

- scintillation conditions during high solar activity (namely when the solar flux is higher than 193),
- behaviour in boreal area
- correlation effects (time, space and frequency for amplitude and phase)

One additional purpose of MONITOR is to focus the analysis, on the occurrence of abnormal events, on the receiver transfer function and to illustrate the impact on GNSS of some extreme events through dedicated system simulations. This analysis will greatly benefit from the processing of various data and products from the same event, maintaining the integrity of the specifications

III. MONITOR ARCHITECTURE

Monitor is composed by the following elements:

- Central Archiving and Processing Facility (CAPF), installed in ESTEC, Noodwijk, The Netherlands which includes the following features:
  - Internal processors.
  - Interface for public and private users (web based).
  - Interface with external processors and external data providers.
  - Interface with Ionospheric Experimental Stations.
  - Archiving and backup system
- Ionospheric Experimental Network (IEN) including several Ionospheric Experimental Stations (IES)
- External Processors
- External Data Providers

These modules are depicted in Figure 1.

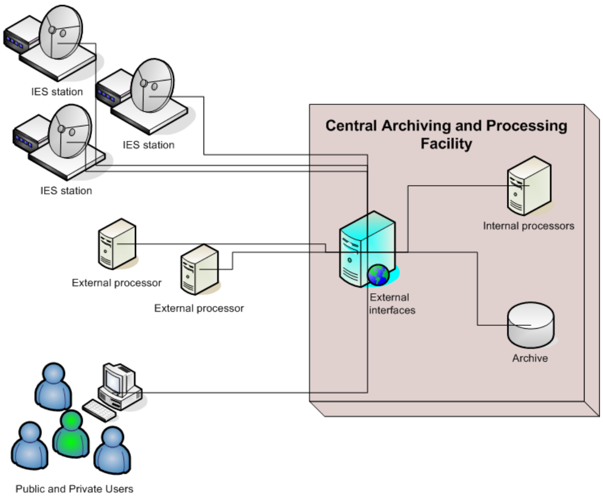

Figure 1. High level architecture of MONITOR

For the IEN, existing stations from a previous project (PRIS [3]) have been incorporated, however they do not provide data in near real time. The current network of stations is shown in Figure 2. A number of potential new sites are under consideration .

Four different types of ionospheric scintillation receivers have been installed in the stations. Existing PRIS sites include GSV4004 (based on Novatel COTS) or Javad receivers. The new Monitor stations include Novatel GSV4004 and Septentrio PolaRxS. Two of those stations (Sodankylä, in Finland and Sal Island in Cap Verde) include additionally one Galileo Scintillation Monitor (GISMO) connected to a digital IF bitgrabber. The station in Milano, Italy includes only a GISMO. GISMO is a receiver developed during MONITOR activity, based on previous developments in Thales Alenia Space Italy, adapted for ionospheric scintillation monitoring with Galileo and GPS signals.

Before deployment of the different receivers, a benchmark was carried out at ESA / ESTEC for several scintillation scenarios varying from low fluctuations to high fluctuations. This benchmark has been used to feed the Spirent generator and all receivers have been successfully tested against these scenarios providing coherent results [4].

All new sites incorporate Internet connection allowing a near real-time data delivery to the Central Archiving and Processing Facility (approximately 1-hour latency for most products).

