South American regional ionospheric maps computed by GESA: 
A pilot service in the framework of SIRGAS

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Abstract

SIRGAS (Geocentric Reference Frame for the Americas) is an international enterprise of the geodetic community that aims to realize the Terrestrial Reference Frame in the America’s countries. In order to fulfill this commitment, SIRGAS manages a network of continuously operational GNSS receivers totalling around one hundred sites in the Caribbean, Central, and South American region. Although the network was not planned for ionospheric studies, its potential to be used for such a purpose was recently recognized and SIRGAS started a pilot experiment devoted to establish a regular service for computing and releasing regional vertical TEC (vTEC) maps based on GNSS data. Since July, 2005, the GESA (Geodesia Espacial y Aeronáutica) laboratory belonging to the Facultad de Ciencias Astronómicas y Geofísicas of the Universidad Nacional de La Plata computes hourly maps of vertical Total Electron Content (vTEC) in the framework of the SIRGAS pilot experiment. These maps exploit all the GNSS data available in the South American region and are computed with the LPIM (La Plata Ionospheric Model). LPIM implements a de-biasing procedure that improves data calibration in relation to other procedures commonly used for such purposes. After calibration, slant TEC measurements are converted to vertical and mapped using local-time and modip latitude. The use of modip latitude smoothed the spatial variability of vTEC, especially in the South American low latitude region and hence allows for a better vTEC interpolation. This contribution summarizes the results obtained by GESA in the framework of the SIRGAS pilot experiment.

Keywords: Total Electron Content; GPS; Regional ionosphere map; SIRGAS

1. Introduction

Since the early 90’s, a worldwide network of continuously operational dual-frequency GPS receivers has rapidly grown under the management of the International GNSS Service (IGS) (Beutler et al., 1999). Although it was not conceived for ionospheric studies, this network has become a global-distributed observatory routinely used for that purpose. Among other benefits, this observatory provides time continuity, worldwide coverage (at least over lands), well-established standards for data interchange, and easy and free data availability. In order to exploit these potentialities, on May 1998 IGS created the Ionosphere Working Group (Feltens et al., 1998) and soon after, five analysis centers started computing and delivering to the community two-dimensional worldwide grids of vertical Total Electron Content (vTEC) or, in the IGS argot, Global Ionospheric Maps (GIMs). The analysis centers operate under the responsibility of the Jet Propulsion Laboratory (JPL) (Manucci et al., 1999), the European Space Agency (ESA) (Feltens, 1998), the Center for Orbit Determination in Europe (CODE) (Schauer, 1999), the Universidad Politécnica de Cataluña (UPC) (Hernández-Pajares et al., 1999), and the Energy Mines and Resources of Canada (EMR) (Gao et al., 1994). A combi-
nation center under the responsibility of UPC (Hernández-Pajares, 2006) computes the final IGS GIMs, which result from the weighted average of the individual GIMs computed by each analysis center.

SIRGAS was established during an international meeting in Asunción, Paraguay, in October 1993 by representatives of most of the South American countries, the International Association of Geodesy, the Pan American Institute of Geography and History, and the National Imagery and Mapping Agency, now National Geospatial-Intelligence Agency, as the “Sistema de Referencia Geocéntrico para América del Sur” (South American Geocentric Reference System) Project (Fortes et al., 2006). The project structure includes an Executive Committee made up by the representatives of all participating countries and international institutions, a Directive Board, a Scientific Council, and three Working Groups (WGs): WGI “Reference Systems”, WGII “Geocentric Datum”, WGIII “Vertical Datum”. In 2000, the project was extended to Central and North America and it was renamed “Geocentric Reference System for the Americas”, keeping the acronym SIRGAS. In order to fulfill part of its commitments, SIRGAS manages, through its WGI, a network of continuously operational dual-frequency GPS receivers totaling around one hundred sites in the Caribbean, Central, and South American regions. The network includes all IGS global stations plus several regional stations managed by national organizations. Although the large gap around the Amazonian region, this network provides the best data coverage currently available in South America. Fig. 1 shows the distribution of the SIRGAS stations that we are currently using to compute the ionospheric maps.

