New indicator for definition of ionospheric operational conditions

J. Miguel Juan, Jaume Sanz, Manuel Hernández-Pajares, Roberto Prieto-Cerdeira, Stefan Schlüter
Introduction

The goal of the ICASES project is to build a set of ionospheric scenarios for EGNOS ionosphere assessment, based on real GPS measurements.

These scenarios are selected taking into account different thresholds for the ionospheric activity (for availability and integrity), defined from an ionospheric activity indicator (AATR values) along the last solar cycle.
Layout

• AATR Indicator Definition and Assessment
• Main results of AATR Evolution over the last Solar Cycle
• Relationship between EGNOS user performance and Iono Activity Indicator.
• Conclusions
Definition of an indicator of ionospheric activity

Along-Arc derivatives of the geometry-free combination measurements (L1-L2) are commonly used to detect ionosphere effects such as Scintillation, Solar-Flares, Ionospheric gradients, TIDs..., where different statistics are used in function of the phenomena to monitor.

In our case, we define the Along-Arc TEC Rate (AATR) indicator as the hourly Root Mean Square (RMS) of “weighted” Along-Arc Vertical TEC Rate.

\[
AATR = \frac{\Delta \text{STEC}}{(M(\epsilon))^2 \Delta t}
\]

Where \(\Delta t\) can be 30 or 60 seconds

Comments:

- The RMS of all the AATRs (all the satellites) during 1 hour is computed for a given receiver, in order to mitigate spurious values of AATR.
- With the squared mapping, we mitigate the effect worst VTEC computed at low elevation.

Note: These Along-Arc derivatives involve both spatial and temporal STEC variations.
Benefits:

In front of other ionospheric activity indicators (based on global geomagnetic activity as DST o Ap) the RMS of AATR has the following advantages:

- It is computed from the data of any 2-frequency receiver, so any station or any user can compute, nearly in real time, its own ionospheric activity indicator.

- Depending on the spatial correlation of the ionospheric perturbation, this indicator can account for local or regional perturbations.

- The indicator also accounts for the local time variation of the post-fit residuals RMS of the ionospheric model.

- It is also sensitive to ionospheric perturbations not linked to geomagnetic indices, such as Solar Flares.
Layout

• AATR Indicator Definition and Assessment
• Main results of AATR Evolution over the last Solar Cycle
• Relationship between EGNOS user performance and Iono Activity Indicator.
• Conclusions
Correlation coefficient between the RMS of the post-fit residuals of a ionospheric model and other indices: Local Time (LT), AATR, DST, Ap and Solar Flux (SF).

From the analysis of the ionospheric activity along an entire solar cycle at several geomagnetic latitudes:

<table>
<thead>
<tr>
<th>RECEIVER</th>
<th>LAT (Deg)</th>
<th>Correlation (x 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LT</td>
<td>AATR</td>
</tr>
<tr>
<td>REYK</td>
<td>64</td>
<td>18</td>
</tr>
<tr>
<td>ONSA</td>
<td>57</td>
<td>10</td>
</tr>
<tr>
<td>POTS</td>
<td>55</td>
<td>11</td>
</tr>
<tr>
<td>CAGL</td>
<td>37</td>
<td>26</td>
</tr>
<tr>
<td>MAS1</td>
<td>27</td>
<td>47</td>
</tr>
<tr>
<td>NKLG</td>
<td>0</td>
<td>52</td>
</tr>
</tbody>
</table>

The study includes six different receivers (see map) during some tens of days with high ionospheric activity (all days with DST<-100nT are included).
Results: Low-latitude receivers (e.g. NKLG or MAS1)

The large values of AATR are linked to after Solar Terminator events during high values of Solar Flux.

Thence, large values are experienced during equinoxes and close to solar maximum, lasting several hours after the Sunset.

This would explain the correlation found between the local time and the pos-fit residuals of the ionospheric model. The frequency of such events depends on the latitude: the lower latitude (e.g. NKLG) the larger frequency.
Results: Low-latitude receivers (e.g. NKLG or MAS1)

The large values of AATR are linked to after Solar Terminator events during high values of Solar Flux.

Thence, large values are experienced during equinoxes and close to solar maximum, lasting several hours after the Sunset.

Example of solar terminator events not linked with a geomagnetic storm. Note: here we plot the P2-P1 code.

Geomagnetic storms are not the main source of activity here, but can also affect these stations.
Medium-Low-latitude receivers (e.g. CALG)

This is a more stable region, being the ionospheric activity mainly linked to the Solar-Flux. In general, there is no scintillation and the storms have moderated effects.

Unlike in low latitude receivers, the maximum values occurs linked to the ionization (i.e. at noon), and the AATR show lower values.

Geomagnetic storm (Ap >97)
But, rarely, they can be affected by Solar Terminator events (like scintillation) in the same way than African receivers. This is the case for CAGL receiver during the day 2005 163 (DST=-105nT) where the AATR reaches the largest value, which is comparable to the African receiver RABT (RABAT) and quite different from the European receiver ZIMM.
Medium-High-latitude receivers (e.g. POTS, ONSA)

Ionospheric activity occurs also linked to the Solar Flux. But, unlike the previous cases, the largest ionospheric activity around these receivers is linked to the geomagnetic index.
Medium-High-latitude receivers (e.g. POTS, ONSA)

2001-328 was the day with the largest AATR. **TI Ds** with oscillations above 1-2m L1-L2 delay were experienced.

