In depth characterization of EGNOS ground stations response to space weather disturbances

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BIOGRAPHIES

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Claudia Paparini holds a Master degree (2009) in Astrophysics and Space Physics and a PhD (2013) in Civil and Environmental Engineering. After her PhD, she started working at the International Center for Theoretical Physics (ICTP-UNESCO) in Trieste where she has been involved in TREGA (Training on EGNOS-GNSS in Africa) project, on the assessment of GNSS-SBAS performance in Sub-Saharan Africa and on the evaluation of related space weather effects. In September 2016 she started working at ESSP as Performance Expert.

Ulrich Ngayap holds in 2012 a BSc in aeronautical and aerospace engineering in the polytechnic of Turin (Italy), before graduating in 2014 with a MSc in GNSS co-organized by ENAC/ISAE in Toulouse France.
In December 2014, Ulrich Ngayap joined ABBIA GNSS Technologies as Research and Development Engineer working in tools for performance evaluation of EGNOS Currently, he is involved as consultant in the EGNOS System Performance Team in ESSP.

Bernard Duparc is performance engineer at ESSP; he is in charge of the navigation data collection, post processing and analysis. During his career he was involved in several projects related to space, aeronautics and telecommunications.

ABSTRACT

GNSS/SBAS systems are subject to different kind of signal degradations including multipath, jamming and ionosphere disturbances. [1] The latter has a non-negligible impact on GNSS systems and users especially at high and low latitudes even if during severe space weather incidents also mid-latitudes may experience a substantial impact on performance. One of the main facts associated to space weather events is their dependency on multiple uncorrelated facts such as solar sunspots, magnetic field, time of day and geographical location. This property makes the process very difficult to grasp and to predict through reliable mathematical models [2] [3] [9].
Analysis based on the processing of GNSS raw measurements issued by multiple ground stations has been considered in the present paper to provide some insight on the characterization of the ionosphere process and the way it impacts measurements. A focus on the northern scintillation has been considered due to its higher relevance to EGNOS.

In this context, EGNOS RIMS (Ranging and Integrity Monitoring Station) archived data combined with broadcast SiS (Signal in Space) during two years period (2014 and 2015) have been deeply analyzed and processed. Selected time period combined both quiet and disturbed ionosphere episodes. Relevant ionosphere indicators such as the TEC (Total Electron Content) and AATR (Along Arc Tec Rate) have been computed. These parameters are based on TEC evaluation through the TEC Calibration Techniques developed by ICTP/ ICT4D laboratory [4].

After a brief introduction of the system, this paper will illustrate and analyze how EGNOS ground stations are affected by northern space weather events [5]. Furthermore the impact on Signal in Space performance in terms of Satellite and Ionosphere monitoring performance is evaluated. The subsequent section tackles the characterization of L2 losses from a statistical perspective and for different ground stations.

The second part of the paper is dedicated to the characterization of the ionosphere disturbance through the analysis of the AATR [6] [7] correlation function. Short and long terms correlations has been analyzed for different stations in order to provide a better understanding of how ionosphere disturbance propagate with time. Inter-station AATR cross-correlation has been also computed to assess and investigate the level of correlation between different stations giving some insight on spatial propagation.

1 INTRODUCTION

An increase of the solar activity is observed since 2010 as part of Solar Cycle #24. This affects the ionosphere behavior and impacts in particular on SBAS performance. This work presents the impact of strong ionospheric conditions on EGNOS with illustrations based on recent observations.
Different types of degradations are observed depending on the different considered regions While the southern reference stations are affected more by the high solar flux that occurs at and near the equatorial crest level, the northern station are subject to geomagnetic fields perturbations that are typical for polar regions [8]. In contrast with high TEC episodes where high temporal and spatial TEC gradients impact is mainly limited to the south of the ECAC region, scintillations effects concern both the North and the South. Nevertheless, it has been observed that the nature of the effect may be different with regard to the concerned location. In other terms the observed impacts of these scintillations are not exactly the same for all stations. Figure 1 provides an example of EGNOS performance degradation in relation with disturbed space weather condition. The displayed result corresponds to the disturbance experienced on March the 17th 2015.

