Recent progress in characterizing multiscale ionospheric phenomena with GNSS and applications: 

*Solar Flare over-ionization & Medium Scale Travelling Ionospheric Disturbances*

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Outline

1. Ionospheric electron content and GNSS
2. Characterizing some of the underlying phenomenae: realistic assumptions on spatial distribution
3. Example 1: Solar Flare overionization
4. Example 2: Medium Scale Travelling Ionospheric Disturbances
5. Conclusions
1) Ionospheric electron content and GNSS
Ionospheric Electron Content & GNSS

- GNSS iono delay is prop. to Slant Total Electron Content (STEC) & inversely proportional to squared frequency.
- Dual-freq users can cancel out 99.9% of iono delay.
- Dual-freq permanent GNSS nets.: VTEC & Ne for improving single and multi-frequency GNSS precise navigation, Space Weather monitoring, Seismic-related signatures...
Ionospheric variability at large horizontal and vertical scales

Global Vertical Total Electron Content (VTEC) map computed from ~100 GPS dual-freq CORS (units: 0.1 TECU).

Electron density (Ne) profile computed from LEO GPS data (units: Te-/m**3).
Ionospheric variability at diff. time scales

**Scintillation**
- Observed ambiguous STEC for PRN01 (UPC, Barcelona, Spain)
- 0.1-10 seconds
  - STEC: 6-APRIL-2000
  - STEC: 7-APRIL-2000
  - \( d(\text{STEC})/dt + 9.0: 6-\text{APRIL}-2000 \)
  - \( d(\text{STEC})/dt + 4.5: 7-\text{APRIL}-2000 \)

**Solar Flare sudden overioniz.**
- 1-20 minutes

**Travelling Ionospheric Disturb.**
- PRN01 from USOC: Lon=138 deg, Lat=36 deg (LT=UT+9.22 hours)
- 1-90 minutes

**Solar-cycle, seasonal, solar rot.**
- Solar Flux and TEC at IGS GPS station JPLM (242,34) during the last 11 years
- 27-4000 days

Scintillation effect on STEC (TECU) vs. dSTEC/dt (meters/min in L1)

Solar flux and TEC 12LT (TECU) vs. TEC 00LT (TECU)

10.7-CM_Solar_Radio_Flux / 2 [10^-22 W/m^2/Hz]

UT (hours) vs. UT (years-1990)
3) Characterizing some of the underlying phenomenae by realistic assumptions on spatial distribution
3a) Solar Flares
Global and sudden STEC increase in the day hemisphere due to Solar X-flares

High and sudden STEC variations are experienced in the day hemisphere GPS receivers due to the arrival of the X-rays extra radiation due to Solar X-flares (example: event during 28 Oct. 2003, 11UT approx, preceding the previous mentioned superstorm).
Recent example: M-class Solar Flare during day 072, 2015 (preceeding St. Patrick’s geom. storm)

VTEC drift rate vs. Latitude

VTEC drift rate vs. Local Time

VTEC drift rate vs. Cosinus of Solar-zenith angle

The slope (GSFLAI) vs. time
Overionization model: First principles, GPS... and GSFLAI

Halloween X-class SF snapshot: the regression line slope (GSFLAI) reacts well.

\[ \dot{V} = a_1 \cos \chi + a_2 \]

During the next day major geomagnetic storm peak, the higher variations doesn’t follow the SF spatial pattern, and GSFLAI (=0) performs again well.
GSFLAI is a good proxy of direct EUV rate meas., also for M- and C-class Solar Flares.
The GSFLAI, a proxy of EUV flux rate for X, M & C-class S. Flares

- GSFLAI (point with fastest increase per flare, if above the GNSS measurement error) vs. EUV flux rate data (from SOHO-SEM in 26-34 nm range).

- From top to bottom: X, M and C class Solar Flares meeting the criteria since 2001 until 2014.

- Regression lines, with slopes 0.165, 0.157 and 0.159 for X, M & C-class => high consistency of the simple physical model & technique.

Singh et al. (2015), Estimation of Solar EUV flux rate during Strong, Mid and Weak Solar flares using GPS satellite data, in submission to JGR-Space Physics.

<table>
<thead>
<tr>
<th>Flares</th>
<th>Slope</th>
<th>Intercept</th>
<th>Corr. Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>Number</td>
<td>All Peaks</td>
<td>All Peaks</td>
</tr>
<tr>
<td>X</td>
<td>60</td>
<td>0.18</td>
<td>0.0022</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.155</td>
<td>0.0046</td>
</tr>
<tr>
<td>M</td>
<td>320</td>
<td>0.12</td>
<td>0.0012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.157</td>
<td>0.0012</td>
</tr>
<tr>
<td>C</td>
<td>300</td>
<td>0.11</td>
<td>0.0008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.159</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

\(a\) The units are \(\text{Tm/s}\) for GSFLAI and \(\text{photons.10}^{-9}/\text{cm}^2/\text{s}^2\) for EUV flux rate.
The Solar Flare location distance to the disc center (proximity to limb) matters....

After applying a simple extinction law from Solar disc distance, a relationship of GSFLAI with GOES X-ray based classification is disclosed, making feasible its usage as geophysical index (a potential proxy of GOES classification...).
Recent findings on Solar Flares by analyzing GSFLAI time series since 2001

- The solar flare time series have extreme properties regarding amplitude and time correlation.

- The fractional Brownian model proposed in
  

  accounts for the probability of the observed extremely high values of the time series, and also with the fact that the flares appear in bursts.

- Another practical consequence is that the statistical characterization done in this paper allows for the estimation of the probability of a given GNSS solar flare indicator value and also the length of a given burst of flares.

