Ionospheric Tomography with GPS Data from CHAMP and SAC-C

Miquel García-Fernández[1], Angela Aragón[1], Manuel Hernandez-Pajares[1], Jose Miguel Juan[1], Jaume Sanz[1], and Victor Rios[2]

[1] gAGE/UPC, Mod C3 - C. N.- Jordi Girona 1-3, 08009 Barcelona, Spain
[2] Physics Department, Univ. Nacional de Tucuman, Argentina

Summary. Abel inversion offers a straightforward way to obtain the vertical distribution of electron density with low computational load. Nevertheless the treatment of the electron density above the LEO orbit must not be neglected, specially for satellites with very low orbit such as CHAMP. This work extends previous results obtained by inverting real GPS data from LEO data, coming from satellites such as CHAMP or SAC-C. In this work, the topside ionosphere is modelled using positive elevation data. To overcome the spherical symmetry assumption, occultations are processed with the aid of Vertical Total Electron Content, estimated from ground GPS data or models. The resulting electron density profiles are compared with external real data consisting basically on basic parameters or true-height vertical profiles obtained from ionosonde measurements.

Key words: GPS, LEO, Electron density, Occultations, Abel transform, Separability hypothesis

1 Introduction

As it is known, Abel inversion techniques are used to obtain high vertical resolution electron density profiles ([3],[4],[9]) which performance may vary between 10% and 20% for foF2 estimations. The assumption of spherical symmetry is not realistic in general, and in particular for occultations where high Vertical Total Electron Content (VTEC) gradients take place. For Low Earth Orbiters (LEO) such as GPS/MET or SAC-C (with nominal orbits of 700km approximately), an exponential extrapolation may be enough to account for the electron content above the LEO [7]. Nevertheless, a more accurate modeling for LEOs at very low orbit such as CHAMP (approx. 400km) is required in order to avoid this assumption leading to incorrect vertical profiles. Therefore, other approaches should be considered. For instance, a modelling of the topside ionosphere with an external model [8]. This work proposes to extend the performance study of two modifications on the classical approach in order to, first, overcome the assumption of spherical symmetry by using horizontal VTEC gradients and, second, model the electron content above the LEO satellite, which becomes crucial for LEOs such as CHAMP, by using LEO GPS observations associated to positive elevation.

The classical approach of Abel inversion assumes spherical symmetry (i.e. electron density only dependent on height) and neglects the electron content above the LEO receiver. Considering that each ray of a radio occultation defines a spherical shell of the atmosphere, the Slant Total Electron Content (STEC) seen by the LEO can be modelled using a discrete form as shown in Eq. 1. Therefore the electron density can be computed in a recursive way starting from the outer ray (the one with greatest distance between ray and earth surface)

$$STEC(p_i) = \sum_{j=1}^{i} 2 \cdot l_{ij} \cdot N_e(p_j) \tag{1}$$

where l_{ij} and $N_e(p_j)$ stand for the ray path length crossing the j-th layer when the i-th observation is carried out and the electron density value at the j-th layer, respectively. In order to overcome the limitations of the assumption of spherical symmetry, an alternative formulation was introduced in [7] and further developed in [2] stating the *separability hypothesis* expressed in Eq. 2.

$$N_e(LT, LAT, H) = VTEC(LT, LAT) \cdot F(H) \tag{2}$$

The vertical profile can be expressed as the product between a VTEC function depending on the latitude, longitude and universal time and a height (H) dependent shape function F, the unknown to be determined through the iterative process of Abel inversion. Moreover, an extra unknown is added to the STEC in order to account for the electron content above the LEO, F_p. Therefore, taking into account the STEC expression and the upper ionosphere and plasmasphere contribution, the $L_I \equiv L_1 - L_2$ (GPS geometric free combination) can be expressed as:

$$\begin{aligned} L_I(p_i) &= b_I + \alpha \cdot l_p \cdot VTEC(LT_{ip}, LAT_{ip}) \cdot F_p + \\ &\alpha \cdot \textstyle\sum_{j=1}^{i} l_{ij} \cdot [VTEC(LT_{ij}, LAT_{ij}) + VTEC(LT'_{ij}, LAT'_{ij})] \cdot F(p_j) \end{aligned} \tag{3}$$