A WGI action plan for the coming years was discussed during the SIRGAS meeting, held in December 2004, in Aguascalientes, Mexico. The general consensus was to drive WGI efforts toward the consolidation of the GPS network as the cornerstone for the reference frame maintenance. In addition, SIRGAS entrusted WGI the mission to promote new scientific researches that diversify the applications of the SIRGAS observations. Following this mandate, WGI promoted a “call for participation” in a pilot experiment devoted to establish a regular service to compute and deliver South American regional ionospheric maps of vTEC (hereafter called “ionospheric maps” for short) based on (but not exclusively) SIRGAS observations. The call for participation encouraged researches aimed to improve the performances of the currently available GPS-based vTEC models in South American region. One of the outstanding goals of the service is to improve the reliability of the ionospheric correction for GNSS applications. In particular, it aims to contribute to the “Solución de Aumentación para el Caribe, Centro y Sudamérica” (Augmentation Solution for the Caribbean, Central, and South America) project (http://www.rlasacas.com), promoted by the International Civil Aviation Organization to extend the SBAS (Satellite Based Augmentation Service) coverage to the region (Martínez, 2005).

Since July 2005, GESA (Geodesia Espacial y Aeronomía) laboratory belonging to the Facultad de Ciencias Astronómicas y Geofísicas of the Universidad Nacional de La Plata computes hourly ionospheric maps in the framework of the SIRGAS pilot experiment. These ionospheric maps exploit all the GPS data available in the South American region and are computed using the La Plata Ionospheric Model (LPIM). This contribution summarizes the results achieved until now, focusing on the main characteristics of the LPIM approach, i.e.: GPS data calibration and vTEC interpolation. The paper is organized as follow: Section 2 provides a short description of the LPIM. Section 3 presents the problems that the so-called “levelling carrier-to-code” procedure (often used to reduce the effects of carrier-phase ambiguities from the GPS observations) causes in the calibration of the GPS slant TEC (sTEC); and shows how these problems are overcome by the calibration procedure implemented in LPIM. Section 4 discusses the interpolation problem that arises from the need to create a regular data grid from the scattered observations in order to map the vTEC in the desired region; it shows that the use of the modip latitude instead of geomagnetic produces an smoother representation of the vTEC and allows for a better interpolation, especially in the South American low latitude region. Finally, Section 5 remarks the outstanding points of the paper.
2. Brief description of LPIM

LPIM implements ionospheric maps computation in three stages: (i) pre-processing; (ii) calibration; and (iii) interpolation. This section provides a brief overview about the general process performed by LPIM; the interest reader is referred to (Brunini et al., 2004a,b) for details. Stages (ii) and (iii) are described with more details in Sections 3 and 4.

The main task performed by the pre-processing stage is the computation of the ionospheric observable from dual-frequency carrier-phase GPS observations, which is obtained based on the fact that the range-delay that the ionosphere produces in the GPS measurements is proportional to the stEC along the satellite–receiver line-of-sight and inversely proportional to the square of the signal frequency. Hence, subtraction of simultaneous observations at different frequencies leads to an observable in which all frequency-independent effects disappear but the ionospheric and any other frequency-dependent effects remain present:

\[ L_{i,arc} = sTEC + B_R + B^S + C_{arc} + \varepsilon_L, \]

(1)

where \( L_{i,arc} \) is the carrier-phase ionospheric observable – the sub-indices arc refers to every continuous arc of carrier-phase observations, which is defined as a group of consecutive observations along which carrier-phase ambiguities do not change –; \( B_R \) and \( B^S \) are the so-called satellite and receiver inter-frequency biases (IFB) for carrier-phase observations; \( C_{arc} \) is the bias produced by carrier-phase ambiguities in the ionospheric observable; and \( \varepsilon_L \) is the effect of noise and multi-path. All terms of Eq. (1) are expressed in Total Electron Content units (TECu), being 1 TECu equivalent to 10\(^{16}\) electrons per square meters.

Dual-frequency P-code observations lead to an analogous ionospheric observable:

\[ P_I = sTEC + b_R + b^S + \varepsilon_P, \]

(2)

where the meaning of the terms is analogous to Eq. (1) with the following distinctions: different satellite and receiver IFBs (\( b_R \) and \( b^S \) instead of \( B_R \) and \( B^S \)); there is not any ambiguity term; and the effect of noise and multi-path, \( \varepsilon_P \), is around 100 time greater.

