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Combining ionosonde with ground GPS data for electron density estimation

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Abstract Dual frequency Global Positioning System (GPS) receivers provide integrated total electron content (TEC) along the ray path (slant TEC, affected by a bias). By inverting this observable, it is possible to obtain the vertical total electron content with some assumptions about the horizontal structure of the ionosphere. The large number of permanent receivers distributed around the world provide enough information to obtain such TEC observables with high spatial and temporal resolutions. Nevertheless, the geometry (mainly vertical) of the ground GPS observations does not allow to solve the vertical structure of electron density of the ionosphere. Mixing different kinds of complementary data in a tomographic context helps to overcome this problem. Several works have obtained successful results achieved by combining occultation and ground GPS data to estimate the local three-dimensional structure of ionospheric electron density. This paper proposes the use of just ground data to obtain similar or better results. To do this, the ground GPS data are mixed with vertical profiles of electron density derived from ionosonde data instead of GPS occultation observations. In this paper, the complementarity between vertical profiles of electron density (estimated using the NeQuick model) and ground GPS data (from GPS IGS permanent network) are shown as well as the performance of the resulting combination.

Keywords: GPS; Ionosonde; GPSMET; Occultation; Electron density 3D description

1. Introduction

The main advantages of the ground Global Positioning System (GPS) data for ionospheric sounding is that one can expect to obtain accurate total electron content (TEC) esti- mates (with typical errors of few TECU). Moreover, for the time being, there are extensive GPS networks that provide the user with worldwide data availability. Nevertheless, this kind of data are unable to offer good vertical resolution for ionospheric tomography. On the other hand, ground-based ionosonde data offer high resolution up to the hmF2, but no real data are given about the topside ionosphere. Besides, only local vertical profiles are available. Recognizing that the advantages of one data type may compensate for the weakness of the other, one can expect two main features of this method: the acquisition of infor- mation above hmF2 (i.e. the “topside”), and a certain degree of vertical resolution where ionosonde data is not available. Several efforts have been made in the field of data combination for ionospheric sounding using ground and LEO GPS receivers (see for example Hernández-Pajares et al., 1998). Following the idea of data combination, the present paper is focused on obtaining a 3D description of the ionospheric electron density distribution by combining ground GPS data and vertical profiles of electron density re- trieved from ionosonde instead of GPS occultation data. To do this, a voxel approach has been chosen since it offers an easy and versatile way to combine data types with different features and properties (note that ionosonde data are only up to NmF2, whereas GPS data are up to 20000 km height). The paper is organized as follows: Section 2 (Combin- ing complementary data) contains an explanation on how the method is carried out. Section 3 (Results) is divided into two scenarios: the first one consists of picking up the minimum number of vertical profiles from ionosondes (one or two at most) and expanding in longitude/latitude (using ground GPS data) their vertical resolution. To evaluate the performance of the method in this scenario, the ionoson- des that have not taken part in the process have been used for comparison. The second scenario deals with the recon- struction of STEC profiles obtained by GPS/MET

observa- tions (using the proposed combination scheme) and offers a comparison with the actual ones. Finally, a section with the Conclusions ends the paper.

2. Combining complementary data

The ionospheric tomography considered in this work is based on voxels in which the electron density, in a Sun-fixed reference frame, is assumed to be constant within each cell. Previous works (Hajj et al., 1994) that have studied the va- lidity of this approach state that the voxel size must be small enough so that the actual variations within a cell are low with respect to that constant value. As done in Hernández-Pajares etal.(1999), the size of these cells has been set to 7:5◦ ×5◦ in local time and latitude, respectively. Taking into account that the data set considered occurs in the year 1995, during low solar activity, and the area of study is mid-latitude, this size does not introduce a significant mismodelling. Nevertheless, cell size should be reduced when studying low-latitude re- gions or periods with high solar activity. To account for the vertical variability of the electron den- sity, the ionosphere is divided in height as well. The con- figuration of the layer height is chosen based on geometric considerations, to be precise on how this configuration al- lows to distinguish between layers. This implies that cells must be large enough in height. The number of layers (eight in this work) is limited firstly by the geometry of data, and secondly by computer load. The second step in this approach is to estimate the elec- tron density using the carrier phase ionospheric combination of ground GPS receivers. In this work, we have used the LI ≡ L1 − L2, i.e. the ionospheric (geometric free) combi- nation of GPS carrier phases. This is due to the small er- ror of this observable (millimeter level) compared to the error that offers PI ≡ P2 − P1 or ionospheric (geometric free) combination of GPS code (meter level). The LI in a voxel model can be written according the following equa- tion (Hernández-Pajares et al., 1999, 2000):