- The probability of observing a GNSS solar flare indicator threshold value 2 times greater than the maximum observed one in last solar cycle (Solar flare preceeding the Halloween geomagnetic storm), is once every 44 years approximately.
3b) Medium Scale Travelling Ionospheric Disturbances
MSTIDs

- Medium Scale Travelling Ionospheric Disturbances (MSTIDs) are ionospheric signatures of waves with some potential origins (Solar Terminator, Weather activity, Perkins inst.).
- Up to few TECUs of amplitude (1 TECU ~ 0.16 m L1).
- MSTIDs propagate equatorward in daytime (autumn & winter) and westward in night-time (spring & summer).
- Typical periods: 500-2000 sec, velocities: 50-400 m/s.
GNSS ionospheric interferometry scenario
Rationale of recent MSTID research

Lack of dense Local GNSS Networks

Ambiguity Resolution in GNSS Ionospheric Interferometry (ARGII)
MSTID vel. est., natural extension to dense networks with diameters $>\lambda_{\text{MSTID}}/2 \approx 50\text{km}$ (comput. burden affordable).

Ionospheric Doppler MSTID (IDEEM)
- MSTID vel. est.,
- very simple,
- no distance limitation,
- no large network required (either any receiver can be used for MSTID velocity monitoring elsewhere)

Direct GNSS Ionospheric Interferometry (dGII)
- MSTID vel. no needed, smooth,
- potentially applicable to scales of $\sim 100\text{ km}$

Precise GNSS Troposphere determination

Precise GNSS positioning (RTK)

Hernández-Pajares et al. (2015) in prep. for GRL

Improved

Hernández-Pajares et al. (2015) in prep. for JGR-SP
Example: Implementation of dGII

subnet_from_world.SCIGN_LN-SW.2011.001.eli
Example: STEC from LI calibrated with UPC GIM

Consistent with measured (and expected, Hernández-Pajares et al. 2012) equatorward winter day-time (LT 10.5 to 15.5h) MSTID propagation.
Example: \( \frac{dVTEC}{dt} \) directly observed @ 60 sec
Example: Significant and dominant MSTID time delay from cross-correlation

Satellite 15, detrending interval = 60 sec, corr_min = 0.9, slid.window = 600s, amp > 0.25 max.a
Example: $d\text{VTEC}/dt\text{ obs},\text{ applying predominant MSTID time delay.}$
STEC (from LI calibrated with GIM) after applying pred. MSTID time delay with consistent mapping
The ref STEC synchronized with the predominant time delay:
1) works slightly better (specially at 22-22.8h) than the instantaneous one
2) excepting for very low elevation.
Error reduction of 70-85% of the initial error in MSTID peaks:
3) from +1.5 TECU reduced to 0.2-0.7 TECU.
Extensive dGII application (range domain): winter day (353, 2014 @ Poland)

Map of dGII analyzed receivers in RTKfinal-SW-large (left), RTKfinal-NE-large (central) and BERNESE-final networks (right), and corresponding performance of dGII for different baselines, vs. no applying it, with northern reference sites wrki, elbl and wlad, respectively (right column, Poland, winter day of 353, 2013).
Extensive dGII application (range domain): summer (168, 2014 @ Poland)

Map of dGII analyzed receivers in RTKfinal-SW-large (left), RTKfinal-NE-large (central) and BERNESE-final (right) networks, and corresponding performance of dGII for different baselines, vs. no applying it with eastern reference sites koni, krol and sokl, respectively (right column, Poland, summer day of 168, 2013).
Positioning – ambiguity and coordinate domain
60-80 km baselines, summer day (168/2013)

Red.RNX  Mod.RNX+Prop.STEC

Table: RTK positioning performance statistics

<table>
<thead>
<tr>
<th>Baseline</th>
<th>strategy</th>
<th>ASR [%]</th>
<th>TTFF [epochs]</th>
<th>N std [m]</th>
<th>E std [m]</th>
<th>U std [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOR1-KONI</td>
<td>Original obs.</td>
<td>53</td>
<td>29.9</td>
<td>0.011</td>
<td>0.006</td>
<td>0.029</td>
</tr>
<tr>
<td></td>
<td>MSTID-corrected</td>
<td>78</td>
<td>12.8</td>
<td>0.012</td>
<td>0.007</td>
<td>0.035</td>
</tr>
<tr>
<td>GNIE-KONI</td>
<td>Original obs.</td>
<td>74</td>
<td>18.3</td>
<td>0.013</td>
<td>0.008</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>MSTID-corrected</td>
<td>83</td>
<td>15.7</td>
<td>0.013</td>
<td>0.009</td>
<td>0.036</td>
</tr>
</tbody>
</table>

Fig. Time to fix, baseline BOR1-KONI on 168/2013
(top panel – original observations, bottom panel – MSTID-corrected)

Fig. Baseline BOR1-KONI on 168 DOY
(left panel – original observations, right panel – MSTID-corrected)

Improvement in the ambiguity resolution domain.
Improvement in the troposphere modeling

Original RINEX files:
smaller AR%, ZTD estimates close to EPN final solution

Reduced/modified RINEX files with MSTID dGIi models:
small differences in WL and NL AR%, improvement in QIF AR% up to 14%
different ZTD estimates than using CODE iono model (but equal formal errors)
Conclusions

• Recent findings on the study of Solar Flares and MSTIDs with GNSS have been summarized as far as its applications

• GNSS proves again its versatility and power in order to become not only an extremely sensitive and accurate global ionospheric sounder but a calibrated solar observational instrument as well.

Thank you