The calibration module of LPIM relies on the thin-shell and the mapping function approximations (Davies and Hartmann, 1997). Based on those approximations, Eq. (1) is written in the following way:

\[ L_{i,arc} = \sec(z') \cdot \nuTEC + \gamma_{arc} + \varepsilon_L, \]

(3)

where \( \sec(z') \) is the mapping function, \( z' \) being the zenith distance of the satellite as seen from the point where the signal crosses the thin-shell (the so-called piercing point) that, in the case of LPIM, is located 450 km above the Earth’s surface; \( \nuTEC \equiv \cos (z') \cdot sTEC \), is the equivalent vTEC at the piercing point; and \( \gamma_{arc} \equiv B_R + B^S + C_{arc} \) is a calibration constant that encompasses, all together, receiver and satellite IFBs and the ambiguity term. The calibration, i.e. the estimation of \( \gamma_{arc} \) for every continuous arc, is performed independently for every observing receiver in the network. To accomplish this task, the equivalent vTEC is approximated by a bilinear expansion dependent on the piercing point coordinates:

\[ \nuTEC \equiv a(t) + b(t) \cdot (\hat{\lambda}_t - \lambda_0) \cdot \cos(\mu_t) + c(t) \cdot (\mu_t - \mu_0), \]

(4)

where \( t \) is the Universal Time of the observation, \( \hat{\lambda}_t \) and \( \mu_t \) the geographic longitude and the modip latitude of the piercing point and \( \lambda_0 \) and \( \mu_0 \) the geographic longitude and the modip latitude of the observing receiver (readers not familiarized with modip latitude are referred to Section 4). The dependence on time of the expansion coefficients is approximated with ladder functions:

\[ x(t) = a_i, \quad \text{for} \quad t_i \leq t < t_i + \delta t, \quad i = 1, 2, \ldots, \]

(5)

where \( x \) represents anyone of the coefficient \( a, b, \) or \( c \); and \( \delta t \) is the interval of validity of every planar approximation (5\(^m\) in the case of LPIM).

Merging all together the observations gathered by a receiver in a given interval \( \Delta t (\Delta t = \delta t) \), and arranging appropriately Eqs. (3)–(5), LPIM forms an overdetermined linear system of equation of observations that contains, as unknowns, the calibration constants for all observed continuous arcs, \( \gamma_{arc} \) (\( arc = 1, 2, \ldots, N_{arc} \)), and the constant coefficients of the planar fits, \( a_1, \ldots, a_m, b_1, \ldots, b_m, c_1, \ldots, c_m \) (\( m = \Delta t/\delta t \)). Since we are not interest on the coefficients, they are reduced from the system by means of a Gaussian elimination process and then, the system is solved by the Least Squares methods, hence estimating the \( n_{arc} \) calibration constants, \( \hat{\gamma}_{arc} \). Finally, the observations are calibrated and the equivalent vTEC are estimated from Eq. (3):

\[ \nuTEC \equiv \nuTEC_{\text{c}} + \frac{\varepsilon_L}{\sec(z')} = L_{i,arc} - \frac{\hat{\gamma}_{arc}}{\sec(z')} \]

(6)

In order to ensure calibration of complete arcs, LPIM processes, in any run, 36\(^h\) of data from \( -6^h \) to \( 30^h \) UT, but retains the vTEC values for the interval from \( 0^h \) to \( 24^h \) UT.

The interpolation module of LPIM starts from the equivalent vTEC given by Eqs. (1)–(6) for all receivers in the network. Those values are binned into UT intervals of \( 1^h \) and then, a set of coefficients of a spherical harmonic expansion up to degree and order 15 are estimated by the Least Squares method, for every interval. The expansion is expressed in terms of the geographic longitude and the modip latitude of the piercing point. After the coefficients are estimated, they are used to compute a regular grid of vTEC every 1 h.