$$L_{\mathrm{I}} = k \cdot \sum_i \sum_j \sum_k (N_{\mathrm{e}})_{i,j,k} \cdot l_{i,j,k} + bias$$

where LI is expressed in length units, (Ne)i;j;k is the elec- tron density in cell (i;j;k), li;j;k is the length of the por- tion of ray in cell (i;j;k), the constant k = 1:0506 [meters of delay m2 =1017 electron], and bias includes the unknown corresponding to the instrumental delays and phase ambi- guity. The inverse problem is solved in order to find the electron densities and biases by means of a weighted least mean square approach. The reference frame considered is a Sun-fixed one, and the area of study is a regional (European) zone. Due to the Earth's rotation, it gives the system dy- namics, the ground GPS and ionosonde stations illuminate cells corresponding to the selected European zone within a time span of less than 3 or 4 h. Within this period the electron density is considered stationary. Therefore, Kalman filtering is not necessary in this case. Nevertheless, this as- sumption may introduce a significant mismodelling during ionospheric storms. The geometry of rays between GPS satellite and ground receiver is mainly vertical. This fact causes high correlations on the estimations of the different cells in the vertical because there is no reliable information about vertical distribution of the electron densities. In order to compensate for this lack, the combination of complementary data is considered. This combination is done in the last step of the process, where the estimation computed with GPS ground data is modified using constraints obtained with the additional data.

2.1. Complementarity of ionosonde data

The feasibility of tomography of the ionosphere has been conducted previously by several works (see for example Howe et al., 1998). In Hajj et al. (1994), the complementarity between ground and low Earth orbiter data was stated using simulated data, while on the other hand, Hernández-Pajares et al. (1998) performed ionospheric tomography using ground and space GPS real data. The re- constructed vertical profiles were compared with the actual ionosonde derived values. Fig. 1 is an example in which the complementarity of models can be seen based on

ionosonde data with respect to ground GPS data. In this figure, an example of an esti- mated profile (for Slough, see Fig. 3) is plotted using only ground GPS data and the solution after constraining with an ionosonde (in this case El Arenosillo is the constraining ionosonde). Before using vertical information (ionosonde), one can expect good estimations of TEC (GPS ground data solution). But regarding the vertical performance, since the 1000 -0.1 0 0.1 0.2 0.3 0.4 0.5 Height (km) Electron density Estimation for Slough at 10hUT constraining El Arenosillo NeQuick for Slough Before Ionosonde Constraining After Ionosonde Constraining values of cells in the vertical are highly correlated, the pro- cess gives nonrealistic profiles. If data with vertical informa- tion is introduced, these correlations are diminished giving a more realistic solution and results close to actual profiles derived from ionosonde data. This result shows that profiles of electron density modelled by using ionosonde data sig- nificantly helps to orientate the solution computed with only ground GPS data. In this work, the vertical information of electron density will be given by the vertical profiles of NeQuick model in- stead of LEO GPS data. This model is constructed up to the hmF2 from ionosonde NmF2 and M3000 measurements, see Hochegger et al. (2000). Before constraining the GPS solution, the values of electron densities obtained from ionosondes are averaged in height (according to the width of the tomographic model layers). By doing this, one will have averaged the values of electron densities at the same heights that were selected to compute the GPS solution. After this has been done, one proceeds to apply the con- straining scheme. This is divided into two parts: (1) Up to hmF2, actual values of averaged electron den- sities from the constrained ionosondes are used to constrain the GPS solution. The reason is because the values of electron density under the hmF2 are calcu- lated from observed parameters. (2) Above hmF2, ratios between values of modelled elec- tron density are used to fix a relationship in height between densities in cells. This type of constraint is used to consider a model for the topside ionosphere (the NeQuick values for the topside are based on a semi-Epstein function). To compute the final solution a Gauss–Markoff model with constraints (see Koch, 1988) obtained from ionosondes has been implemented, which is equivalent to stating that the data coming from ionosonde are given a very high weight than the GPS data.