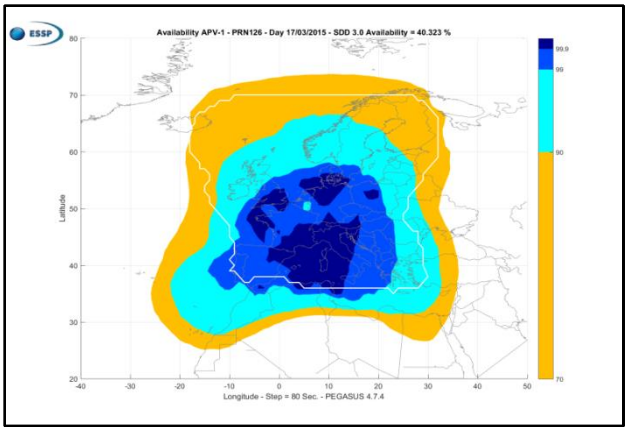


Figure 1 : PRN126 APV-1 availability on March 17 2015 (Saint Patrick storm)

Ionospheric scintillations occur mainly near the magnetic equator and at high latitudes. They have a solar cycle dependence reaching their maximum amplitude during the 11 year solar cycle maximum, and a seasonal dependence depending on the longitude and latitude. Nevertheless, based on our observations, such phenomena, especially in the north of ECAC, may occur any time regardless the phase of the solar cycle. Ionospheric scintillations at low latitudes (generally designated by equatorial scintillation) occur mainly after the sunset, their main impact on GNSS signals concerns amplitude variations whereas. At higher latitudes (auroral scintillation) signal amplitude variations are much less observed giving place to high phase scintillation.

In this paper, a focus is made on auroral scintillations as they are the most relevant to EGNOS.
Provided results are mainly based on stations signal quality and validity as well as specific ionosphere indicator such as AATR indices [2]. The AATR parameter is provided by the following equation:

$$AATR = \sqrt{\frac{1}{N}\sum AATRi^2}$$

Where $AATR_i$ corresponds to the differential Slant-Tec divided by a mapping function:

$$AATRi = \frac{\Delta STEC}{(M(\varepsilon))^2 \Delta t}$$

The location of considered RIMS stations used during the analysis is provided in Figure 2. Concerned data collection period, we have considered space weather event observed during 2014 ad 2015 years as they correspond to the disturbed years as part of solar cycle #24. Event experienced on February 2014 and March 2015 were particularly analyzed.

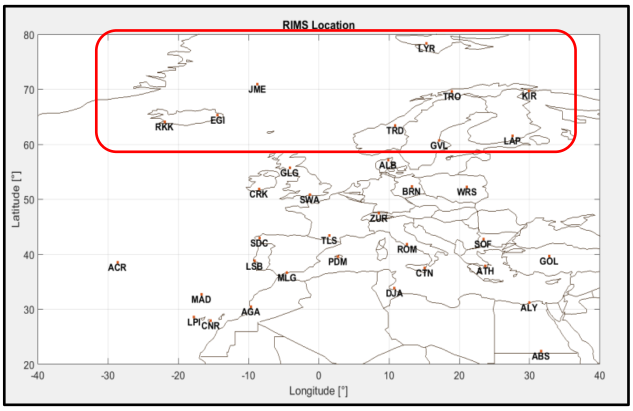


Figure 2 : List of Analyzed RIMS stations

2 GROUND STATION MEASUREMENTS AND PERFORMANCE ANALYSIS

2.1 Ground station response to space weather events

Northern latitudes stations reception quality is mainly affected during high geomagnetic activity. RIMS receiver suffers from relatively high L2 signal loss rate. This behavior was already discussed in previous works and shown to be mainly linked to high signal phase variation and narrow receiver tracking loop bandwidth for the L2 signal [1][3]. Receiver tracking algorithm implementation was also identified as a major driver of the L2 tracking capabilities during ionosphere disturbances.

Figure 3 illustrates the relationship between geomagnetic activity measured by the AATR indicator and the probability of L2 signal loss on Tromsoe RIMS during the severe weather event that has been experienced on mid-March 2015. We note here that the probability of L2 Loss if obtained by the following equation:

$$P_{L2Loss} = \frac{Number\ L1\ valid - Number\ L2\ valid}{Number\ L1\ valid}$$

Where $Number\ Li\ valid$ correspond to the number of valid LoS for frequency Li.

Tromsoe ground station exhibits quite high L2 loss rate average under severe conditions and high L2 loss rate is observed.