To close this section we would like to remark that two different mathematical representations of the vTEC have been used: one is the bilinear expansion given by Eqs. (4) and (5), which is used for a single-site representation in the network.
3. TEC calibration

The so-called “levelling carrier-to-code” (or simply “levelling”) is a widely used procedure to reduce the ambiguity term, $C_{arc}$, from the carrier-phase ionospheric observable given by Eq. (1). It relies on the fact that, even if the P-code ionospheric observable is much more contaminated by noise and multi-path than the carrier-phase one, Eq. (2) shows that it is not affected by the ambiguity term. If Eqs. (1) and (2) are subtracted, and all the differences for every continuous arc are averaged, results:

$$
\langle L_{arc} - P_i \rangle_{arc} = C_{arc} + B_R - b_R + B_s - b_s - \langle \varepsilon_P \rangle_{arc},
$$

where the symbol $\langle \cdot \rangle_{arc}$ indicates the average for all data in the continuous arc; noise and multi-path on carrier-phase observations have been neglected in Eq. (7). Then, subtracting Eq. (7) from Eq. (1), the ambiguity term is reduced from the carrier-phase ionospheric observable:

$$
\tilde{L}_{arc} = L_{arc} - \langle L_{arc} - P_i \rangle_{arc}
= sTEC + b_R + b_s + \langle \varepsilon_P \rangle_{arc} + \varepsilon_L,
$$

where $\tilde{L}_{arc}$ is the levelled ionospheric observable. Eq. (8) shows that, after the levelling process: (i) the carrier-phase IFBs are replaced by the corresponding P-code IFBs (often called differential code biases, DCBs); and (ii) the levelled ionospheric observable may be affected by a levelling error, $\langle \varepsilon_P \rangle_{arc}$ due to the P-code noise and multi-path that may not average to zero in a continuous arc.

A very simple experiment to assess the magnitude of the levelling error may be performed with data from two GPS receivers, $A$ and $B$, separated one from another by few meters, so that the sTEC can be considered equal for both receivers. From Eq. (8) follows that the differences $\Delta L_{arc}$ of the levelled ionospheric observable from the same satellite collected simultaneously by both receivers:

$$
\Delta \tilde{L}_{arc} \equiv \tilde{L}_{arc,A} - \tilde{L}_{arc,B}
= b_{RA} - b_{RB} + \langle \varepsilon_P \rangle_{arc,A} - \langle \varepsilon_P \rangle_{arc,B} + \varepsilon_L - \varepsilon_L,
$$

should be equal to a constant that does not depend on the observed satellite but on the difference of the receivers DCBs, $\Delta b_{RA} = b_{RA} - b_{RB}$. It is expected that the data belonging to different arcs deviate from $\Delta b_{RA}$ by the combination of the levelling errors of the same arc observed by the two receivers, $\Delta \langle \varepsilon_P \rangle_{arc} \equiv \langle \varepsilon_P \rangle_{arc,A} - \langle \varepsilon_P \rangle_{arc,B}$. Small deviations, $\Delta \varepsilon_L \equiv \varepsilon_L,A - \varepsilon_L,B$, are also expected due to carrier-phase noise and multi-path. Carrying out this experiment with several pairs of nearby GPS receivers belonging to the IGS network, and also from some dedicated experiment performed by ourselves, we found leveling errors due to P-code multi-path that ranged from 1.4 to 5.3 TECu in a way that strongly depends on the receiver/antenna configuration (Ciraolo et al., 2007). Just to illustrate the problem, Fig. 3 shows differences of the levelled ionospheric observable computed with observations gathered by two nearby GPS receivers. In order to make the figure readable, we have depicted the results for a few satellites and days, but the general behaviour observed in this figure, i.e. a large spread between the results belonging

![Fig. 2. Typical South American regional ionospheric map of vTEC for quiet ionospheric conditions (August 23, 2005, 0h–1h UT) computed with LPIM in the framework of the SIRGAS pilot experiment; vTEC values are in TECu.](image)

![Fig. 3. Differences of the levelled carrier-phase ionospheric observable in TECu from two nearby GPS receivers (stations WTZA and WTZJ, Wetzel, Germany) for five satellites along four consecutive days.](image)
to different arcs, is present for all satellites and for other days and, also, for other pairs or nearby receivers.