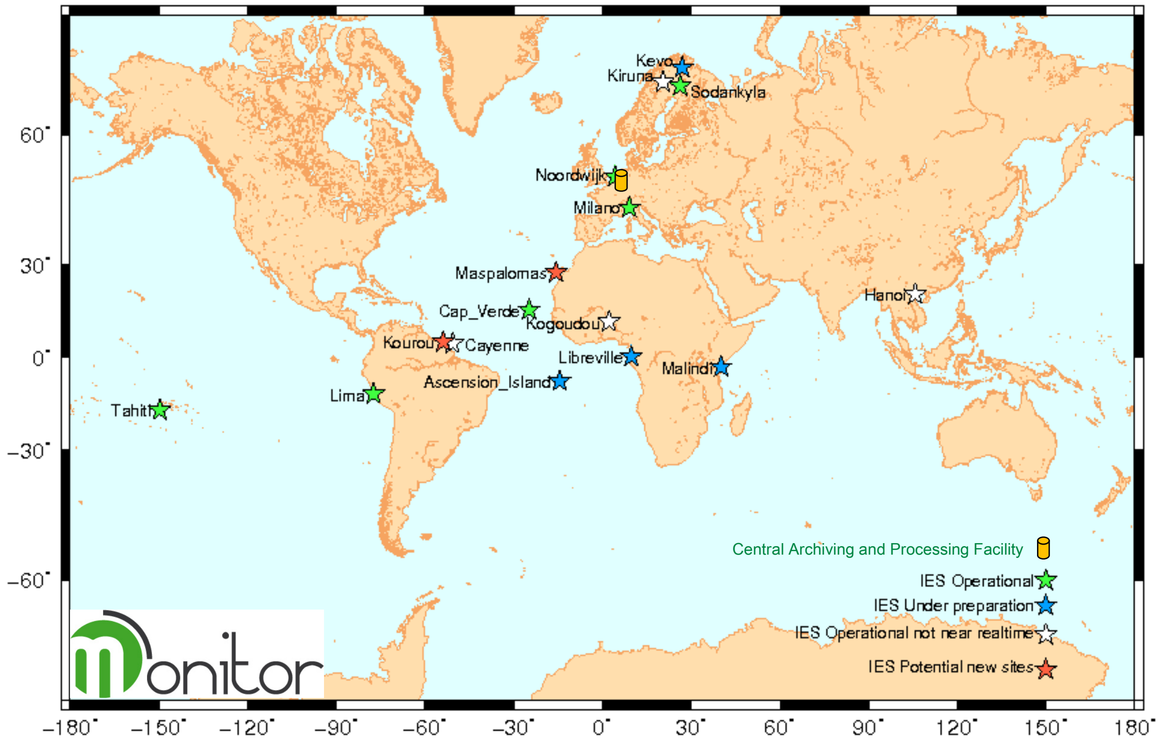

Figure 2. **Monitor Ionospheric Experimental Stations**

IV DATA AND PRODUCTS

In the IES stations, three types of data are recorded and sent to CAPF: raw data at 50 Hz, 1 minute pre-processed scintillation data and dual-frequency GNSS measurements at 1 Hz in RINEX format.

The CAPF external processors correspond to heritage services from some of the MONITOR teams. They process data through existing or adapted services and make available products to CAPF. On the contrary the internal processors are implemented inside the CAPF and provide new functionality using data from IES stations, external processors or external data providers and provide processed data. Some of them are processed routinely and some others on demand.

In terms of electron density, the following products are generated and archived routinely:

- Global VTEC maps from TOMION software every 15 minutes
- European VTEC maps every 15 minutes from SWACI
- Rapid (2 hours) and ultra-rapid (15 minutes) 3D electron density grid data from EDAM assimilative model
- GEC Global Electron Content index
- Higher-order ionospheric estimation error

From the IES stations, the following data and products are calculated routinely:

- Scintillation statistics, mapping and raw data analysis (fades and spectrum characterization) for IES stations.
- IES stations Slant TEC & Station Differential Code Biases

The CAPF also calculates routinely a set of optimised Az parameters (following the Galileo Single Frequency Correction algorithm [5]) using a Slant TEC from a large set of IGS-Real Time stations and updated every 6 hours.

In addition, Monitor provides a number of indicators among which some of them can be used for space weather awareness such as:

- Sidereal day variability index
- Travelling Ionospheric Disturbance (TID) variability index (able to detect TIDs with amplitudes higher than 0.5 TECU)
- Solar Flare variability index (able to detect most X-class and many of mid-class Solar Flares)

As an example, Figure 3 below shows a local map of scintillations over Peru corresponding to one day of measured data. The data recorded in Lima (map center) has been used for this purpose. In a few locations several receivers are closely located allowing exhibiting the coherence properties of the medium. Both the time, space and frequency are calculated.

The analysis of the observations will support the understanding of abnormal events, characterisation of disturbed periods and the synthesis into new or updated models, recommendations and conclusions useful for characterisation of GNSS performance and development of mitigation techniques.