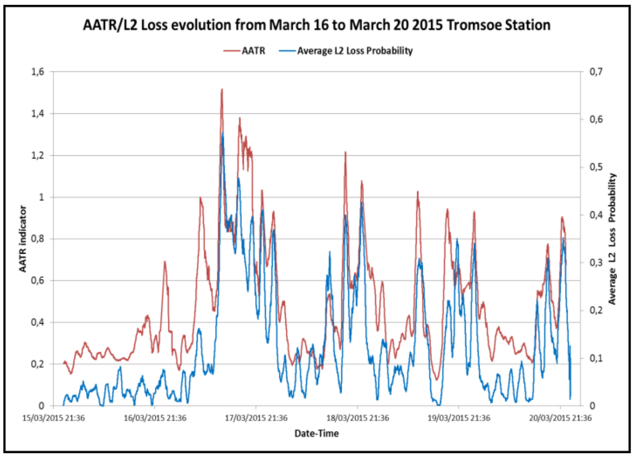


Figure 3: AATR/L2 Loss probability evolution from March 16 to March 20 2015- Tromsoe Station

A long term analysis has been achieved and the evolution of the L2 Loss rate and the AATR value has been computed over three months period (from February to April 2014) for some RIMS stations with all lines of sight considered. Results for LYR and TRO are depicted by Figure 4 showing the probability of L2 Loss and a function of the AATR. While the trend is obvious, it could be observed that the risk of L2 loss could not be provided with very high confidence based on the AATR only. This is an expected behavior as other aspects such as satellite elevation and azimuth could also be important factors that impact the L2 loss probability.

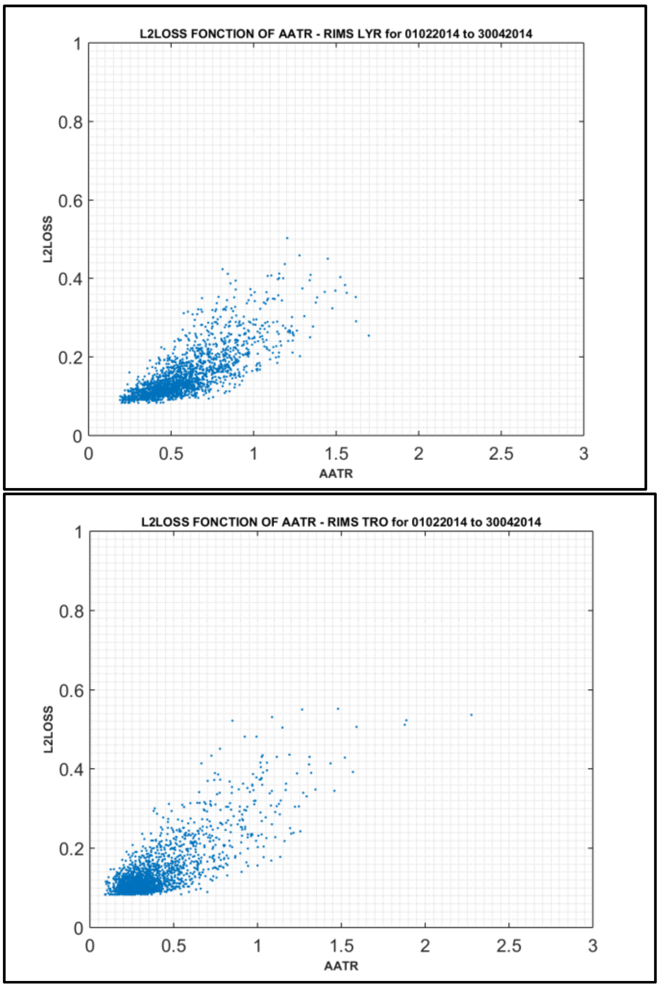


Figure 4: L2 Loss evolution as function of the AATR, February to April 2014, Longyearbyen (top) and Tromsoe (bottom) stations

2.2 Ground station L2 Loss profile

The present sub-section aims at the analysis of RIMS L2 loss profile during space weather disturbances. In order to define a methodology to characterize this profile, two indicators have been considered. The first one is the duration of a L2 loss event, while the second one is the time between two consecutive L2 loss events.

Figure 5 displays the distribution of the time taken for considered RIMS to track L2 signal following its loss. The four considered stations show quite similar distribution. As observed, the major part of signal recovery happens few seconds after its loss. Nevertheless, other peaks could be identified, at approximately at 75s and 150s. The full justification of these peaks is not identified at this stage of the analysis, but we expect them to reflect receiver design and architecture rather than the ionosphere process itself.

