DEFINITION OF AN SBAS IONOSPHERIC ACTIVITY INDICATOR AND ITS ASSESSMENT OVER EUROPE AND AFRICA DURING THE LAST SOLAR CYCLE

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Summary. In this work, an ionospheric activity indicator is defined based in the “weighted” Along Arc TEC rate (AATR). It is shown that this indicator, which can be easily computed from the GPS carrier phases, is well correlated with the ionospheric activity and, unlike other global indicators linked to the geomagnetic activity, can be sensitive to regional behaviours of ionospheric activity.

1 INTRODUCTION

The ionosphere is a highly variable and hardly predictable environment. Phenomena of different geographical and temporal characteristics may affect the performances of ionospheric monitoring methods based on real time GPS measurement data. Specifically, this is a problem to generate case scenarios for validating ionospheric models for SBAS systems (like EGNOS). Indeed, given that the performance thresholds for availability and integrity must be guaranteed, these scenarios shall be representative of both quiet and disturbed ionospheric conditions over sufficiently long periods.

Some attempts have been done to relate ionospheric worst case scenarios with planetary geomagnetic indices, but as it is shown in this study, the correlation between these indices and the ionospheric activity is not valid in all situations, in particular when considering regional disturbances.

In this work we define a new ionospheric activity indicator which is able to detect regional ionospheric disturbances. This indicator has been assessed over Europe and Africa during the last Solar Cycle, with the target of defining challenging test scenarios for EGNOS. A summary of the obtained results is presented here.

2 AATR INDICATOR DEFINITION AND ASSSESSMENT

We define the *Along-Arc TEC Rate (AATR) indicator* as the hourly Root Mean Square (RMS) of “weighted” Along-Arc TEC Rate given by:

$$AATR = \frac{\mathrm{VTR}}{\mathrm{M}(\varepsilon)} = \frac{\Delta STEC}{(\mathrm{M}(\varepsilon))^2\,\Delta t} \qquad (1)$$

where VTR is Vertical TEC Rate, STEC is Slant Total Electron Content, t is time, and $\mathrm{M}(\varepsilon)$ is mapping function with respect to elevation ε, AATR measured in cm/s of LI (L_1-L_2). Initially, this indicator has been assessed over different European receivers and/or sub-networks along a period of time which include the Halloween Storm (2003 from DoY 302 to DoY 304). During these days we have built a very precise ionospheric model (with accuracies better than 1 TECU in nominal conditions). As it was expected, the modelling of the GPS ionospheric delays during the disturbed days was clearly worse than during the quiet days. In this sense, the post-fit residuals (i.e. actual GPS delays minus modelled GPS delays) provided a measure of the ionospheric activity. Then, the assessment of the AATR indicator was done by comparing the hourly RMS of the iono-model post-fit residuals with the AATR.

Examples of such comparisons are depicted in Figure 1, for a sub-network in the North of Europe (POTS, left plot) and a sub-network in the South of Europe (LLIV, right plot). It is shown the good correlation between the RMS of the ionospheric model post-fit residuals and the RMS of the AATR. This good correlation occurs not only during disturbed periods but also during the daily variation of the RMSs (larger at noon). Finally, notice the different figures of RMS values found in the North and in the South of Europe, which confirms the need of using regional indicators instead of global indicators as the Solar Flux or DST.

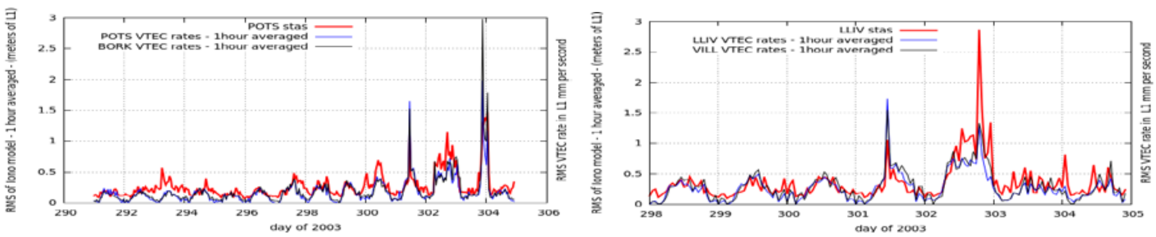

Figure 1: Comparison of the post-fit residuals RMS of an ionospheric model (red) and the RMS of AATR (blue and black) for two selected receivers. Left plot is for POTS sub-network (receivers POTS and BORK with 445km of baseline). Right plot is for LLIV sub-network (receivers LLIV and VILL with 544km of baseline).

3 MAIN RESULTS OF AATR EVOLUTION OVER THE LAST SOLAR CYCLE

In order to select worst case ionospheric scenarios, the evolution of the AATR indicator has been analyzed along the last Solar Cycle (i.e. 2000-2012) over European and African stations.

Results show that the main events occur before 2006. For the Northern receivers (up to 60 deg of Latitude) these events are related with geomagnetic superstorms (large values of Ap or

DST). However, for South European receivers, the influence of the geomagnetic activity in the ionosphere decrease with the latitude, being the main factor correlated to the Solar Flux at 10.7cm.

Finally, for low latitude receivers in Africa, the most important source of ionospheric activity, in nominal conditions, is correlated with Solar Flux. But the largest values of AATR occur after the Solar Terminator. As it is known, during such hours (lasting 1/3 of the day) events such as bubbles, depletions... are experienced in these regions, often related with ionospheric scintillation. Outside this period, observed values are comparable to those of the European region.