3. Results

The formal errors will depend, among other factors, on the noise level of the measurement and the relative weights assigned to each of the data types considered in the proce- dure (in this work an error of 0:1TECU for all GPS phase measurements has been assumed). To determine the value of these weights may be a diQcult task and, besides, the formal error of the model may be realistic only to a limited extent and only useful to discard the estimates with large errors (outliers). The formal errors obtained show typical values of 0:1e10e=m3 . These values provide an RMS ≈ 1TECU in the observation minus calculus (residual). To complete the evaluation of the error, actual measure- ments that have not taken part in the estimation of the elec- tron densities have been used for comparative purposes. In this context, and based on the different real data consid- ered to evaluate the performance, two different scenarios are proposed: (1) estimation of electron density using data from ground GPS receivers and the minimum number (one or two at most) of ionosondes, and (2) reconstruction of GPS/MET occultations STEC using data from ground GPS receivers and all ionosonde data available. This study has been carried out for the days of October 17th, 18th and 19th, 1995. An ionospheric storm began in the evening of day 18 as shown in Fig. 2. The GPS network used in this work and the ionosonde locations correspond to the European re- gion (see Fig. 3). The distances between ionosondes can be seen in Table 1. The centers of the eight considered layers have been placed at 100, 150, 200, 250, 300, 400, 500 and 1000 km. The boundaries of the layers can be computed as the mid-distance between centers and it has been consid- ered an ionosphere is considered to start at 60 km and end at 2000 km.

3.1. Vertical profile reconstruction

The experiment of this section consists of computing ver- tical profiles using the ground GPS network and profiles up to hmF2 derived from the minimum number (one or two at most) of ionosonde measurements using NeQuick model. To evaluate its performance, the resulting profiles have been compared with the ones provided by the remaining ionoson- des that have not taken part in the process. Note that the ver- tical resolution obtained with the

