REAL-TIME IONOSPHERIC DETERMINATION AT GLOBAL SCALE: CHALLENGES AND GNSS APPLICATIONS

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Abstract

The global ionospheric determination has been possible in the last 15 years thanks to the availability of a new type of ionospheric sensor with a very high spatial and temporal sampling: the dual-frequency GPS receivers. Indeed, several hundreds of them, worldwide distributed, are freely available, tracking typically 6+ GPS satellites in view, providing at every epoch several thousands of line-of-sight integrated free electron densities (Slant Total Electron Content, STEC). This has allowed in particular to compute and freely distribute global Vertical Total Electron Content (VTEC) maps, in the context of the open-product organization called International GNSS Service (IGS), which applications run from single frequency receivers (accurate mitigation of ionospheric delay), calibration of new altimeters (such as the SMOS mission) up to the potential use for increasing the performance of positioning based on carrier phase measurements.

One of the next challenges, in particular in IGS, is computing the global VTEC maps, in real-time, which involves much less permanent receivers, increasing much more the difficult task of interpolating in a realistic way the electron content over large regions with few receivers (south hemisphere, oceans...).

In this paper the actual status of the problem will be presented, from the perspective of gAGE/UPC, one of the four IGS Ionospheric Analysis Centers, participating in the Real-Time IGS Pilot Project.

1 Introduction

The computation of reliable global maps of Vertical Total Electron Content of the Ionosphere (Vertical TEC or VTEC maps) is at the same time an useful and challenging goal. Useful because, in both Science and Technology fields, they can provide valuable information (Space Weather, Empirical Model predictions, Global Navigation Satellite System -GNSS- user navigation improvement, among others). Challenging because, at global scale, there are important parts of the Ionosphere which are not illuminated by any close GNSS-satellite-to-receiver ray. This is due to a lack of ground receivers of the first and predominant GNSS system so far (Global Positioning System, GPS), specially over the Oceans and at South Hemisphere, among other regions.

Moreover, the Inverse Problem to retrieve such VTEC maps from the Slant TEC (STEC) measurements is not straightforward because these measurements do not directly provide the STEC (the carrier phases are affected by the ambiguity term, and the pseudoranges by the inter-frequency code bias), and due to the variation of the electron content in space and time, with special difficulties close to the Equatorial Anomalies, and/or during Ionospheric storms.

In this scenario, and with the main initial purpose of generating reliable VTEC maps, the Ionosphere Working Group of the International GNSS Service (IonoWG-IGS) was created in 1998 (see [2]). With this purpose a similar approach to the one used by older IGS Working Groups to provide reliable GNSS products (such as satellite orbits and clocks) was taken: the individual products (in our case global VTEC maps) independently computed (software and hardware) by different computation centers are ranked and combined with the corresponding weight in terms of single IGS global VTEC maps. The different maps are computed by the so called Ionospheric Associate Analysis Centers (IAACs), the corresponding ranking is computed by the so called Ionospheric Associated Evaluation Centers (IAECs) and the IGS-combined product is produced by the so called Ionospheric Associate Combination Center (IACC). Finally a validation with independent sources of VTEC data is performed by the Ionospheric Associated Validation Centers (IAVCs).

The main details on how the IGS VTEC maps are generated, in both rapid and final schedules, an update of the corresponding performances with some representative snapshots (including the inter-frequency biases as secondary product), the product usage, the main VTEC evolution trends during near one Solar cycle, as far as potential future improvements, can be found in [11].

On the other hand IGS has created recently an specific real-time pilot project as part of its strategic plan to meet the needs of the Precise Point Positioning (PPP) community it serves. The participants in the IGS Real-time Pilot Project are working towards the implementation of a two year plan. The key Pilot Project activities include network management, format specifications, product generation and distribution, product accuracy and real-time precise point positioning results (see `http://www.rtigs.net/`and a recent update in [1]). Within the Pilot Project, IGS real-time analysis centers are computing GNSS clock corrections using IGS ultra rapid predicted orbits and real-time data streams from over 100 stations in the IGS network. Independent real-time analysis center solutions are being combined into a real-time correction product which is being delivered to real-time users. Real-time analysis centers are also generating low latency conventional products, such as the ionospheric VTEC maps. This is the main target of this presentation: to summarize the present status of this activity, from the point of view of gAGE/UPC, one of the participants in the RT IGS pilot project.

2 Computation: RT-TOMION

The computation of global VTEC maps is based on an ionospheric software developed at gAGE/UPC during the last 15 years. Indeed, the development of the tomography approach used in the TOMographic IONosphere model (TOMION) was started at UPC in the second half of the 1990s ([5], [7], [13]). At that time, the main focus was to assess the feasibility of computing better TEC maps with a coarse tomography algorithm. TOMION has been developed to provide several versions which are able to process ground based GNSS ionospheric data, GNSS LEO radio occultation data ([6], [8]), GNSS geodetic data,[9], and ionosonde data, [3]. In real-time processing is also possible to provide corrections for precise user positioning (Wide Area Real-Time Kinematic (WARTK), see [10] and [12]. Since 1998, TOMION has been used in the UPC Ionospheric Analysis Centre for the IGS [11].