After those experiments we decided to abandon the leveling procedure and work directly with the carrier-phase ionospheric observable. Thus implies to estimate an arc dependent calibration constant, \( \gamma_{\text{arc}} \), for every observing receiver, as stated in Eq. (3). Just to exemplify the benefit of this approach, Fig. 4 shows the equivalent vTEC computed with LPIM from GPS data gathered by four nearby receivers, by applying: (a) the leveling procedure and then estimating the satellites and receivers DCBs; and (b) overcoming the leveling procedure and estimating an arc-dependent calibration constant, \( \gamma_{\text{arc}} \), for every receiver. The improvement from the point of view of self-consistency of the result is quite evident.

Before closing this Section, it is work to mention that carrier-phase ambiguities can be accurately estimated by applying precise geodetic techniques and then reduced from the ionospheric observable (e.g.: Hernández-Pajares et al., 2002), but this procedure increase the complexity of the computation.

4. vTEC interpolation

The interpolation problem arises from the need to create a regular data grid from scattered observations in order to map the vTEC in the desired region. As it was mentioned in Section 2, LPIM accomplishes this purpose by adjusting a spherical harmonic expansion every 1st UT to the equivalent vTEC computed from the observations of all receivers of the network. A well-known rule for interpolation states that the smoother the function to be interpolated, the better the accuracy of the interpolated values. This simple rule helps to understand why the use of the modip latitude improves the accuracy of the vTEC interpolation in the South American region in respect of the results obtained with the most commonly used geomagnetic latitude (Azpilicueta et al., 2005).

The modip latitude, \( \mu \), was firstly proposed by Rawer (1984) for modeling the F2-layer and the top-side ionosphere and it is defined by:

\[
\tan \mu = \frac{I}{\sqrt{\cos \varphi}},
\]

where \( I \) is the magnetic dip at 350 km above the Earth’s surface and \( \varphi \) is the geocentric latitude. Modip equator is the locus of points where the magnetic dip is 0. Approaching the equator, modip isolines become closer one to each other and parallel to the modip equator, but as modip increases they become sparser and come nearer to those of constant geographical latitude. Both, geographic and modip poles are identical. The geomagnetic latitude is obtained by best fitting a dipolar magnetic field to the main Earth’s magnetic field (Fraser-Smith, 1987).

Both panels of Fig. 5 show the same data set: the vTEC derived from dual-frequency observations performed by the TOPEX altimeter onboard the TOPEX/Poseidon (T/P) mission (http://www.aviso.cls.fr/html/missions/tp/wellcome_uk.html). The figure encompasses 90-days of data (from 60 to 150 of 1999), just the period that T/P needs to sample all local times all over the Earth. Fig. 5 depicts those data that fall within the 14h–16h LT interval, which is the period of the day when the Equatorial Anomaly gets its maximum deployment. It is worth to note that TOPEX does not need strong approximations (as GPS do) to extract the vTEC from the measurements. In the panel (a) of Fig. 5 we have superimposed isolines of modip latitude, while in panel (b) we have superimposed isolines of geomagnetic latitude. Due to the action of the South Atlantic Geomagnetic Anomaly, the largest deviation between modip and geomagnetic isolines occurs at low latitudes in the South American and the surrounding oceanic areas. Fig. 5 shows that, particularly in that region, the vTEC structures measured by TOPEX approach closely the modip isolines (a) rather than the geomagnetic isolines (b).
From the previous analysis it follows that the vTEC interpolation should perform better if the modip latitude (instead of the geomagnetic one) is used because the low latitude vTEC is less variable when it is represented as a function of that coordinate. In order to quantify this assertion, we have compared LPIM’s GIMs computed using the modip latitude, with the corresponding GIMs computed by two analysis centers that belong to the IGS Ionosphere Working Group (CODE and JPL) and make use of the geomagnetic latitude. The following procedure was applied (Azpilicueta and Brunini, submitted for publication-a): (i) 2-hourly LPIM GIMs were computed for the whole year 1999; (ii) the corresponding 2-hourly GIMs computed by CODE and JPL were downloaded from the IGS-IWG web site; (iii) TOPEX vTEC values for the whole year 1999 were computed from raw dual-frequency TOPEX observations provided to users through the AVISO facility; (iv) CODE, JPL, and LPIM GIMs were evaluated for the time and location of every TOPEX vTEC value (in order to treat all the GIMs with the same computational procedure, LPIM’s GIMs were presented in the same format than the other GIMs, i.e. 2-hourly IONEX format grids); (v) finally, the differences (hereafter called “residuals”) between TOPEX vTEC and every GIM were computed.

