UPC-IonSAT recent contributions to ionospheric modelling: monitoring with Global Ionospheric Maps of VTEC in general, storm, polar and real-time conditions

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by
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We are going to present an executive summary of the positive answers recently found on the following questions on the Global Ionospheric Maps (GIMs) of Vertical Total Electron Content (VTEC): UQRG rapid & UADG real-time (RT) GIMs generated by UPC-IonSAT for IGS with a time res. of 15 minutes:

Can the rapid GIMs:

1) show realistic features of the polar ionosphere electron content distribution?

2) provide reliable estimation of the spatial and temporal components of the VTEC gradients with comparable results to the corresponding indices proposed and generated from raw GNSS data (Jakowski & Hoque 2019)?

3) provide a sensitive Ionospheric storm scale index, with comparable results to the I-scale index proposed and generated by (Nishioka et al. 2017) from raw GNSS data?

4) provide a general reliable monitoring of the ionospheric VTEC?

5) Can the RT VTEC interpolation, one bottleneck in the accuracy of RT-GIMs, be significantly improved?
Context: GNSS-based UQRG Global Ionospheric Map (GIM)

LOS Carrier phases in length units: $L_1 - L_2$ 
(measurement, corrected from wind-up)

Associated L1-L2 ambiguity, $B_1$ 
(unknown)

Electron density of LOS illuminated voxels: $N_e$ (unknowns)

Straight line LOS length within given voxel: $l_{j,k,l}$

**UPC Quarter-of-an-hour time resolution Rapid GIM (UQRG)**

Two-Layer voxel tomographic estimation without ionospheric background model and with dual-frequency carrier phase input data only, with in-house TOMION software.

Kriging interpolation which preserves the details

Resolution: 15min x 5° x 2.5° in time x Ion.xlat
Context: TOMION software

- TOMION is a data driven ionospheric model originally developed by MHP, in continuous development during the latest 25 years.
- It allows a tomographic estimation of the density of free ionospheric electrons from GNSS carrier phase dual-frequency data only, without any background model.
- It incorporates a Kalman filter and a kriging-based interpolation for the vertically integrated electron density (the vertical total electron content, VTEC, see Hernández-Pajares et al. 1997, 1999, Orús et al. 2005).
- TOMION is the software used in the generation of UPC-IonSAT global ionospheric maps (GIMs) of VTEC for the International GNSS Service (IGS), such as the UQRG one, one of the outperforming GIMs, or even the best behaving GIM in IGS (Hernández-Pajares et al. 2009, 2017, Roma-Dollase et al. 2018).
- UQRG GIM produced by TOMION is, for instance, able to detect realistic features of the polar ionosphere as well (Hernández-Pajares et al. 2020a) and to provide a realistic and sensitive storm index (Qi et al. 2021).
- The tomography performed by TOMION is able to ingest different geometries and types of input measurements (Hernández-Pajares et al. 2020b), in agreement with independent measurements and models (Kotov et al. 2018, 2019).
1) Can the rapid GIMs show realistic features of the polar ionosphere electron content distribution?

- The electron content distribution of the north and south polar ionosphere from 2001 to the beginning of 2019 was analyzed by using the UQRG global ionospheric map (GIM) of vertical total electron content (VTEC), computed every 15 min by UPC-IonSAT with a tomographic-kriging combined technique. We first showed that the accuracy of UQRG GIM is slightly better than that of the GIMs of other analysis centers on the whole and also over both poles.

- Second, we showed examples of polar VTEC features in UQRG GIM, previously reported by different authors and with higher-resolution techniques.

- Third, by means of an unsupervised clustering algorithm, learning vector quantization, we characterized the main features of the ionospheric electron content climatology, separately for the north and south polar regions.

Figure: VTEC in South Pole region during 15 September, Day 258, of year 2005 at 1915 UT (extracted from UQRG GIM; the red star represents the corresponding magnetic pole).
The summary of the research associated to point 1 can be found in:

**JGR Space Physics**

**RESEARCH ARTICLE**

10.1029/2019JA027677

**Key Points:**
- The UPC GIM has been analyzed over both poles during 1.5 solar cycles confirming its slightly better performance compared to other IGS GIMs.
- It presents realistic VTEC features over two poles, in agreement with previous higher resolution works and using non-GNSS measurements.
- The climatology of the main VTEC polar features is obtained by means of the learning vector quantization (LVQ) unsupervised technique.