When it comes to the time between two consecutive L2 losses the shape of the distribution is quite similar. Nevertheless the peak (at around 80s) is much less pronounced.

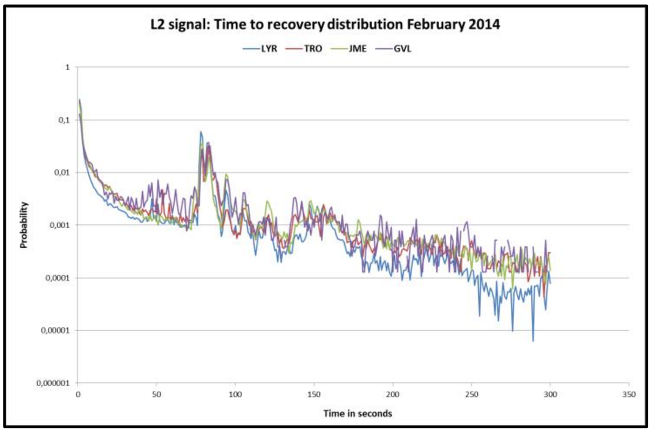


Figure 5: L2 signal Time to recovery distribution, February 2014

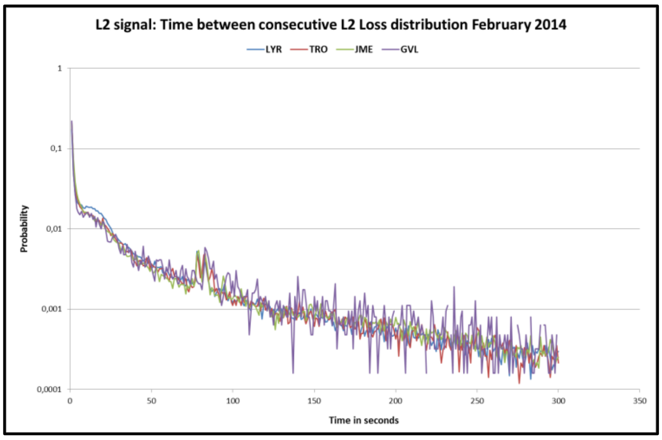


Figure 6:L2 signal: Time between consecutive losses distribution, February 2014

2.3 Impact on final system performance

The loss of L2 signals at RIMS level prevents the navigation algorithms from computing the ionosphere delay for concerned lines of sight. In the situation where a group of neighboring RIMS are concerned (typically northern RIMS in our case), the ionosphere monitoring will suffers from the lack of valid ionosphere observable preventing a nominal monitoring of multiple IGP whose see their GIVEi set to high values. In the extreme case these IGP could be set to Not Monitored. Regarding satellite monitoring performance only a slight impact is experienced. Actually, only satellites whose monitoring is exclusively based on northern RIMS measurements are impacted during Space Weather events. Figure 7 gives an illustration of the evolution of APV-1 coverage over the north of ECAC during severe geomagnetic storm. The tight link between AATR, IGP monitoring performance and the service coverage is straightforward.

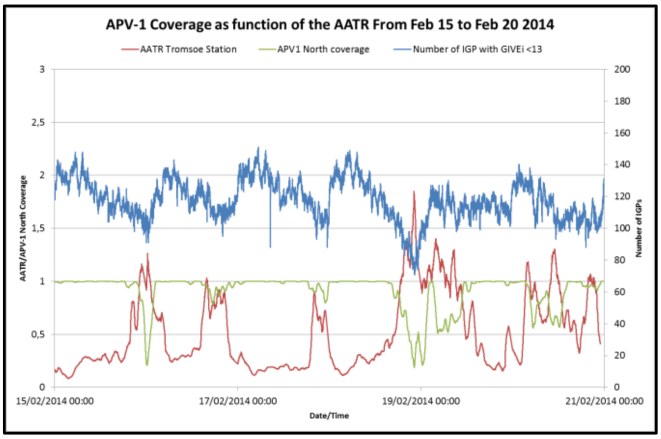


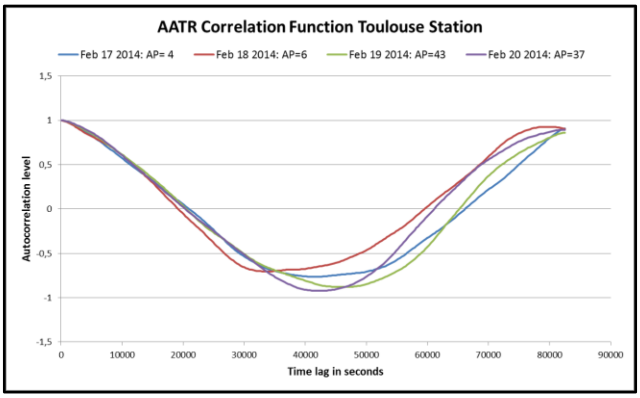
Figure 7: APV-1 Coverage over the North of ECAC From Feb. 15 to Feb. 20 2014