Fig. 6 shows the residuals of the CODE (a), JPL (b), and LPIM (c) plotted versus modip latitude. The solid line and the bars represent the average and the standard deviation of the residuals inside every 1° interval of modip latitude. Since residuals are defined as TOPEX- minus GPS vTEC, positive values mean that GPS vTEC is underestimated with respect to TOPEX vTEC (which is inconsistent with the fact that GPS satellites are much higher than the TOPEX/Poseidon satellite). The mean global residual (i.e. the residuals averaged for all latitudes) for JPL’s GIMs is close to 0, while for CODE’s and LPIM’s GIMs is close to +4/+3 TECU. A variety of bias sources coming from either, GPS and TOPEX vTEC, have been suggested as candidates to cause a systematic underestimation of the GPS vTEC or overestimation of the TOPEX vTEC (e.g. Imel, 1994; Brunini et al., 2005; Azpilicueta and Brunini, submitted for publication-b), but the analysis of this problem is not the matter of this paper. Disregarding this issue, Fig. 6 shows that LPIM’s GIMS residuals are characterized by more stabilized residuals and by a reduction of around 25% of the standard deviations in the Equatorial Anomaly region.

5. Final remarks

SIRGAS manages the largest network of continuously observing GNSS receivers in the Caribbean, Central, and South American regions (around 100 receivers by 2006). In spite that the Amazonian and surrounding regions are almost not covered by SIRGAS observations, the network provides the best data coverage currently available in South America. With the aim to promote new scientific researches that diversify the applications of the GNSS observations, SIRGAS initiated an experiment devoted to establish a regular service to compute and deliver ionospheric maps based on (but not exclusively) SIRGAS observations. The experiment aims to improve the performances of the currently available GPS-based vTEC models, particularly in the South American region, where the presence of the Equatorial and the South Atlantic anomalies makes the vTEC distribution extremely complex.

GESA laboratory belonging to the Facultad de Ciencias Astronómicas y Geofísicas of the Universidad Nacional de La Plata computes ionospheric maps in the framework of the SIRGAS pilot experiment. These ionospheric maps...
exploit all the GPS data available in the South American region and are computed using the La Plata ionospheric Model (LPIM). The outstanding characteristics of LPIM are the \( s \text{TEC} \) calibration procedure and the use of the modip latitude for \( v \text{TEC} \) interpolation. The calibration procedure relays on the estimation of an independent calibration constant for every observed arc and every observing receiver that encompasses altogether the ambiguity term and the receiver and satellite DCBs. This procedure avoids the errors caused by the levelling procedure that, depending on the receiver/antenna configuration, may reach 5 TECu. The analysis of TOPEX observations confirms that the low latitude \( v \text{TEC} \) distribution approaches better the modip rather than the geomagnetic latitude, particularly in the region of the South Atlantic Anomaly. By using the modip latitude, LPIM improves up to 25\% the interpolation of the \( v \text{TEC} \) with respect to other approaches that make use of the geomagnetic latitude.

Since July 2005, a continuous time series of hourly maps are released to the community through the Internet (http://cplat.fcaglp.unlp.edu.ar) in the framework of the SIRGAS experiment. Once the reliability of those maps, as well as the continuity and regularity of the service can be affectively assessed by SIRGAS, the experiment will conclude with the establishment of a regular service. The accumulation of a large time series of hourly maps may be useful to characterize the variability of the \( v \text{TEC} \) in the complex South American region, as well as the effects that large geomagnetic storms produces on that ionospheric parameter. Some applications of the maps are also foreseen in the framework the studies that are being carrying out with the aim to establish a GNSS augmentation service in the region.

Concerning the future of this initiative, three main tasks are currently being done: (i) validating and assessing the accuracy of the maps by means of comparisons with external results; (ii) increasing the time resolution of the maps; and (iii) preparing the LPIM algorithm for real time computation.

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