**Polar Electron Content From GPS Data-Based Global Ionospheric Maps: Assessment, Case Studies, and Climatology**

Manuel Hernández-Pajares\(^1,2\), Haixia Lyu\(^1,2\), Ángela Aragón-Ángel\(^3\), Enric Monte-Moreno\(^4\), Jingbin Liu\(^5,6,7\), Jiachun An\(^8\), and Hu Jiang\(^8\)

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2) Can the rapid GIMs provide reliable estimation of the spatial and temporal components of the VTEC gradients?

The spatial and temporal components of VTEC gradient at grid points of UQRG GIM on a global scale are introduced.

The VTEC gradient derived from UQRG GIMs (VgUG, Liu et al. 2022), allows to obtain full (non-relative) values of TEC spatial gradients and temporal variations separately at any worldwide grid point, considering the distances on the corresponding parallels and meridians at the ionospheric effective height, ΔDLON & ΔDLAT, separated 5° & 2.5° respectively, and the time difference between GIMs Δt (30 minutes, centered, 15 minutes, uncentered).

\[
\begin{align*}
\nabla V_{x,i,j} &= \frac{(VTEC_{i,j} - VTEC_{i-1,j})}{\Delta DLON} \\
\nabla V_{y,i,j} &= \frac{(VTEC_{i,j} - VTEC_{i,j-1})}{\Delta DLAT} \\
\nabla V_{i,j} &= \sqrt{\nabla V_{x,i,j}^2 + \nabla V_{y,i,j}^2} \\
\n\vec{V} &= (\nabla V_{x,i,j}, \nabla V_{y,i,j}) \\
\n\hat{V}_{i,j} &= \Delta VTEC_{i,j}/\Delta t = (VTEC_{i,j,t} - VTEC_{i,j,t-1})/\Delta t
\end{align*}
\]
Example of global distribution of VTEC spatial gradient

Compared with the quiet ionospheric state, the VTEC spatial and temporal gradient directly derived from the GIM are able to capture the extraordinary VTEC variations during the disturbed ionospheric state, split in north, east and time components.

St. Patrick’s Day 2015 Geomagnetic Storm

From UQRG GIM (VgUG) (Liu et al. 2022)

From raw GNSS data (Jakowski & Hoque (2017)

Spatial gradient norm

Latitudinal gradient component
The summary of the research associated to point 2 can be found in:

**Space Weather**

**RESEARCH ARTICLE**

10.1029/2021SW002926

**Key Points:**
- A new ionospheric temporal and spatial gradient index based on UPC-IonSAT Global Ionosphere Maps (UQRG) are presented at the selected region
- The new ionospheric spatial gradients indices at grid points of UQRG are presented
- The derived ionospheric spatial gradients and temporal variations indices are analyzed during quiet and disturbed ionosphere states

**A New Way of Estimating the Spatial and Temporal Components of the Vertical Total Electron Content Gradient Based on UPC-IonSAT Global Ionosphere Maps**

Qi Liu¹, Manuel Hernández-Pajares¹,², Heng Yang¹,³, Enric Monte-Moreno⁴, Alberto García-Rigo¹,², Haixia Lyu¹,⁵, Germán Olivares-Pulido¹, and Raül Orús-Pérez⁶

¹Universitat Politècnica de Catalunya (UPC-IonSAT), Barcelona, Spain, ²Institut d’Estudis Espacials de Catalunya (IEEC), Barcelona, Spain, ³School of Electronic Information and Engineering, Yangtze Normal University, Chongqing, China, ⁴Department of TSC, TALP, Universitat Politècnica de Catalunya, Barcelona, Spain, ⁵GNSS Research Center, Wuhan University, Wuhan, China, ⁶Wave Interaction and Propagation Section (TEC-EFW) ESA ESTEC, Noordwijk, The Netherlands
3) Can the rapid GIMs provide a sensitive Ionospheric storm scale index?