Some authors suggest that the ionospheric activity has a correlation with the DST index. But, as we commented before this is only partially true for the Northern receivers In order to analyse this dependence we compare in Figure 2, left plot, the daily maximum values of the AATR RMS with the DST geomagnetic index. From this plot it is clear that there is a threshold around 0.13 LI cm/s for the AATR RMS (all of them correspond to Northern receivers), having in all the cases DST indices below -100nT. Over this threshold, the largest AATR RMS values correspond to large negative values of DST. But the contrary is not true, i.e. large negative values of DST do not implies large values for the ionospheric activity indicator as it is shown in the plot at right of Figure 2, associated to the days in 2004 313-315. As it can be seen, during these days the DST was close to -400nT, but this was not translated to an unusual increase of the ionospheric model post-fits over Europe (the maximum value is 0.5 LI m, clearly smaller than in figure 1), which agrees with the low AATR values (which, for this receiver, is below than 0.05 LI cm/s).

Eleven cases with AATR RMS above a value of 0.13 LI cm/s have been found over the whole solar cycle, which are depicted in Figure 2, These cases are the same as identified in previous works by other authors.

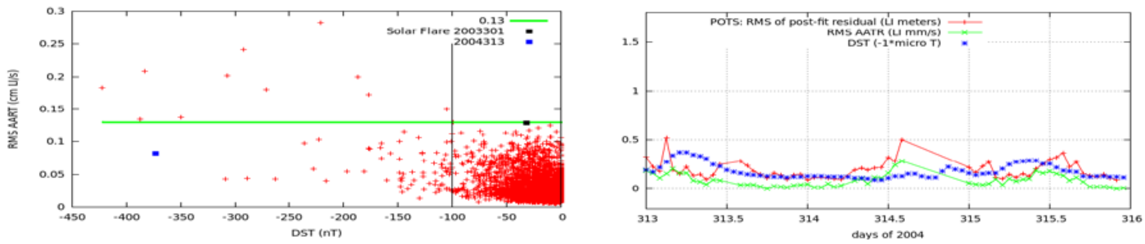

Figure 2. Left plot: Maximum daily values of DST, during a Solar Cycle, versus maximum daily values of AATR RMS for the eight European receivers (4 in the North and 4 in the South). Right plot: Relationship between the DST, AATR RMS and RMS of the ionospheric model post-fits for the receiver POST. This plot shows an example of large DST negative values (over 400 micro Teslas) not associated to large AATR RMS.

We have noticed that the AATR values for Southern receivers are related mainly with the Solar Flux index. In order to show this, we represent such relationship in Figure 3, separately for four South European receivers right hand plots, and four North European receivers, left hand plots. The results show a clear correlation between both magnitudes except for the days with large values of Ap index (or for large negative values of DST index, in blue). Thus:

- The large values of the AATR RMS in the Northern receivers are related with geomagnetic activity, but a large Ap value is not enough to produce a large value of AATR RMS: a high value of Solar Flux (>150) is also required, this could explain why the days 2004 DoYs 313-314 do not have values of AATR RMS above 0.13 LI cm/s: The Solar Fluxes are 124 and 127 respectively.

- For the Southern receivers, there is also a quite linear relationship between the Solar Flux and the AATR, where the slope of this relationship depends on the latitude of the stations and being larger for the south European stations. In this sense, receivers in the very low latitudes, such as Canary Islands or in Africa, can experience AATR RMS values during non-disturbed days similar to those of mid latitude or Northern receivers in the worse disturbed days (but these values are related with Solar Terminator events, as commented above).

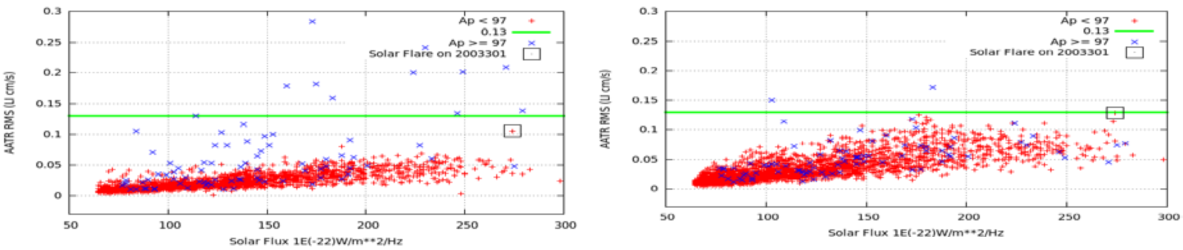

Figure 3. Relationship between the AATR RMS and the Solar Flux for two European networks of receivers. Left plot is for the North European receivers. Right plot is for the South European.

Finally, the daily APV1 EGNOS availability and Continuity Risk has been analyzed for a three years period, from 1 October 2009 to 30 September 2012. Global and regional performances have been assessed in order to identify anomalies related with the ionosphere and the EGNOS ionospheric modeling. The AATR RMS has been used as an indicator of the "expected goodness of ionospheric modeling" to identify the conditions where a worsening in the performance of the ionospheric models in general, and in EGNOS in particular, is expected. This AATR index has been assessed against the daily EGNOS performances showing a high linear correlation between both parameters.

Afterwards, and in order to assess its feasibility to predict user APV1 availability anomalies linked to the ionosphere, the AATR indicator has been computed for a set of stations around central Europe and the border of the coverage area on several selected days: the worst ten performance days for each station. This assessment has been based on a detailed analysis of the user availability and Continuity Risk maps together with the ionospheric EGNOS corrections map against the AATR index, using an experimental threshold of 0.04cm/s. Results show that high values of this index for a given station leads to worse performances in the surrounding area.