3 IONOSPHERE CORRELATION ANALYSIS

3.1 Short and long term correlation

This subsection tackles the evolution of the AATR correlation function over 24 hours for some specific stations. The goal is to identify the way the ionosphere activity changes with time. The outcome of the analysis is of interest as it indicates whether it could be envisioned to elaborate a reliable ionosphere prediction technique. To achieve this, the correlation function of the AATR indicator has been computed for each day of 2014 and for four stations (TLS, GVL, TRO and LYR).

As expected, the results show high discrepancy in that the shape of the correlation depends on the ionosphere disturbance level and on the site location. Figure 8 depicts the AATR autocorrelation for Toulouse and Tromsoe site for four days (February 17 to February 20 2014). We note that Ap indicator reported in the following graphs suggested that the 19th and the 20th of February were particularly affected by a geomagnetic storm over the north of ECAC. Provided results show quite consistent results for Toulouse site suggesting that the ionosphere process was driven by the same laws (actually sun exposure, i.e. daily ionosphere normal behavior) and was not affected by the same geomagnetic/ionospheric process (disturbance/irregularity) that was affecting the northern part of ECAC area. Considering the case of Tromsoe day by day, the patterns are drastically different in terms of AATR correlation function. This latter suggests that the involved processes are, as expected, quite complex and not easily predictable.



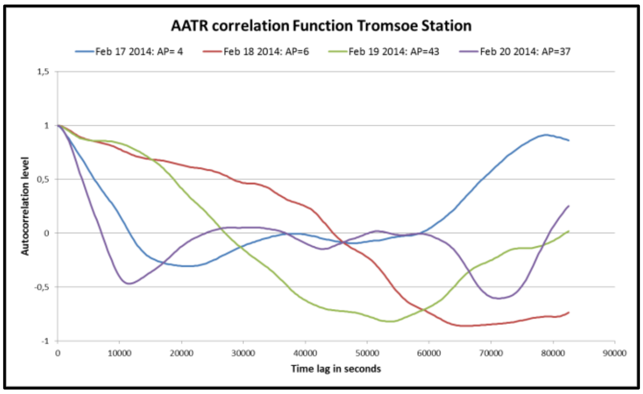


Figure 8: AATR correlation function (24hours) for Toulouse (top) and Tromsoe (bottom) stations on Feb. 17, 18, 19 and 20 2014

The above results were confirmed when computing the average daily autocorrelation function for each station based on entire year 2014. For a given station the 24hour Normalized AATR correlation R_N is computed by the following:

$$R(k) = \frac{1}{N}\sum_{n=1}^{N} AATR(n)\,.\,AATR(n+k)$$

$$R_N(k) = \frac{R(k)}{max\ (R)}$$

Where:

AATR function is computed each 30 seconds and N reflects the number of AATR samples over 24h =2880 samples. We note here that AATR values for two days are used to produce the daily auto-correlation.

Results depicted in Figure 9 to Figure 12 show that the correlation dispersion (given by the gap between 95% and 5% percentiles) increases with the station latitude indicating that in average the overall process is more versatile for these locations. The graph also shows that the average correlation level decreases more quickly for higher latitudes suggesting higher unpredictable ionosphere variation. It is also seen that high latitudes stations show a flats correlation function for most of the part of the day, this fact does not necessarily means low systematic correlation level (for one given day) but rather linked to the random (near-zero mean) nature of the daily correlation shape.