We propose the Ionospheric Storm Scale Index Based on UQRG (IsUG) as a direct extension of the I-scale index proposed at regional level (Japan) and from raw GNSS data by Nishioka et al. (2017):

\[
P_{TEC} = \frac{100 \times (O_{TEC} - R_{TEC})}{R_{TEC}} \quad \hat{P}_{TEC} = \frac{P_{TEC} - \mu}{\sigma}
\]

It is defined as the standardized Ptec, \( \hat{P}_{TEC} \), where Ptec is the percentage deviation of VTEC, Otec is the hourly median VTEC derived at grid points of GIM. The hourly median VTEC is the median of the five VTEC values during 1-h interval, under the GIM VTEC temporal resolution of 15 min. The hourly median VTEC is calculated every hour (for example, 0, 1, 2 UT). Rtec is the reference median value at the same local time and geographic location in the past 27 days.

<table>
<thead>
<tr>
<th>IsUG</th>
<th>Description</th>
<th>Definition</th>
<th>Probability on a global scale (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP3</td>
<td>Severe positive storm</td>
<td>( 5 &lt; \hat{P} \leq 5 )</td>
<td>0.17</td>
</tr>
<tr>
<td>IP2</td>
<td>Strong positive storm</td>
<td>( 3 &lt; \hat{P} \leq 5 )</td>
<td>0.72</td>
</tr>
<tr>
<td>IP1</td>
<td>Moderate positive storm</td>
<td>( 1 &lt; \hat{P} \leq 3 )</td>
<td>12.43</td>
</tr>
<tr>
<td>I0</td>
<td>Quiet</td>
<td>(-1 &lt; \hat{P} \leq 1 )</td>
<td>73.96</td>
</tr>
<tr>
<td>IN1</td>
<td>Moderate negative storm</td>
<td>(-3 &lt; \hat{P} \leq -1 )</td>
<td>11.72</td>
</tr>
<tr>
<td>IN2</td>
<td>Strong negative storm</td>
<td>(-3 &lt; \hat{P} \leq -2 )</td>
<td>0.95</td>
</tr>
<tr>
<td>IN3</td>
<td>Severe negative storm</td>
<td>( \hat{P} &lt; -3 )</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Comparing $\hat{P}_{TEC}$ n GIM $\hat{P}_{TEC}$ n raw GNSS data over Japan since 1997 to 2014 (3 months of seasonal data per year)

From UQRG GIM (VgUG)
(Liu et al. 2021)

(a) 20 LT, March Equinox, 130° E, 30° N
(b) 20 LT, June Solstice, 130° E, 30° N
(c) 12 LT, March Equinox, 130° E, 30° N
(d) 20 LT, March Equinox, 140° E, 40° N

From raw GNSS data
(Nishioka et al., 2017))

(a) 20JST, March Equinox, 29° N
(b) 20JST, June Solstice, 29° N
(c) 12JST, March Equinox, 29° N
(d) 20JST, March Equinox, 41° N
Animation of IsUG maps during a ionospheric storm period
The summary of the research associated to point 3 can be found in:

**Ionospheric Storm Scale Index Based on High Time Resolution UPC-IonSAT Global Ionospheric Maps (IsUG)**

Qi Liu¹, Manuel Hernández-Pajares¹,2, Haixia Lyu³,1, Michi Nishioka⁴, Heng Yang⁵,1, Enric Monte-Moreno⁶, Tamara Gulyaeva⁷, Yannick Béniguel⁸, Volker Wilken⁹, Germán Olivares-Pulido¹, and Raül Orús-Pérez¹⁰

¹Universitat Politècnica de Catalunya (UPC-IonSAT), Barcelona, Spain, ²Institut d’Estudis Espacials de Catalunya (IEEC), Barcelona, Spain, ³GNSS Research Center, Wuhan University, China, ⁴National Institute of Information and Communications Technology (NICT), Tokyo, Japan, ⁵School of Electronic Information and Engineering, Yangtze Normal University, Chongqing, China, ⁶Department of TSC, TALP, Universitat Politècnica de Catalunya, Barcelona, Spain, ⁷IZMIRAN, Moscow, Russia, ⁸Informatique, Electromagnétisme, Electronique, Analyse numérique (IEEA), Courbevoie, France, ⁹German Aerospace Center (DLR), Neustrelitz, Germany, ¹⁰Wave Interaction and Propagation Section (TEC-EFW) ESA ESTEC, Noordwijk, The Netherlands
4) Can the rapid GIMs provide a general reliable monitoring of the ionospheric VTEC?