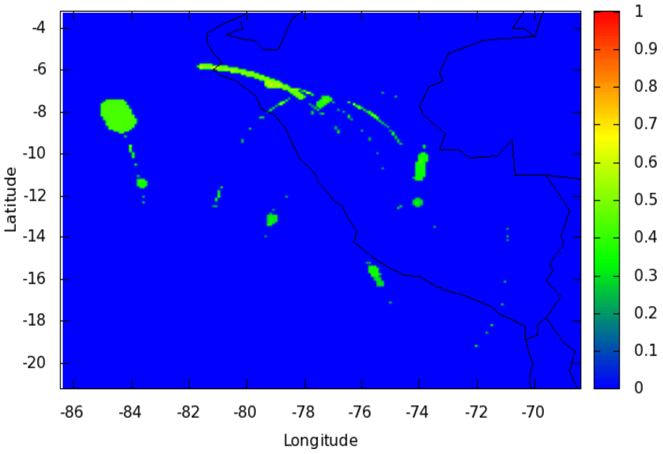

Figure 3. **Scintillations over Lima, Peru, year 2011, day 54**

IV. MONITORING OF STRONG SCINTILLATION EVENTS

One important challenge for the project is the capability to monitor severe scintillation events in order to validate existing scintillation models in extreme conditions and to gain a better insight into the behavior in boreal and equatorial regions. One usual way of scintillation monitoring is to use GNSS receivers with specific processing of samples at output of tracking loop (classically at 50 Hz rate). However when scintillation conditions are very strong, often those receivers are no longer able to track the signal not allowing the collection of relevant data and the proper modeling and analysis of scintillation effects. To overcome these limitations a specific instrumentation setup has been developed. It is composed of:

- 2 bitgrabbers (Ettus USRP2)
- 1 GPS/Galileo receiver (GISMO)
- 1 workstation controlling the acquisition of data and communication with central facility

Each bitgrabber is dedicated to a given frequency band (L1/E1, L2 or L5/E5 depending on the selected configuration) and records digitised RF signal with a current default bandwidth of 4 MHz. Because the amount of data becomes rapidly huge, the recording is triggered for a limited duration with a flag based on scintillation indices computed by the GISMO receiver. Data is stored on an external hard disk of 3 TB which is sent at regular intervals to Thales Alenia Space premises in Toulouse for offline processing.

Indeed, post-processing techniques open the possibility to a better characterisation of the phenomena since they can mimic the behaviour of a standard receiver in terms of acquisition and tracking but with flexibility in receiver configuration and replay capability. In addition to the standard scintillation indices, the experimentation will aim to assess the key parameters useful for GNSS design and performance budget:

- correlation time of fading and phase excursions, on each signal
- correlation of scintillation effects between different frequencies.

The bitgrabber high frequency sampling will allow a detailed spectrum analysis. The spectrum cut-off frequency depends on the medium structure parameters namely the inhomogeneities size and the ionosphere drift velocity. This last is assumed to be of particular importance. Its estimation will also be made possible through the Monitor measurement campaign using the signal correlation properties derived from measurements recorded at two closely spaced ground receivers. Such a calculation can be based in particular on slant TEC variations. The correlation properties between the cut off frequency and the drift velocity can then be obtained. An inappropriate setting of the receiver filter parameters with respect to the cut-off frequency might explain the fact that at high latitudes, the scintillation receivers usually experiment higher phase scintillation than amplitude scintillation values.

At low latitudes the focus will be on extreme events and assessment of cycle slip / loss of lock performance. This currently occurs for scintillation index values S4 greater than 0.7. Several parameters are involved in this process as the signal to noise ratio, the fades distribution, the peak to peak amplitude fluctuations (related to S4) and the receiver parameters as the integration time and the phase loop bandwidth. On such an occurrence, there is a need to perform a detailed analysis to obtain the signal characteristics. This could be used in the future to implement mitigation techniques allowing coping with these extreme events.

VI SPACE WEATHER AWARNESS

One new concept and capability of detecting space weather has been implemented as well in MONITOR project, in real-time and mid rate (each 30 seconds): the usage of GNSS data streams of dual-frequency carrier phase measurements gathered from global networks of distributed GNSS receivers to detect (at mid rate) solar flares, and provide direct solar flux measurements (at high rate). Indeed, this is done in order, not only to provide prompt warnings of occurrence of mid and strong geo-effective solar flares, but also providing a proxy of solar EUV flux rate, especially when high rate measurements (each second) can be used.

