Assessment of the 4-D SIRGAS ionospheric model

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Introduction

The IAG Subcommission 1.3b, Regional Reference Frame for Central and South America (SIRGAS - Sistema de Referencia Geocéntrico para las Américas) operates a regular service for computing regional ionospheric maps, based on dual frequency GNSS observations collected from the SIRGAS Continuously Operational Network (SIRGAS-CON). A continues time series of maps describing the vertical total electron content (vTEC) distribution with time resolution of one hour, from 2008 to present, is available at the SIRGAS web page (www.sirgas.org). The computation of these maps relay upon a thin layer ionospheric model specially tailored for the SIRGAS region.

In recent years SIRGAS established a close cooperation with the research group of Astronomy and Geomatics, from the Universitat Politècnica de Catalunya, Spain, aimed to upgrade the ionospheric products of SIRGAS. The main result of that cooperation has been the development of a 4-D (space and time) model of the electron density (ED), based on the simultaneous ingestion of ground- and space-based GNSS observations into a semi-empirical model of the Earth's ionosphere.

The NeQuick model (the same that is being implemented by the Galileo GNSS) was the basis for developing the 4-D SIRGAS model. It is parameterized in terms of the parameters that describe the ED of the F2 ionospheric layer. Ground-based slant total electron content (sTEC) estimates from the SIRGAS-CON network, and ED estimates from FORMOSAT-3/COSMIC radio occultations, are ingested into the model in order to improve its parameters.

The base-model

NeQuick-2[1] is used as base-model for the ingestion of GPS slant TEC and FORMOSAT-3 / COSMIC electron densities from improved Abel inversion.

It is an empirical model for computing the electron density, N_{eN}, at any given location, λ , φ , h, and time, t.

Total Electron Content, TEC_N, for any given ray-path, γ, can be computed by numerical integration.

For a given location and time the vertical profile provided by NeQuick is anchored to the F-2 peak parameters, f_0F2 and $M_{3000}F2$.

$$N_{eN} = F(\varphi, \lambda, h, t \mid f_0F2, M_{3000}F2)$$
$$TEC_N = \int_\gamma N_{eN} \cdot d\gamma$$

1) Nava, Coisson, Radicella, 2008. A new version of the NeQuick ionosphere electron density model, JASTP 70, 1856-1872.

The CCIR database

In absence of measured values, NeQuick computes f_0F2 and $M_{3000}F2$ from the CCIR database.

For each month of the year CCIR provides 2 sets (low and high solar activity) of 998 + 441 = 1429 coefficients, U_f, and U_M, for computing monthly median values of f_0F2 and $M_{3000}F2$.

According to Jones & Gallet mapping technique[1], the U_f and U_M coefficients for the corresponding month must be linearly interpolated for the current solar activity and used to compute the Fourier expansion coefficients:

$$a_j(\varphi,\lambda) = \sum_{k=0}^{K} U_{2j,k} G_k(\varphi,\lambda),\ j \ge 0 \qquad K = 75 \text{ for } f_0F2$$
$$b_j(\varphi,\lambda) = \sum_{k=0}^{K} U_{2j-1,k} G_k(\varphi,\lambda),\ j \ge 1 \qquad K = 49 \text{ for } M_{3000}F2$$

which are later used to compute the monthly median values of f_0F2 and $M_{3000}F2$:

$$f_0F2(\varphi,\lambda,t) = a_0(\varphi,\lambda) + \sum_{j=1}^{6} a_j(\varphi,\lambda) \cos jt + b_j(\varphi,\lambda) \sin jt$$
$$M_{3000}F2(\varphi,\lambda,t) = a_0(\varphi,\lambda) + \sum_{j=1}^{4} a_j(\varphi,\lambda) \cos jt + b_j(\varphi,\lambda) \sin jt$$

The explicit form of the G_k functions depends on φ and λ and also on the modip latitude.

1) Jones & Gallet, 1965. The representation of diurnal and geographical of ionospheric delay by numerical methods, Telecomm. J., 32, 18.

Limitations of the CCIR database

It is based on observations collected from 1954 to 1958 by a network of ~150 ionospheric sounders with uneven global coverage;

It provides monthly median values;

Values for intermediate solar activity must be linearly interpolated from the tabulated values for low ($R_{12} = 0$) and high ($R_{12} = 100$) solar activity).