It is not enough a large value of -DST or Ap, also a large SF is needed for the largest AATR.

<table>
<thead>
<tr>
<th>Year</th>
<th>Day</th>
<th>AATR (LI cm/s)</th>
<th>DST (nT)</th>
<th>Ap</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>102</td>
<td>0.1</td>
<td>-236</td>
<td>154</td>
</tr>
<tr>
<td>2001</td>
<td>328</td>
<td>0.28</td>
<td>-200</td>
<td>154</td>
</tr>
</tbody>
</table>
High-latitude receivers (e.g. REYK)

The large AATR values are linked to the Solar Terminator events during high values of Solar Flux, and are directly affected by geomagnetic storms. But also scintillation can appear.

Large AATR values can appear, even with no so high values of DST or Ap. This region is more affected by magnetic activity.

Geomagnetic storm (Ap >97)
High-latitude receivers (e.g. REYK)

Large AATR values can appear, even with no so high values of DST or Ap.

AATR = 0.36 LI cm/s    DST ~ -50nT

Scintillation and other perturbations with a larger temporal scale variation

AATR = 0.43 LI cm/s    DST ~ -200nT

Precise IONO F-PPP (2x2 grid)

IGS GIM (IONEX)

True STEC
Layout

• AATR Indicator Definition and Assessment
• Main results of AATR Evolution over the last Solar Cycle
• Relationship between EGNOS user performance and Iono Activity Indicator.
• Conclusions
As commented before, the RMS AATR has been introduced as an indicator of the “expected goodness of ionospheric modelling”.

APV1 Availability and the Maximum hourly value of RMS(AATR) in 24h are compared for a receiver (MAS1) in Canarias islands.

A RMS(AATR) threshold of 0.043cm/s of L1-L2 delay can be defined. Over this value performance is clearly degraded.
Relationship between daily EGNOS APV1 availability (in red colour) and the daily maximum value of RMS of AATR (in blue colour). Left plot is for MAS1 receiver. Right plot is for FUNC receiver. The time where the EGNOS system was updated to V2.3.1P is indicated by a vertical purple line.

A RMS(AATR) threshold of 0.043 cm/s can be defined. Over this value performance is degraded.
Relationship between daily EGNOS APV1 availability (in red colour) and the daily maximum value of RMS of AATR (in blue colour). Left plot is for MAS1 receiver. Right plot is for FUNC receiver. The time where the EGNOS system was updated to V2.3.1P is indicated by a vertical purple line.

A RMS(AATR) threshold of 0.043cm/s can be defined. Over this value performance is degraded.
Relationship between daily EGNOS APV1 availability (in red colour) and the daily maximum value of RMS of AATR (in blue colour). Left plot is for MAS1 receiver. Right plot is for FUNC receiver. The time where the EGNOS system was updated to V2.3.1P is indicated by a vertical purple line.

A RMS(AATR) threshold of 0.043cm/s can be defined. Over this value performance is degraded.
RMS(AATR): Threshold 0.043cm/s (L1-L2delay)

Large AATR values in North stations (ONSA) South and South-East stations (MADR, CALG) degrade performance around central Europe.

SBAS-IONO Meeting 20, 12-13 July 2013, Bath, U.K.
RMS(AATR): Threshold 0.043 cm/s (L1-L2 delay)

North stations (ONSA) are not experiencing large AATR values. Only South and South-East stations (MADR, TLSE, CALGMATE) being the performance degraded in South and South-East Europe, but North is well covered.
Very low AATR values are found for all stations and a very good availability and Integrity Risk figures are found.

RMS(AATR): Threshold 0.043cm/s (L1-L2delay)
### EGNOS IONOSPHERIC CONDITIONS

### AVAILABILITY AND INTEGRITY THRESHOLDS

<table>
<thead>
<tr>
<th>Region</th>
<th>RMS AATR (L1 mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High (φ &gt; 61 Deg.)</td>
<td>2.32</td>
</tr>
<tr>
<td>Mid (32 &lt; φ &lt; 61 Deg.)</td>
<td>1.55</td>
</tr>
<tr>
<td>Low (φ &lt; 32 Deg.)</td>
<td>2.47</td>
</tr>
</tbody>
</table>

**Availability threshold**
( representative of ~99.7-th percentile of Solar Cycle 24)

<table>
<thead>
<tr>
<th>Region</th>
<th>RMS AATR (L1 mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High (φ &gt; 61 Deg.)</td>
<td>10.82</td>
</tr>
<tr>
<td>Mid (32 &lt; φ &lt; 61 Deg.)</td>
<td>7.73</td>
</tr>
<tr>
<td>Low (φ &lt; 32 Deg.)</td>
<td>10.82</td>
</tr>
</tbody>
</table>

**Integrity threshold**
( representative of 100-th percentile of Solar Cycle 24 + ~50% → Gaussian over-bounding, value @ 5.33sigma )

*LI= L1-L2*
Conclusions

A ionospheric activity indicator has been defined based in the AATR.
• The indicator can be easily computed from GPS data and, unlike other global indicators which are related with the geomagnetic activity, it is sensitive to the different ionospheric activity in different regions.