Table 2  Summary of the GIMs assessment versus +190 millions of altimeter VTEC measurements, including an overall period of up to almost 5000 days and a common period of 21 days (remarks: [*] For the newest period of EMRG product submission to IGS only, days 117–365, 2015; [**] Very limited sample)

<table>
<thead>
<tr>
<th>GIM Id.</th>
<th>Up to more than 1 solar cycle, within days 180, 2001 to 007, 2016</th>
<th>21 common days, within 117, 2015 to 007, 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># days</td>
<td>Std. dev./TECU</td>
</tr>
<tr>
<td>IGSG</td>
<td>4927</td>
<td>3.9</td>
</tr>
<tr>
<td>CODG</td>
<td>4934</td>
<td>4.3</td>
</tr>
<tr>
<td>ESAG</td>
<td>4926</td>
<td>5.3</td>
</tr>
<tr>
<td>JPLG</td>
<td>4912</td>
<td>4.1</td>
</tr>
<tr>
<td>UPCG</td>
<td>4925</td>
<td>3.9</td>
</tr>
<tr>
<td>CASG</td>
<td>4914</td>
<td>3.9</td>
</tr>
<tr>
<td>EMRG</td>
<td>255[*]</td>
<td>(4.8)</td>
</tr>
<tr>
<td>WHRG</td>
<td>4416</td>
<td>4.6</td>
</tr>
<tr>
<td>WHUG</td>
<td>42[**]</td>
<td>(5.9)</td>
</tr>
<tr>
<td>UQRG</td>
<td>3063</td>
<td>3.6</td>
</tr>
</tbody>
</table>
The summary of the research associated to point 4 can be found in:

Journal of Geodesy
https://doi.org/10.1007/s00190-017-1088-9

Consistency of seven different GNSS global ionospheric mapping techniques during one solar cycle

David Roma-Dollase¹,² ID · Manuel Hernández-Pajares¹ ID · Andrzej Krankowski³ · Kacper Kotulak³ · Reza Ghoddousi-Fard⁴ · Yunbin Yuan⁵ · Zishen Li⁶ · Hongping Zhang⁷ · Chuang Shi⁷ · Cheng Wang⁷ · Joachim Feltens⁸ · Panagiotis Vergados⁹ · Attila Komjathy⁹ · Stefan Schaar¹⁰ · Alberto García-Rigo¹ · José M. Gómez-Cama² ID

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5) Can the RT VTEC interpolation, one bottleneck in the accuracy of RT-GIMs, be significantly improved?

- We proposed a method for the generation of real-time global ionospheric map (RT-GIM) of vertical total electron content (VTEC) from GNSS measurements.

- The need for interpolation arises from the fact that the ionospheric pierce point (IPP) measurements from satellites to stations are not distributed uniformly over the ionosphere, leaving unfilled gaps at oceans or poles.

- The method we propose is based on using a high-quality historical database of post-processed GIMs that comprises more than two solar cycles, calculates the GIM by weighted superposition on a subset of the database with the compatible solar condition.

- The linear combination of GIMs in the database was obtained by minimizing a \( L_2 \) distance between VTEC measurements at the IPPs and the VTECs from the database, adding a \( L_1 \) penalization on the weights to assure a sparse solution. The process uses a Sun-fixed geomagnetic reference frame.

- This method uses the atomic decomposition/least absolute shrinkage and selection operator (LASSO), which will be denoted as atomic decomposition interpolator of GIMs (ADIGIM). As the computation is done in milliseconds, the interpolation is performed in real time.