The physical model is simple: under typical solar flare time scales of seconds to tens of seconds, the ionosphere suffers a sudden over ionization which can be considered (in good approximation due to the short time scale) proportional to the solar flux increase, through a ionization efficiency constant (which will depend on the given spectral range geo-effectiveness) and a cross-section factor, which basically depends on the cosine of the solar-azimuthal angle [5]. Other factors, like effect of magnetic field, thermospheric winds, plasma transport in general, can be neglected due to the short time scale of the phenomena. And the sudden over ionization can be directly measured with the very precise ionospheric (geometric-free) combination of dual-frequency GPS carrier phase measurements (thousands independent measurements worldwide distributed for each observation time).

This parameter is called GNSS Solar FLAre Detector (GSFLAD) when it is defined at 30 seconds, computed from double differences in time of the ionospheric combination of dual-frequency GPS carrier phases. An example is presented in **Figure 4**. It is being used successfully in MONITOR as a simple solar flare warning parameter, quite correlated with the real-time warning provided by the Ionospheric Prediction Service by using GOES satellite X-ray flux measurements (IPS, http://www.ips.gov.au/, see Figure 11 in above mentioned reference). A more sophisticated detector definition (SISTED)
allows the detection of all the X-class flares with known location outside the solar limb (94% of the total), and 65% for M-class flares, during more than half solar cycle.

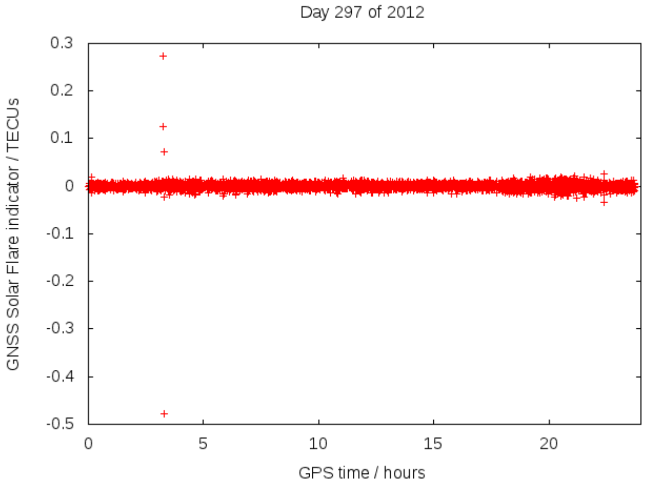

Figure 4. Solar Flare Awareness indicator (GSFLAD) during 23 October 2012: a very intense X-class flare at 04:26 UTC, among other mid solar flares, are clearly seen. This flare is also reported by NOAA (see Figure 4)

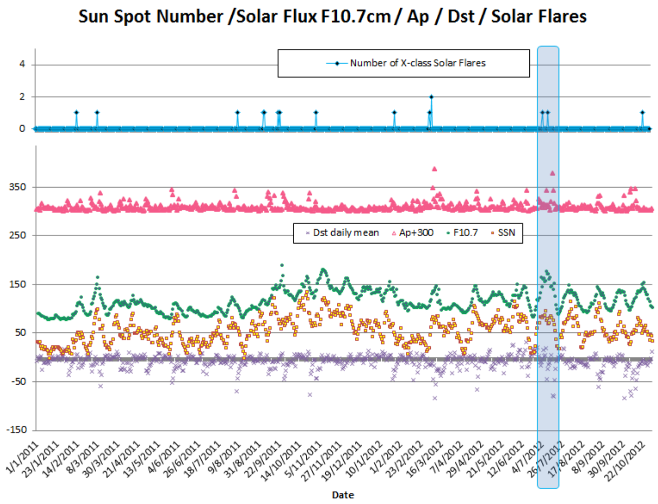

Figure 5. Solar and Geomagnetic indices[1] between Jan-2011 and Oct-2012: Spot Number, Solar Flux at F10.7cm, Ap daily mean, Dst daily mean and Number of X-class solar flares. The selected period of analysis is highlighted.