The RT-TOMION version used in this study generates Global Ionospheric Maps (GIMs) of vertical TEC (vTEC) from RT-IGS datastreams, and includes an interpolation module using Kriging interpolation [14]. The ionosphere is represented by two or more layers of voxels. In each voxel the electron density is assumed to be constant. Global VTEC predicted maps, using an specific regressive technique in the transformed domain developed at UPC [4], are used as background model. The assimilation of data is done in two steps: 1) an initial fit -running continuously on a UNIX pipe- is made to the ground based TEC data with a quite coarse resolution (4 latitude x 6 longitude voxel size) in which a first TEC model, together with the satellite and receiver differential code biases (DCBs), is estimated; 2) data gaps are filled using a modified Kriging interpolation technique to generate GIMs, taking into account the correlation lengths of the vTEC errors in the interpolation process, specially important in ocean and southern hemisphere regions with sparse ground-based GPS data available. For Kriging interpolation, the residuals between observed vTEC (slant TEC corrected for the DCBs of the first fit and mapped to the vertical) and modelled vTEC (from the model of the first fit) are computed. Then by Kriging interpolation over these residuals a more accurate high resolution TEC map can be created. The correlation lengths (or weights) are computed from squared differences between pairs of vTEC residuals at fixed distances. In the second run the resolution can be reduced to 2.5 deg in latitude, 5 deg longitude and 15 minutes time intervals.

3 First results

A summary of the first results, based on four recent days with seamless ionospheric monitoring (days 9, 11, 12 and 28 of February, respectively days 40, 42, 43 and 59 of 2011), can be found in Table 1. In particular the standard deviation of the global VTEC provided in real-time (ionospheric product URTG) can be compared with direct VTEC observations provided over the seas by the dual-frequency altimeter JASON

YEAR	DAY OF YEAR	IONO. PRODUCT	LATENCY (hours)	# STATIONS	STD.DEV. (TECU)	BIAS (TECU)	AVER.JASON VTEC (TECU)	# JASON OBS.
2011	040	URTG	< 0.25	41	3.74	3.14	13.4	43000
		UPRG	< 48	251	2.24	0.58		
		IGRG	< 48	323	2.30	1.17		
2011	042	URTG	< 0.25	71	3.32	2.49	14.2	42000
		UPRG	< 48	252	2.54	-0.42		
		IGRG	< 48	296	2.42	0.14		
2011	043	URTG	< 0.25	72	3.23	2.90	14.2	42000
		UPRG	< 48	251	2.57	-0.80		
		IGRG	< 48	296	2.72	-0.17		
2011	059	URTG	< 0.25	51	4.77	1.52	16.1	42000
		UPRG	< 48	217	3.28	-0.31		
		IGRG	< 48	321	3.26	-0.17		

Table 1: Comparison of GPS VTEC performance: Preliminary real-time product (URTG) vs. UPC and IGS rapid products (UPRG and IGRG respectively). They are compared with direct altimeter VTEC observations in terms of Standard Deviation (6th column) and TOPEX-GPS Bias (7th column; source: dual-frequency JASON altimeter measurements).

(6th column, in TECUs[1]) as main performance parameter. Such performance can be compared in the same table with the performance of the rapid UPC product (UPRG) and the combined IGS product (IGRG), produced with a latency of less than 48 hours. It can be appreciated that the performance is lower for real-time VTEC maps, as it could be expected, but not so low as it could be deduced by the much reduced number of available receiver globally distributed. This is true specially when the huge difference of available GPS receivers is not so dramatic: The standard deviation regarding to JASON VTEC measurements[2] is 23% of the average VTEC value (8th column) for about 70 real-time receivers (days 042 and 043), in front of 28-30% when just 40-50 GPS datastreams are alive (days 040 and 059). The corresponding performance figure for rapid VTEC map (UPRG) is 16-20%, built from the 200-250 worldwide GPS receivers available more than one day later.

4 Conclusions

The first results of real-time global VTEC maps computed by gAGE/UPC in the context of RT-IGS Pilot Project has been presented in this paper. It is shown, comparing with independent VTEC measurements of the JASON altimeter, that the still very limited number of available real-time receivers is the main degradation factor in the performance. The increase in the number of available datastreams at global scale is a must, if a much more precise real-time monitoring is pursued, being this fundamental in the case of precise GNSS navigation, such as the WARTK technique developed by gAGE/UPC.

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[1] 1 TECU = 10^{16}e/m^3

[2] It should be noticed that this comparison gives the performance of GPS VTEC maps in a worst case scenario, over the seas where the altimeter measurements are available. This is typically very far from the GPS receivers where direct Slant Total Electron Content measurements are taken.

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