---

<table>
<thead>
<tr>
<th>GIM Id</th>
<th>Latency</th>
<th>Bias</th>
<th>SD</th>
<th>RMS</th>
<th>ERR%</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGSG</td>
<td>&gt; 15 days</td>
<td>−1.93</td>
<td>2.33</td>
<td>3.03</td>
<td>38.5</td>
</tr>
<tr>
<td>CODG</td>
<td>~5 days</td>
<td>2.46</td>
<td>2.80</td>
<td>35.6</td>
<td></td>
</tr>
<tr>
<td>JPLG</td>
<td>~4 days</td>
<td>2.45</td>
<td>4.15</td>
<td>52.7</td>
<td></td>
</tr>
<tr>
<td>UPCG</td>
<td>~15 h</td>
<td>3.37</td>
<td>3.28</td>
<td>47.4</td>
<td></td>
</tr>
<tr>
<td>ESAG</td>
<td>~4 days</td>
<td>2.83</td>
<td>2.96</td>
<td>37.6</td>
<td></td>
</tr>
<tr>
<td>WHUG</td>
<td>~4 days</td>
<td>2.52</td>
<td>2.87</td>
<td>36.5</td>
<td></td>
</tr>
<tr>
<td>CASG</td>
<td>~4 days</td>
<td>2.46</td>
<td>2.88</td>
<td>36.6</td>
<td></td>
</tr>
<tr>
<td>EMRG</td>
<td>~2 days</td>
<td>2.61</td>
<td>3.11</td>
<td>39.5</td>
<td></td>
</tr>
<tr>
<td>CORG</td>
<td>~7 h</td>
<td>2.64</td>
<td>2.94</td>
<td>37.4</td>
<td></td>
</tr>
<tr>
<td>JPRG</td>
<td>~7 h</td>
<td>2.48</td>
<td>4.24</td>
<td>53.9</td>
<td></td>
</tr>
<tr>
<td>UQRG</td>
<td>~16 h</td>
<td>2.86</td>
<td>3.04</td>
<td>38.6</td>
<td></td>
</tr>
<tr>
<td>ESRG</td>
<td>~2 h</td>
<td>2.55</td>
<td>2.89</td>
<td>36.6</td>
<td></td>
</tr>
<tr>
<td>WHRG</td>
<td>~20 h</td>
<td>2.59</td>
<td>3.00</td>
<td>38.1</td>
<td></td>
</tr>
<tr>
<td>CARG</td>
<td>~10 h</td>
<td>2.60</td>
<td>2.90</td>
<td>36.8</td>
<td></td>
</tr>
<tr>
<td>EHRG</td>
<td>~3 h</td>
<td>2.80</td>
<td>3.02</td>
<td>38.4</td>
<td></td>
</tr>
<tr>
<td>CASR</td>
<td>RT(^a)</td>
<td>2.98</td>
<td>3.03</td>
<td>38.5</td>
<td></td>
</tr>
<tr>
<td>CLK9</td>
<td>RT</td>
<td>2.85</td>
<td>3.18</td>
<td>40.4</td>
<td></td>
</tr>
<tr>
<td>USRG</td>
<td>~20 h</td>
<td>2.32</td>
<td>3.13</td>
<td>39.7</td>
<td></td>
</tr>
</tbody>
</table>

**UADG**

<table>
<thead>
<tr>
<th>GIM Id</th>
<th>Latency</th>
<th>Bias</th>
<th>SD</th>
<th>RMS</th>
<th>ERR%</th>
</tr>
</thead>
<tbody>
<tr>
<td>UADG</td>
<td>RT</td>
<td>−1.34</td>
<td>2.43</td>
<td>2.77</td>
<td>35.1</td>
</tr>
</tbody>
</table>

\(^a\) Latency of UADG is the delay for RT-GIM for each epoch
The summary of the research associated to point 5 can be found in:

Journal of Geodesy (2021) 95:71
https://doi.org/10.1007/s00190-021-01525-5

Original Article

Real-time interpolation of global ionospheric maps by means of sparse representation

Heng Yang¹,²,³ · Enric Monte-Moreno¹ · Manuel Hernández-Pajares³ · David Roma-Dollase⁴

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The impact of the improvement of UPC-IonSAT RT GIM on the RT IGS combination will be shown tomorrow, Tuesday 28-J, in the first talk of RT IGS session.
Summary

We have presented an executive summary of the positive answers recently found on the following questions on the Global Ionospheric Maps (GIMs) of Vertical Total Electron Content (VTEC): UQRG **rapid** & UADG **real-time** (RT) GIMs generated by UPC-IonSAT for IGS with a time res. of 15 minutes:

**Can the rapid GIMs:**

1) show **realistic features of the polar ionosphere** electron content distribution?

2) provide **reliable estimation of the spatial and temporal components of the VTEC gradients** with comparable results to the corresponding indices proposed and generated from **raw GNSS data** (Jakowski & Hoque 2019)?

3) provide a **sensitive Ionospheric storm scale index**, with comparable results to the I-scale index proposed and generated by (Nishioka et al. 2017) from raw GNSS data?

4) provide a general **reliable monitoring of the ionospheric VTEC**?

5) **Can the RT VTEC interpolation**, one bottleneck in the accuracy of RT-GIMs, be significantly improved?

Thanks for your attention!