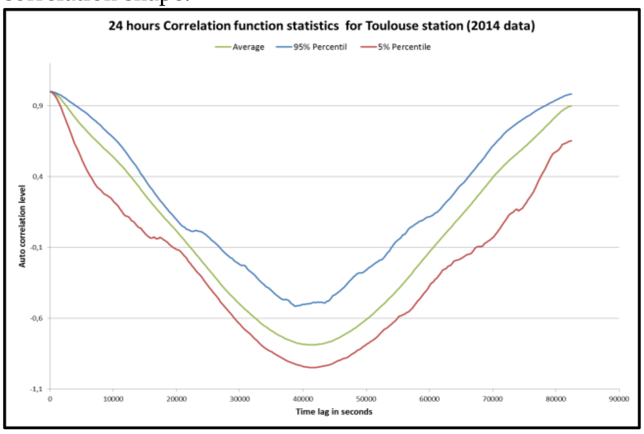


Figure 9: 24 hours AATR correlation function statistics- Full 2014 data-TLS station

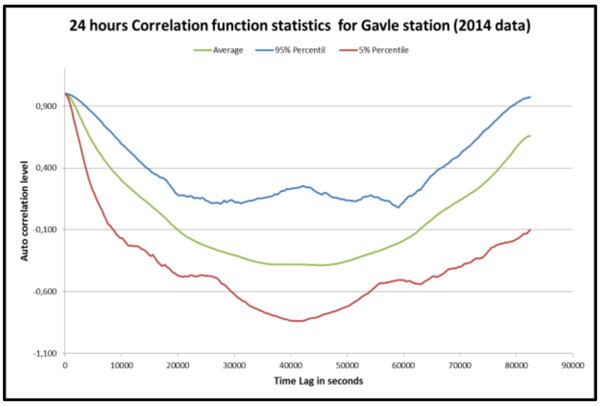


Figure 10: 24 hours AATR correlation function statistics- Full 2014 data-Gavle station

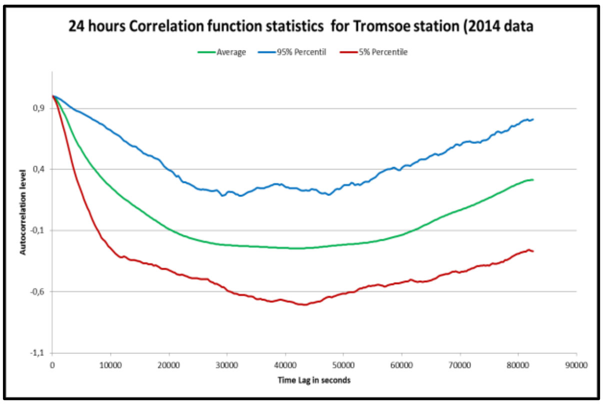


Figure 11: 24 hours AATR correlation function statistics- Full 2014 data- Tromso station

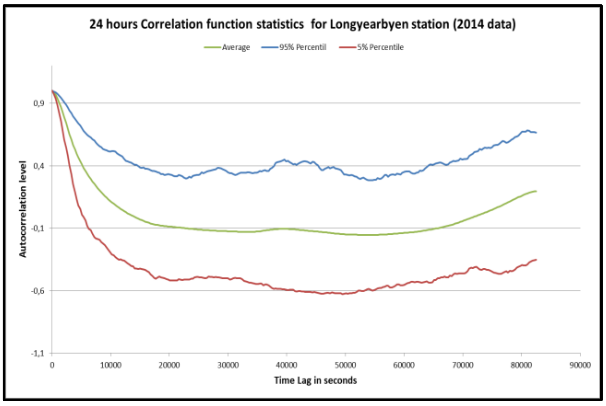


Figure 12: 24 hours AATR correlation function statistics- Full 2014 data- Longyerabyen station

Based on the obtained results, the time period from which the correlation level remains higher than 0.8 (and also higher than 0.5) with 95% confidence has been estimated. Results for each station are provided in the table below and show that the estimated time is shorter when the latitude is higher.

Station	Correlation above 0.8	Correlation above 0.5
Toulouse	41 minutes	1 hours and 25 minutes
Gavle	26 minutes	50 minutes
Tromsoe	26 minutes	50 minutes
Longyearbyen	21 minutes	41 minutes

For example, these results indicate that for Tromsoe location we could assume (with 95% reliability) that the ionosphere will change slowly for the next 26 minutes and could show some moderate variation in the next 50 minutes. These values are of 41 minutes and 1h25 minutes (respectively) for Toulouse location. One potential application of the fact that ionosphere shows greater time variability is to envision different update rates of ionosphere augmentation data. More precisely, high latitudes IGPs (Ionosphere Grid Point) may see their update rate quicker than mid latitudes IGPs. A Potential benefit of this approach is higher bandwidth efficiency and more accurate ionosphere corrections. This latter means better accuracy at the user level.