where $\alpha = 1.05 m_{L_I}/10^{17} e/m^2$, LT_{ip} and LAT_{ip} are the slab plasmaspheric pearce point coordinates and l_p the corresponding length, $VTEC(LT_{ij}, LAT_{ij})$ and $VTEC(LT'_{ij}, LAT'_{ij})$ are the VTECs at the two locations of the j-th spherical layer illuminated by the i-th ray. The information about the VTEC gradients has been obtained by means of a data driven model provided by the Technical University of Catalonia (UPC) in IONEX format ([1] and [6], using the GPS ground receiver network of the Interational GPS Service (IGS). In the data pre-processing a cycle-slip detection is performed, nevertheless a carrier phase ambiguity estimation is required. The extra unknown b_I accounts for the carrier phase ambiguities and clock biases. If the occultation shows large number of cycle slips in the negative elevation observations, it is not possible to estimate all ambiguities and the inverted profile is likely to be unrealistic. Therefore, a manual check of the profiles is required as well as a previous step to validation with ionosondes.

2 Results with Separability Hypothesis

2.1 Scenario

The study performed comprises a period of 16 days, from the 1st to the 16th of November 2002. Abel inverted estimations of electron densities and heights are carried out for CHAMP and SAC-C data for these days. In order to evaluate them, the occultations have been checked with the measured parameters provided by ionosondes that are mainly placed in mid latitudes (the ionosonde data, basically autoscaled for the period of this dataset, has been obtained from the SPIDR web server). As a general procedure for comparison, it has been considered that for a single occultation and ionosonde the valid comparisons were those made with the ionosonde measurements comprising an interval of 1 hour centered at the epoch that the occultation took place. Moreover, the maximum co-location distance between an ionosonde and the occultation has been set to 2000km.

The separability hypothesis requires a constant slab thickness during the occultation ($\tau = VTEC/NmF2$, with NmF2 as the electron density peak over the ionosonde location), that is a proportional relationship between the NmF2 and VTEC. Therefore, the dispersion of the slab thickness as a function of the local time has been studied for checking the consistency of the measured values of peak density of the ionosondes and VTEC computed from the GPS ground data. A statistical filter of τ (bias and standard deviation, σ, for local time) has been designed and outliers (values outside 3σ) have been discarded. This filter basically rejects extremely large/low values of slabthickness and peaks in its temporal variation. Around 10% of measurements are discarded by this filter. Note that the shape function at the peak of the profile is in fact the inverse of the slab thickness. When the slab thickness does not show a constant behaviour, the VTEC will not be able to describe the variations of the electron density, leading to an increase of the error in the estimation.

2.2 foF2 estimation

Table 1 summarizes the performance regarding the comparison of critical frequencies of the F2 layer (i.e. foF2) provided by the ionosondes with spherical symmetry and separability hypothesis Abel transforms of CHAMP and SAC-C data. These results are distinguished through three moments along the day: Day, Dawn/Dusk (D&D) and Night. This distinction is necessary because the D&D period is characterized for a high variability in the profile (both in density and height). For both satellites, the results show that the performance with respect to ionosonde measurements significantly improve under the separability assumption in all cases (about 40%). It is remarkable that under both assumptions, the worst results are obtained at night time, when the foF2 maximum decreases. During this period, as well as during D&D, the

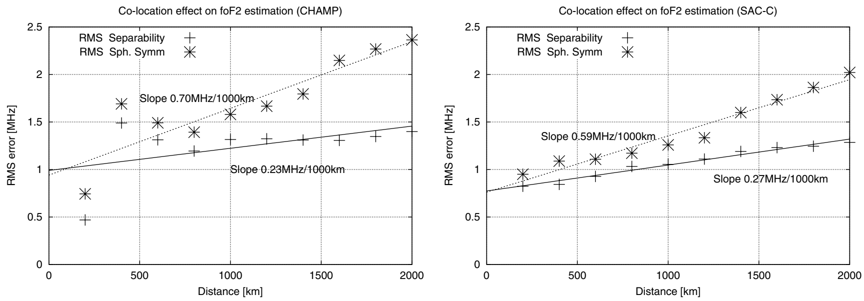

Fig. 1. Effect of the collocation distance to the absolute RMS error of foF2 estimation with respect to Ionosonde measurements: CHAMP vs Ionosondes (left) and SAC-C vs Ionosondes (right). The large absolute error at small distance (in the left plot) is explained by a comparison with high error, while the number of comparisons is still low. As distance increases, the number of comparisons increases as well and the effect of this occultation is mitigated and masked by the effect of the co-location distance.