It makes sense to look for corrections (ΔU_f and ΔU_M) in order to compensate deviations between tabulated ($U_{f,i,0}$ and $U_{M,i,0}$) and actual ($U_{f,i}$ and $U_{M,i}$) values:

$$U_{f,i} = \Delta U_{f,i,0} + \Delta U_{f,i} \qquad i = 1, 2, \ldots, 988$$
$$U_{M,i} = \Delta U_{M,i,0} + \Delta U_{M,i}, \qquad i = 1, 2, \ldots, 441$$

Adaptation of NeQuick for data ingestion

NeQuick is parameterized as a function of the 988 + 441 = 1429, U_f and U_M coefficients:

$$N_{eN} = F\left(f_0F2(U_{f,1},\ldots,U_{f,988}), M_{3000}F2(U_{M,1},\ldots,U_{M,441})\right)$$
$$\cong N_{eN,0} + \sum_{i=1}^{988} \frac{\partial N_{eN}}{\partial f_0F_2} \cdot \frac{\partial f_0F_2}{\partial U_{f,i}} \cdot \Delta U_{f,i} + \sum_{i=1}^{441} \frac{\partial N_{eN}}{\partial M_{3000}F2} \cdot \frac{\partial M_{3000}F2}{\partial U_{M,i}} \cdot \Delta U_{M,i}$$

$$\frac{\partial f_0F_2}{\partial U_{f,2j,k}} = \frac{\partial M_{3000}F2}{\partial U_{M,2,j,k}} = G_k(\varphi,\lambda) \cdot \cos jt \qquad \frac{\partial f_0F_2}{\partial U_{f,2j-1,k}} = \frac{\partial M_{3000}F2}{\partial U_{M,2,j-1,k}} = G_k(\varphi,\lambda) \cdot \sin jt$$

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$N_{eN,0}$ is the electron density computed from the CCIR database; the $\frac{\partial N_{eN}}{\partial f_0F_2}$ and $\frac{\partial N_{eN}}{\partial M_{3000}F2}$ derivatives are numerically computed; and ΔU_f and ΔU_M are corrections to the CCIR coefficients to be estimated through data ingestion.

Data ingestion technique

Two kinds of observations are ingested into NeQuick:

- un-calibrated GPS slant TEC, $sTEC_G$ from the global network

$$sTEC_G \cong \int_\gamma N_{eN,0} \cdot d\gamma + \sum_{i=1}^{988} \left(\int_\gamma \frac{\partial N_{eN}}{\partial f_0F_2} \cdot \frac{\partial f_0F_2}{\partial U_{f,i}} \cdot d\gamma \right) \cdot \Delta U_{f,i} + \beta_R + \beta_S$$

γ is the satellite-to-receiver line-of-sight

β_R and β_S are the satellite and receiver inter-frequency biases

- electron density, N_{eF}, from the FORMOSAT-3 / COSMIC constellation

$$N_{eF} \cong N_{eN,0} + \sum_{i=1}^{988} \frac{\partial N_{eN}}{\partial f_0F_2} \cdot \frac{\partial f_0F_2}{\partial U_{f,i}} \cdot \Delta U_{f,i} + \sum_{i=1}^{441} \frac{\partial N_{eN}}{\partial M_{3000}F2} \cdot \frac{\partial M_{3000}F2}{\partial U_{M,i}} \cdot \Delta U_{M,i}$$

Data ingestion is performed by means of an adaptive and robust Kalman filter.