The main conclusion of the above analysis is that for mid latitude location, the ionosphere correlation does not show a significant day to day variation. This latter suggests that the process behind ionosphere variation is mainly linked to normal daily behavior of the ionosphere. On the other side the picture changes dramatically for high latitude (65°N and above). Actually, for these locations, large day to day variation was observed indicating that the experienced disturbances are driven by multiple factors and contributors interacting with a complex and not easily predictable way. Nevertheless, it has been also shown that with quite high reliability (95%) it is possible to have an idea on the short terms ionosphere disturbance level for a short period of time (some tenth of minutes depending on the location).

3.2 Inter-Station cross-correlation

In this section, the level of AATR cross correlation between different station has been investigated. The obtained values measure the similarity of ionosphere activities experienced by the two different stations at the same time. It obtained by computing the average over one month (February 2014) of the daily AATR cross correlation function.

A list of 10 ground stations has been considered and their mutual cross correlation has been computed. Obtained results are provided by **Figure** 13 where stations are organized based on their latitudes.

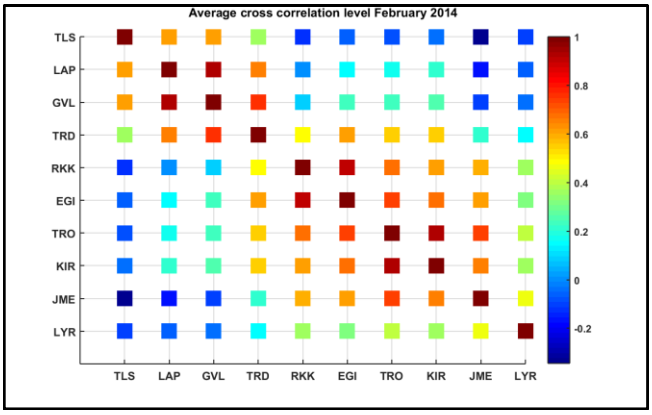


Figure 13: Average RIMS Cross-correlation level on February 2014

The main conclusion that could be derived from the above graph is that latitude (and not the distance between the ground stations) is the most relevant factor regarding the cross correlation level. For example, TRO and JME stations show high inter-correlation then EGI and JME despite the fact that EGI is closer to JME than TRO (700Km against 1000Km). In the case of GVL we observe that its ionosphere behavior is more correlated (in average) with Toulouse ionosphere than with Tromsoe one. The case of LYR station is quite particular in that this station shows very low cross correlation with other ground stations. This means that, from IGP monitoring perspective, stations is these latitudes bring an important innovation in terms of ionosphere behavior.

4 CONCLUSION

In this paper it is shown how EGNOS ground stations can be affected by space weather events, in particular by northern ionospheric/geomagnetic irregularities. These aspects have been seen in terms of Signal in Space analysis for Satellite and Ionosphere monitoring performance evaluation.

Two different elements have been considered for the analysis: on one side the characterization of L2 loss from a statistical perspective and for different ground stations and on the other side the characterization of the ionosphere disturbance through the analysis of the AATR correlation function.

The main preliminary conclusions can be listed in these points:

1. High latitude ground stations exhibits moderate to high L2 loss rate average under severe space weather conditions.

2. Considering a long term analysis (three months), the correlation between L2 loss and high values of AATR is evident although it is observed that the risk of L2 loss could not be provided with very high confidence based on the AATR only as other factors (such as C/N0) have an non-negligible impact on the L2 tracking loss.

3. A methodology to characterize the RIMS L2 loss profile during space weather disturbances has been discussed. Two parameters were used to describe this aspect. The first one is the duration of a single event L2 loss and the second one is the time between two consecutive L2 loss events. While the major part signal recovery happens few seconds after its loss; two local peaks (at 80 s and 160s) have been identified.

4. Considering the evolution of the AATR correlation function over 24 hours for some specific stations, the main conclusion of the analysis is that for mid latitude locations, the ionosphere correlation does not exhibit a significant day to day variation, as expected.

Meanwhile considering the case northern RIMS the patterns show a great variation reflecting the complexity of geomagnetic and ionospheric processes. Obtained results were of interest as they provide a preliminary prediction on short terms level (some tenth of minutes depending on the location) of the ionosphere behavior and disturbance.

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