Using this indicator the following ionosphere behaviours have been found for different latitudes:
• Low latitude receivers (Africa): Ionosphere activity is mainly linked to the Solar terminator events during high values of solar flux.
• Medium Low-Latitude receivers (South or Europe): Ionosphere activity is mainly driven by the Solar Flux.
• Medium-High Latitude receivers (North of Europe): The highest values are linked to geomagnetic storms with DST<-100 nT.
• High latitude receivers (Lat>60º): Large values of ionospheric activity are linked to geomagnetic storms, but also to scintillation.

The feasibility of AATR index to predict user APV1 Availability anomalies linked to the ionosphere has been assessed:
• 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 0.043 cm/s of L1-L2 delay.
• Results show that high values of this index for a given station leads to worse performances in the surrounding area.

The RMS AATR has been chosen as the metric to characterise the ionospheric operational conditions in the frame of EGNOS actitivites (EGNOS Mission Requirements).
Backup slides
A new cycle-slip detector: Robust against to the ionospheric activity has been developed.

This detector is based on the ionospheric free combination of carrier phases and the Melbourne-Wübbena combination, thus it is not directly affected by the ionosphere.
Definition of an indicator of ionospheric activity

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

\[
AATR = \frac{\Delta STEC}{(M(\varepsilon))^2 \Delta t}
\]

Other ionospheric activity indicators and relationships:

\[
AASG = \frac{\Delta STEC}{\Delta s} = \frac{\Delta STEC}{v_{ipp} \Delta t} = \frac{1}{v_{ipp}} AASR
\]

\[
AATR = \frac{\Delta STEC}{(M(\varepsilon))^2 \Delta t} = \frac{1}{(M(\varepsilon))^2} AASR
\]

Note:

- **ROTI** is defined from \( \frac{\Delta STEC}{M(\varepsilon) \Delta t} \)

but, computing the standard-deviation over a few minutes window (i.e. targeting fast TEC variations, specially scintillation)

50 m/s < v_{ipp} < 500 m/s

1 ≤ (M(\varepsilon))^2 < 9
Performance of AATR RMS index:
Comparison with the RMS of post-fit residuals of a ionospheric model

There is a good correlation between the RMS of the post-fit residuals of ionospheric model and the AATR, even for receivers at several hundreds of km (POTS-BORK or LLIV-VILL).

Again, different values of RMS in the North and in the South of Europe are found, confirming the need of regional indicators instead of global indicators (like DST or Ap, as well).

AATR can also reflect regional dependences, which cannot be seen in the geomagnetic indices.
Worse ionospheric activity days
(from the middle of 2000 to the middle of 2012)

After assessing the AATR indicator, we have characterized the days with major ionospheric activity during more than 1 Solar Cycle. The results of such study are shown in the table:

<table>
<thead>
<tr>
<th>RECEIVER</th>
<th># Events</th>
<th>99th (cm/s)</th>
<th>99.9th (cm/s)</th>
<th>100th (cm/s)</th>
<th>L1-L2 delay</th>
<th>DoY</th>
</tr>
</thead>
<tbody>
<tr>
<td>REYK</td>
<td>106359</td>
<td>0,102</td>
<td>0,183</td>
<td>0,474</td>
<td></td>
<td>2003</td>
</tr>
<tr>
<td>ONSA</td>
<td>80819</td>
<td>0,038</td>
<td>0,062</td>
<td>0,282</td>
<td></td>
<td>2001</td>
</tr>
<tr>
<td>POTS</td>
<td>89830</td>
<td>0,039</td>
<td>0,051</td>
<td>0,148</td>
<td></td>
<td>2001</td>
</tr>
<tr>
<td>CAGL</td>
<td>100097</td>
<td>0,057</td>
<td>0,083</td>
<td>0,150</td>
<td></td>
<td>2005</td>
</tr>
<tr>
<td>MAS1</td>
<td>109427</td>
<td>0,095</td>
<td>0,156</td>
<td>0,422</td>
<td></td>
<td>2002</td>
</tr>
<tr>
<td>NKLG</td>
<td>78824</td>
<td>0,115</td>
<td>0,203</td>
<td>0,335</td>
<td></td>
<td>2001</td>
</tr>
</tbody>
</table>

Medium latitude receivers (POTS, CAGL) show AATR values significantly lower than the low or high latitude receivers.

From a deeper analysis of the results, the next classification follows:

- Storm days (DST <-100 nT)
- Here the largest values are not in stormy days (they are around equinoxes in Solar Max.)
Performance of AATR RMS index:
Comparison with the RMS of post-fit residuals of a ionospheric model

AATR is sensitive to several ionospheric features like diurnal variations (large values around noon), Solar Flares (e.g. DoY 301 at noon) both occurring under moderate values of geomagnetic indices.

SBAS-IONO Meeting 20, 12-13 July 2013, Bath, U.K.