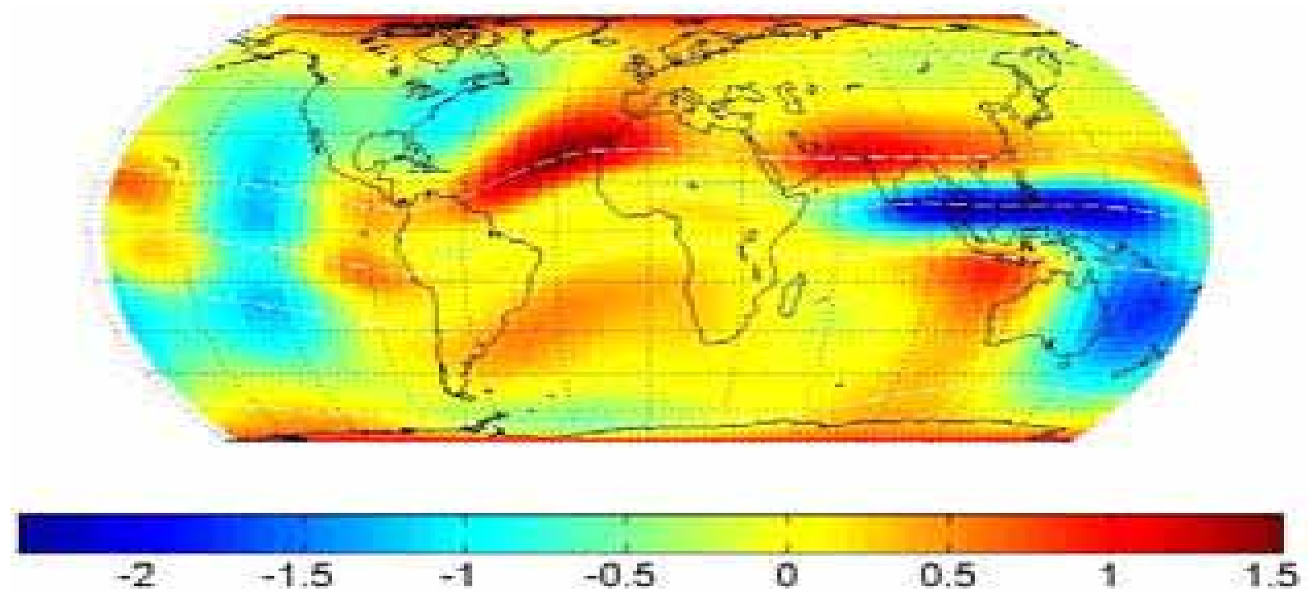
Dataset

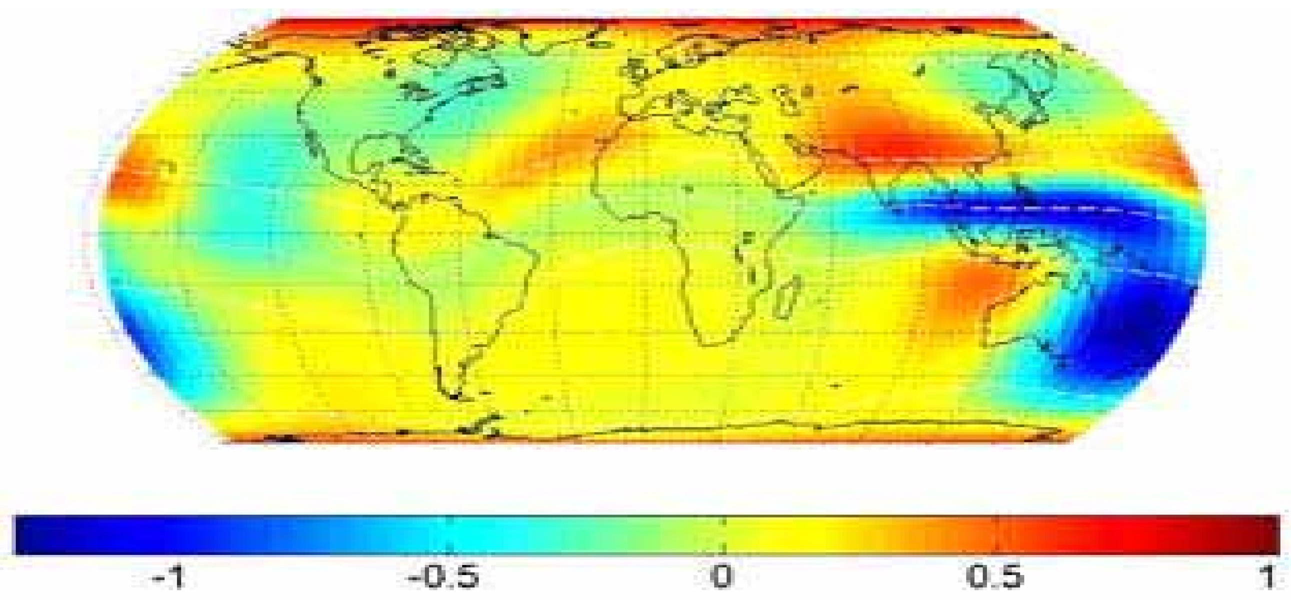
- GPS tracking network: ~350 receivers (blue), ~5×10^6 observations (un-calibrated $sTEC$) per day;
- FORMOSAT-3 / COSMIC: ~600 passes (red), ~ 2×10^5 observations (N_{eF}) per day;
- Ten days, from Jan 6 to 15, 2007.