The corresponding parameter defined at 1 second from single differences in time is called the GNSS Solar FLAre Indicator (GSFLAI), because it exhibits very good correlation behaviour with EUV flux rate, in such a way that it can be used as a corresponding proxy [5, Figure 8]. GSFLAI, which requires to work with the maximum available rate of real-time GNSS measurements (1 Hz), is not implemented as part of Monitor products.

VII EARLY RESULTS

The CAPF is fully operational since June 2012, from that time a period including two X-class solar flares and intermediate geomagnetic storm activity during July 2012 has been selected for early analysis results. The selected period together with the Solar and Geomagnetic indices is presented in **Figure 5**.

During the period between 6 and 16 July, a number of space weather events were observed as reported by NOAA Space Weather Prediction Center. On 6 July (doy 188), an X1.1 Solar Flare was registered by GOES at 23:08 UT. On 8 July (doy 190), the largest daily Solar Flux value observed in 2012 was registered. A mild geomagnetic storm was observed on 9 July (doy 191). Then an X1.4 Solar Flare was registered on 12 July (doy 194) at 16:53 UT followed by a Coronal Mass Ejection. From 14 to 16 July, a mild-to-moderate geomagnetic storm was observed with largest levels observed on 15 July (doy 197).

First, analysis of VTEC maps have been performed over this period, comparing final Global Ionospheric Maps in IONEX format from the International GNSS Service (IGS) as reference, with other VTEC sources: MONITOR Ultra-Rapid

---

[1] Dst from World Data Center for Geomagnetism, Kyoto, other indices from NOAA Space Weather Prediction Center and NOAA National Geophysical Data Center

VTEC maps from UPC/TOMION, GPS single-frequency broadcast ionospheric correction ("Klobuchar model") and EGNOS corrections. The evolution of VTEC over time for three points at different latitudes are presented in **Error! Reference source not found.**. A general good agreement is observed for IGS, MONITOR TOMION and EGNOS. Slightly larger VTEC was observed for doy 190. It is evident that larger sampling in MONITOR TOMION and EGNOS allows to observe more features often smoothed with 2-hours IGS maps.

In order to better characterize the differences, the daily maximum absolute difference for each grid-point was calculated for all the days under investigation.

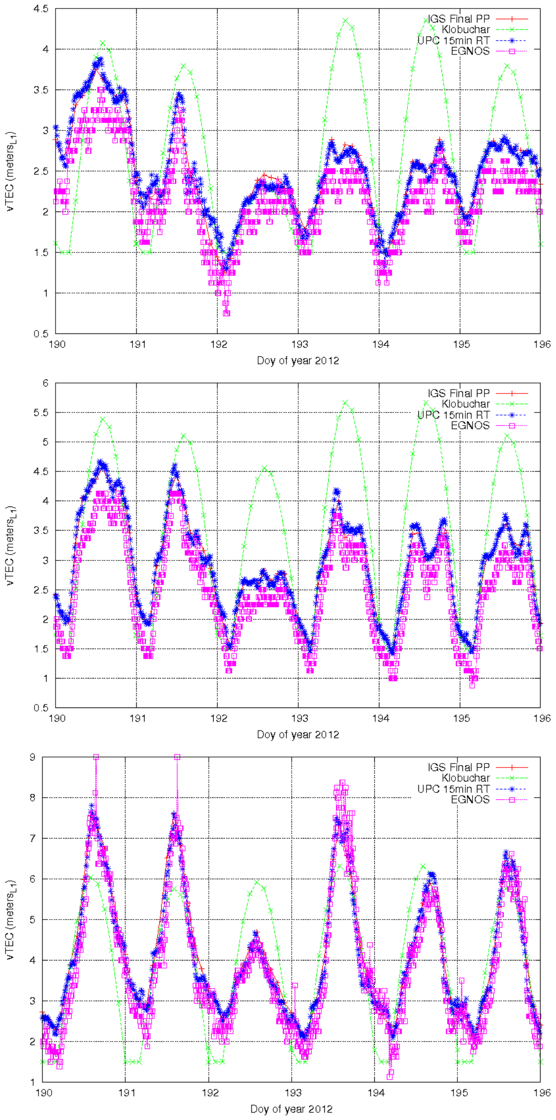

Figure 6. VTEC evolution (in meters of L1) for different models (IGS, GPS Broadcast Ionospheric Correction, MONITOR Ultra-rapid maps from UPC/TOMION and EGNOS corrections, for three points: (top) 60° Lat, -5° Lon (center) 60° 45° Lat, -5° Lon, (bottom) 30° Lat, -5°