Table 1. CHAMP and SAC-C results for foF2 estimation

		nr. compar.	Abs. Err. [MHz] Separability	Rel. Err. [%] Separability	Rel. Err. [%] Classic Abel
CHAMP	Day	1966	1.40	14.4	24.3
vs	Dawn/dusk	189	1.14	21.5	42.0
Ionos.	Night	879	1.55	28.4	54.6
SAC-C	Day	5868	1.29	12.5	19.6
vs	Dawn/dusk	529	0.97	18.1	27.6
Ionos.	Night	1946	1.29	25.4	41.4
CHAMP	Day	286		13.6	22.0
vs	Dawn/dusk	26		23.6	52.0
SAC-C	Night	143		23.2	39.6

slab thickness variations can be coped with to a certain extend by the separability hypothesis, thus providing better results than from spherical symmetry. Notice that the relative error for CHAMP is greater than for SAC-C at any of the day time periods. This is due to the difficulty of modelling the ionosphere above the LEO. Moreover, the increase of distance between the ionosonde and the occultation becomes a source of error, as shown in Fig. 1, being more important in the case of classical Abel inversion.

2.3 Upper ionosphere and plasmasphere estimation

In order to account for the electron density above the LEO, the proposed method includes an extra unknown of the shape function (F_p) as shown in

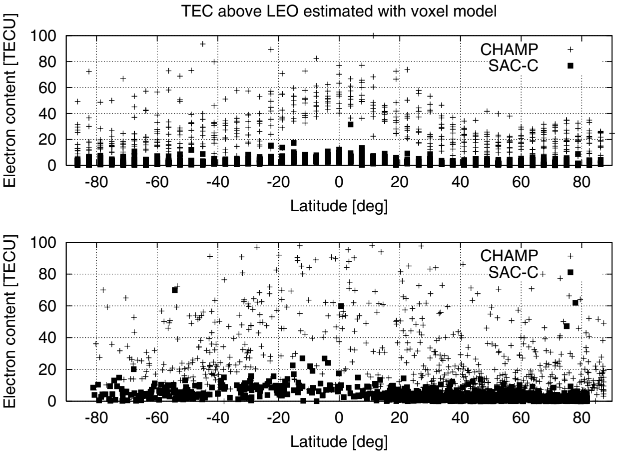

Fig. 2. Electron content estimation above LEO orbit: comparison between voxel model (top) and the independent estimates performed in each occultation (bottom).

Eq. 3. To check the validity of the approach, the upper ionosphere and plasmasphere estimation has been compared to a voxel model [5]. Fig. 2 shows the electron content over CHAMP and SAC-C for the 29th of October 2002 estimated with the voxel model using all Precise Orbit Determination (POD) antenna data simultaneously (with an elevation mask of 10^o, upper plot), and computed as an extra unknown with no aprioris where occultations have been processed separately (bottom plot). It can be seen that the estimations using both approaches are compatible.

3 Summary and Conclusions

This study has been focused on the implementation of shape functions using the CHAMP and SAC-C data set which take into account the height dependency in the electron density expression. This approach is an improvement over the classical spherical symmetry assumption. From comparing with ionosondes and intercomparison between CHAMP and SAC-C, it has been shown that the error due to co-location is significantly reduced by estimating the electron density profile using shape functions, as a consequence, the frequency estimation performance is better (average value 30%). With the proposed method, the upper ionosphere contribution does not affect significantly the electron density estimates.

Acknowledgement. We are grateful to the IGS, UCAR and the GeoForschungsZentrum Potsdam for providing the ground GPS data, the SAC-C data and the CHAMP observations respectively. The ionosonde data have been extracted from *SPIDR*, http://spidr.ngdc.noaa.gov. This work has been partially supported by the *Generalitat de Catalunya* under the fellowship 2000FI00395 and the Spanish projects TIC-2000-0104-P4-03 and TIC-2001-2356-C02-02.

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