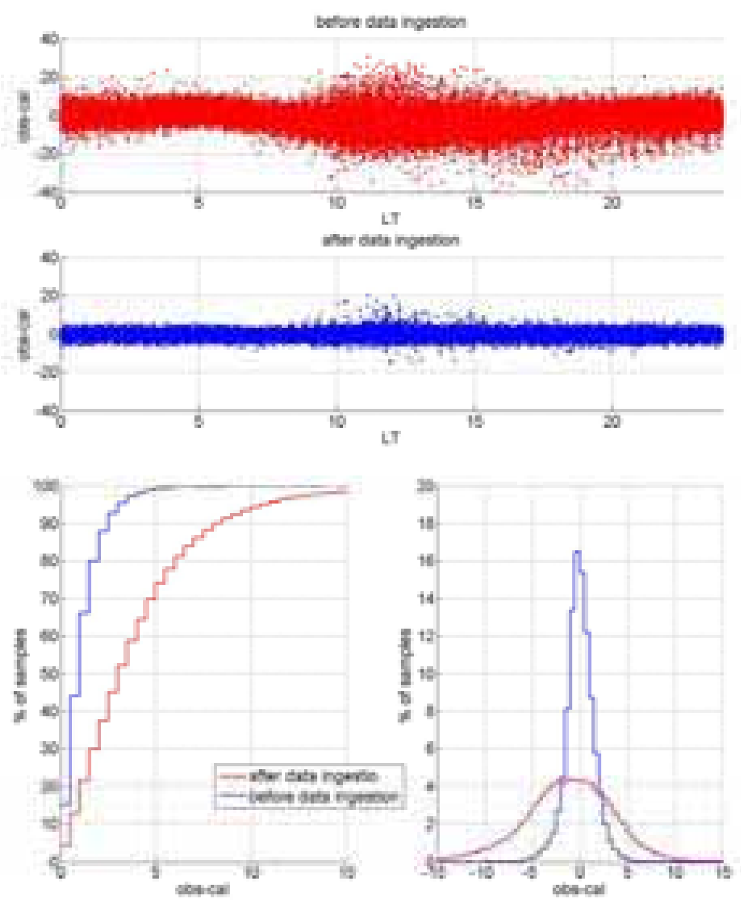
Results

998 + 441 corrections per day were estimated to the f0F2 and M3000F2 coefficients provided by the CCIR database.

The figures show the corrections to f0F2 (upper) and M3000F2 (lower), for a particular day at 17 UT (values are in MHz).







Data ingestion improves the agreement between the observed (GPS) and calculated (NeQuick) slant TEC (upper figure).

Both, bias and standard deviation between observed and computed values are reduced to ~30% of its original values (lower figures).

For example, the 95% deviation is reduced from 11 to 3 TECu.

Conclusions and perspectives

A global technique to ingest ground based GPS sTEC and space based FORMOSAT 3 / COSMIC electron densities into the NeQuick model have been developed by the SIRGAS Ionspheric Analysis Centre.

The technique relies upon the estimation of corrections to the CCIR database in order to minimize the observed minus calculated sTEC and electron density differences.

First experimental results suggested that the technique is self consistent and able to reduce the observed minus calculated differences to ~25-30% of the values computed from the CCIR database.

In the future we intend to:

- analyze the performance of the technique under different solar and geomagnetic conditions;
- validate the obtained sTEC and electron density by comparing to different data sources (e.g.: TOPEX, Jason, ionospheric sounders, etc.);
- Validate the f_0F2 and $M_{3000}F2$ parameters computed with this technique by comparing them to ionospheric sounders and incoherent scatter radar determinations;
- Implement this new technique in the ionospheric map service provided by SIRGAS.