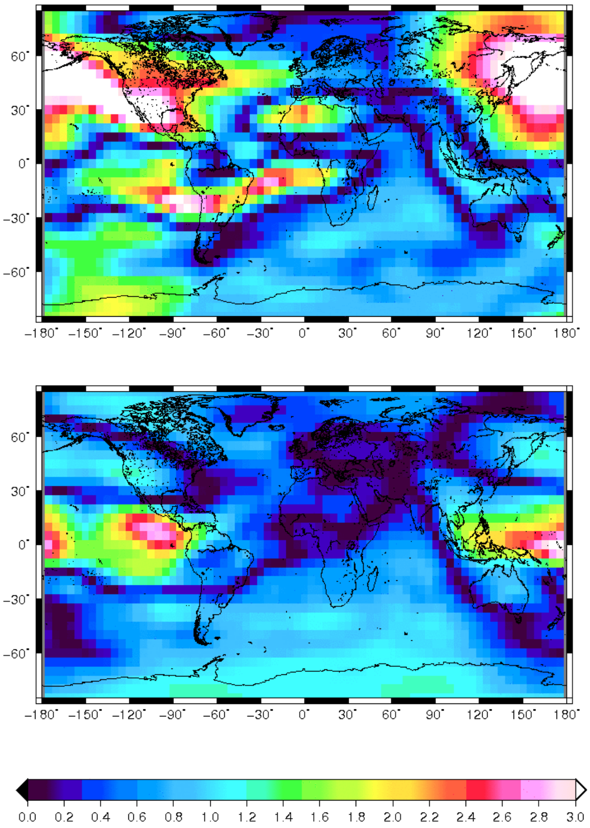

Figure 6. Maximum absolute daily VTEC differences in meters of L1 between GPS ionospheric broadcast correction model and IGS final GIMs for (top) doy 197 - moderate storm- and (bottom) 201 - nominal day of 2012

The maximum absolute differences between GPS model and IGS were largest during the storm days (doy 197 and 190), as presented in **Figure 6**. For doy 197, the largest differences were observed at mid-latitudes in the South West US, Mexico, Pacific, and North of Japan and also at low-latitudes in the coast of Peru and Chile. Doy 190 showed larger differences at low-latitudes in the Pacific and in the North of Africa. A nominal day like 201 shows better agreement, but other nominal day 202 (with extremely low geomagnetic activty) show differences over 3 meters of L1, although mainly at low-latitudes in the Pacific.

Between IGS and MONITOR TOMION maps, the agreements was higher than the case of GPS, but doy 197 showed some maximum daily differences up to 2.5 meters of L1 in some grid points in North Africa, and low-latitude Atlantic Ocean (see **Figure 7**). Differences were calculated at 2-hours sampling coinciding with IGS maps data points to avoid time interpolation errors.

Differences between EGNOS and IGS were rather mild at mid-latitudes. The largest differences were found on doy 197 in the edge of coverage in North-West Africa with differences up to above 2 meters of L1. Differences were calculated at 2-hours sampling coinciding with IGS maps data points to avoid time interpolation errors.

In general, it is observed that largest model differences appear in areas with reduced number of GNSS stations (oceans, North Africa) and during the peak of the storm. And although, the selected storm is mild, some model differences of several meters are observed, raising the question of which dataset should be used as reference for comparison purposes or testing data.

In terms of ionospheric scintillation, activity on Lima (low latitude) and Sodankylä (high latitude) stations has been analysed for the selected period of interest. S4 and SigmaPhi scintillation indices as reported by the GSV4004 Scintillation Monitor are presented for both stations in . Samples below 15° elevation are not considered, furthermore samples possibly contaminated by multipath are also removed through the analysis of the Code-Carrier Divergence RMS, as calculated by the receiver. It is observed that no scintillation activity was observed during the peak of the moderate storm (doy 197) in any of the stations. In general the activity in Sodankylä seems to be close to none. Some activity is observed in Lima, in most cases after sunset local time, except for days 198 and 200 where scintillation indices are high during daytime

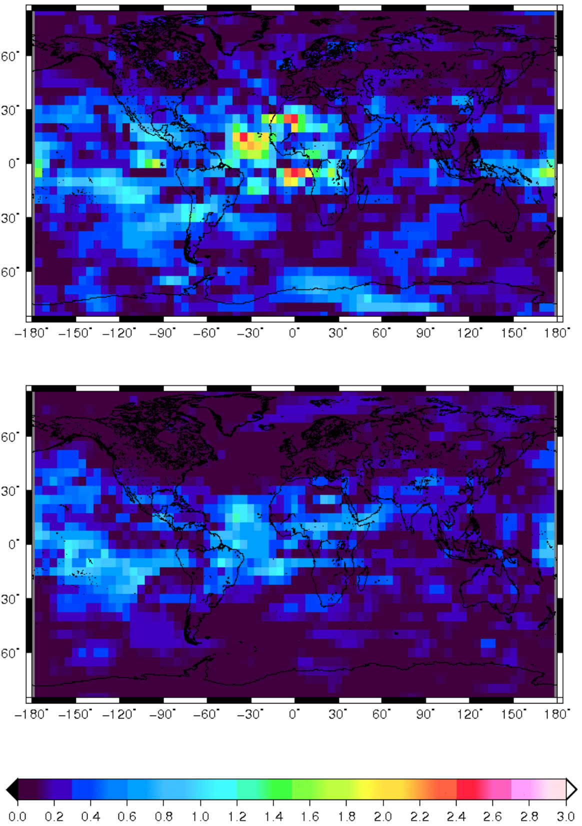

Figure 7. Maximum absolute daily VTEC differences in meters of L1 between MONITOR TOMION Ultra-rapid maps and IGS final GIMs for (top) doy 197 -moderate storm- and (bottom) 201 - nominal day of 2012

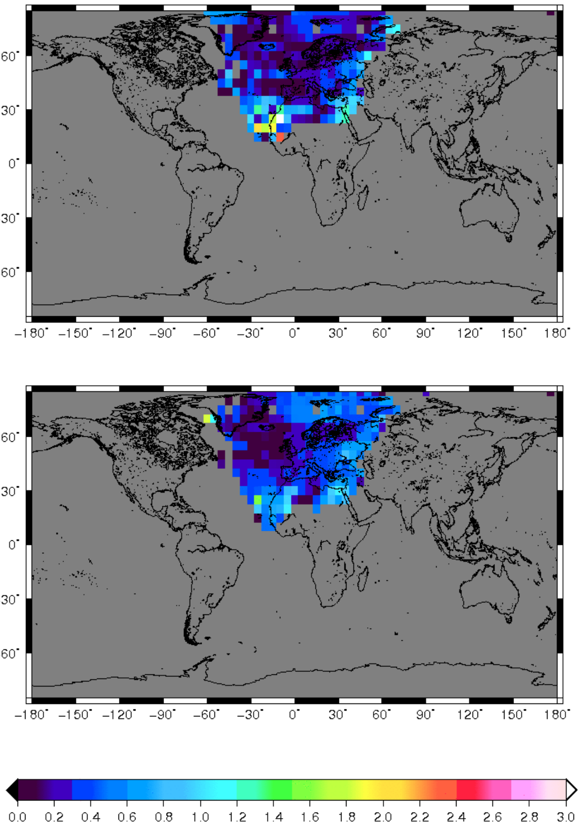

Figure 8. Maximum absolute daily VTEC differences in meters of L1 between EGNOS ionospheric correction and IGS final GIMs for (top) doy 197 -moderate storm- and (bottom) 201 - nominal day of 2012

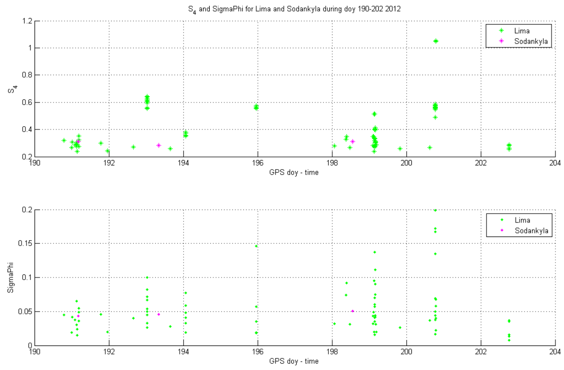

Figure 9. Scintillation activity (S4 and SigmaPhi indices) for Lima and Sodankylä stations for doy 190 to 202, 2012

VIII SUMMARY

The Monitor project offers enhanced capabilities as regards ionosphere variability and its consequences on GNSS systems. A new software receiver has been developed. It is part of a global world base network including several kinds of receivers which were deployed for the project. Software tools were developed concurrently. They complement heritage software products developed by several European expert teams. The overall system allows to address up to a large extent the problems related to ionosphere gradients and more generally to the Space weather for the GNSS systems.

The measurement campaign will last until beginning of 2014 covering consequently the peak of the solar cycle. MONITOR is a near-real time system. It is an scalable system. The network can be extended to include additional stations for different kinds of receivers and additional processors. In both cases protocols were defined to facilitate these tasks.

The high frequency sampling receivers deployed allow to record the signal transmitted by the GPS, GLONASS and Galileo constellations. In addition, a dual frequency software receiver with remotely control capability was developed. This will allow getting the signal frequency correlation properties, of interest for mitigation techniques using frequency diversity.

The space weather extreme events problem, associated to high values of the scintillation indices has been addressed. On such an occurrence, the data will continue to be recorded at levels beyond the phase loop tracking capability. Subsequent analysis will allow getting precise information on the signal characteristics and will help defining more robust algorithms.

GNSS offers again an autonomous, precise and cheap way of monitoring Space Weather, in this case by providing indirect measurements of Solar EUV flux at high rate, and reliable warnings for mid and strong solar flares, this last point demonstrated at mid time resolution in MONITOR.

Early results related to VTEC models and scintillations at low and high-latitudes during mild and moderate geomagnetic activity in July 2012.

VIII DISCLAIMER

The work reported in this paper has been supported under a contract of the European Space Agency in the frame of the European GNSS Evolutions Programme. The views presented in the paper represent solely the opinion of the authors and should be considered as R&D results not necessarily impacting the present EGNOS and Galileo system design.

REFERENCES

[1] Prieto Cerdeira R., Y. Béniguel, "The MONITOR project: architecture, data and products", *Ionospheric Effects Symposium*, Alexandria VA, May 2011

[2] Béniguel Y., P. Hamel, “A Global Ionosphere Scintillation Propagation Model for Equatorial Regions”, *Journal of Space Weather Space Climate*, 1, (2011), doi: 10.1051/swsc/2011004

[3] Béniguel Y., J-P Adam, N. Jakowski, T. Noack, V. Wilken, J-J Valette, M. Cueto, A. Bourdillon, P. Lassudrie-Duchesne, B. Arbesser-Rastburg, Analysis of scintillation recorded during the PRIS measurement campaign, *Radio Sci*., Vol 44, (2009), doi:10.1029/2008RS004090.

[4] Prieto-Cerdeira R. and R. Orus, “Testing ionospheric scintillation monitors based on GNSS using Spirent constellation simulator”, *Ionospheric Effects Symposium*, Alexandria, May 2011

[5] Prieto-Cerdeira, R; S. Binda, I Hidalgo, D. Rodriguez, V. Borrel, J. Giraud, “Ionospheric Propagation Activities during GIOVE Mission Experimentation”, *Proc. 4th European Conference on Antennas and Propagation (EuCAP 2010)*, Barcelona, Spain, 12-16 April 2010.

[6] Hernández-Pajares, M., A. Garcia-Rigo, J.Miguel Juan, J. Sanz, E. Monte, and A. Aragon-Angel (2012): GNSS measurement of EUV photons flux rate during strong and mid solar flares, Space Weather, doi:10.1029/2012SW000826, in press http://www.agu.org/journals/pip/sw/2012SW000826-pip.pdf).