proposed method is limited to eight shells, thus the comparison is done with the result- ing averaged value of electron density in the same layers686 -140 -120 -100 -80 -60 -40 -20 17 17.5 18 18.5 19 19.5 20 Dst Parameter (nT) Day of October (Universal Time) DST Parameter 17 17.5 18 18.5 19 19.5 20 TEC (TECUs) Day of October (Universal Time) VTEC over Europe VTEC @ El Arenosillo (-7E 35N) VTEC @ Slough (0E 50N) 340˚ 340˚ 345˚ 345˚ 350˚ 350˚ 355˚ 355˚ 0˚ 0˚ 5˚ 5˚ 10˚ 10˚ 15˚ 15˚ 20˚ 20˚ 25˚ 25˚ 30˚ 30˚ 35˚ 35˚ 40˚ 40˚ 45˚ 45˚ 50˚ 50˚ 20˚ 20˚ 25˚ 25˚ 30˚ 30˚ 35˚ 35˚ 40˚ 40˚ 45˚ 45˚ 50˚ 50˚ 55˚ 55˚ 60˚ 60˚ 65˚ 65˚ bor1 brus gope gras hers kosg lama madr&vill mas1 mate mets pots upad wett zimm zwen&mdvo ARENOSILLO JULIUSRUH MOSKOW ROSTOV SLOUGH Table 1 Table of approximate distances in km between ionosondes Arenosillo Juliusruh Moskow Rostov Slough 1700 1600 4200 4500 Rostov 5300 3000 1000 Moskow 5300 2700 Juliusruh 3000 computed with NeQuick vertical profiles (vertical resolu- tion of 10 km). Fig. 4 shows two examples of performance with the corresponding RMS, computed as the difference between values of electron densities at different heights. Table 2 shows the RMS of the comparison between the computed and NeQuick profiles in several cases, as well as the mean difference of hmF2 and NmF2. In the hmF2 com- parison takes into account that the lowermost cells are more or less 50 km in width and this point introduces an addi- tional source of error (the resolution of the method is 25 km in hmF2). Moreover, since the values of electron densities are averaged in height as explained in Section 2.1, this in- troduces an additional source of error in the NmF2 com- parison. The table has been divided in order to show the performance in low and high geomagnetic activity condi- tions, DST value above or under −40 nT, respectively (it has only been considered the beginning of the ionospheric storm, before October 20th, which does not include the com- plete evolution of it) and with one and two ionosondes as constraints. Initially, only El Arenosillo is constrained. The choice of this ionosonde is to diminish the spatial–temporal correlation between the constrained and test ionosondes. In this case, the error on high geomagnetic activity is clearly greater than the low activity case. This is due to the fact that the storm affected the central and northern ionosondes in a different way (slight decrease of VTEC over these lo- cations) with respect to those located in southern Europe 1000 0 0.1 0.2 0.3 0.4 0.5 0.6 Height (km) Electron density (*10^12 e/m^3) Comparison for Slough at 12hUT (12hLT) Profile RMS =0.03*10^12 e/m^3 Difference NmF2 = -6.22% Difference hmF2 = +30km Ground GPS data + Nequick data NeQuick profile for Slough 1000 0 0.1 0.2 0.3 0.4 0.5 0.6 Height (km) Electron density (*10^12 e/m^3) Comparison for Juliusruh at 17hUT (18hLT) Profile RMS =0.1*10^12 e/m^3 Difference NmF2 = +14.6% Difference hmF2 = 0km Ground GPS data + Nequick data NeQuick profile for Juliusruh (see Fig. 2). Therefore, since El Arenosillo ionosonde was selected to estimate the northernmost ionosondes, the results worsened significantly. To lessen this error, it was necessary to include to the model data from an ionosonde that was equally affected by this storm. Note that when a second northern ionosonde is added, the effect of the storm in the estimation error decreases. The lack of 100% agreement in the estimation of the con- strained ionosondes data is due to the interpolation scheme used in this work. The grid used is not adapted to the ionosonde coordinates. Thus, to obtain the estimation of a profile, an interpolation between the four nearest grid cen- ters is carried out. This explains why the error in the estima- tion of Juliusruh is smaller than the one from El Arenosillo when both are constrained: the coordinates of the former happen to be close to one of the interpolated grid centers, thus the value of these grid centers are directly the constrain- ing ones and the remaining grid centers' contributions (and thus their errors) are small. In the case of the El Arenosillo, the contributions of the four grid centers are equally impor- tant, thus diminishing the effect on the constraint over this station. From Table 2, it can be seen that this interpolation error ranges between 4e10e=m3 (worst case, El Arenosillo) and 1e10e=m3 (Juliusruh). The possibility of adapting the grid centers to the ionosonde coordinates improves the esti- mations of the constrained ionosondes. But there is no clear improvement in the estimated ionosondes and, besides, this feature increases the needed computer memory and comput- ing time. In high geomagnetic activity conditions the high variability of the ionosphere may increase this interpolation error. A more graphical comparison can be seen in Fig. 5 where the 1 to 1 relation between the NeQuick values of NmF2 (x-axis) and the computed ones (y-axis) has been plotted. It can be seen that Slough, which is inside the area limited by the coordinates of Arenosillo and Juliusruh, has less es- timation errors than Rostov.688 Table 2 Comparison between the computed electron density profiles with respect to those provided by the NeQuick model derived from ionosonde measurements Low geomagnetic activity High geomagnetic activity Profile RMS Di;. NmF2/Di;. hmF2 Profile RMS Di;. NmF2/Di;. hmF2 Arenosillo∗ 4 (112) −15:5%=2:1 km (24) 6 (107) −22:7%= − 16:3 km (19)

Juliusruh 6 (104) −18:6%= − 3:7 km (19) 19 (85) 139:2%= − 54:6 km (13) Moskow 8 (116) −6:4%= − 17:1 km (21) 15 (70) −9:1%= − 166:2 km (8) Rostov 7 (68) −23:8%= − 25:0 km (12) 16 (56) 77:1%= − 66:7 km (6) Slough 5 (88) −4:7%=16:9 km (13) 25 (42) 103:3%= − 87:5 km (8) Arenosillo∗ 4 (111) −11:2%=2:1 km (24) 6 (107) −27:7%= − 16:3 km (19) Juliusruh∗ 1 (97) −10:0%= − 5:0 km (18) 2 (84) −25:6%= − 31:5 km (13) Moskow 6 (102) 15:8%= − 15:6 km (18) 5 (67) −54:0%= − 81:9 km (8) Rostov 5 (56) −5:4%= − 31:1 km (9) 9 (56) −29:0%= − 83:3 km (6) Slough 4 (84) −0:3%=16:9 km (13) 5 (42) 5:7%= − 31:2 km (8) ∗The table gives the RMS (divided by 1010e=m3) of the difference between the complete profiles up to the maximum and the averaged difference of NmF2 and hmF2. It presents different situations, for low and high geomagnetic and with different ionosondes constrained (marked with an asterisk). In parentheses are the number of comparisons made for each case (all points of the profile for the RMS comparison and only the maximum for the NmF2 and hmF2 comparison).

3.2. GPS/MET occultations reconstruction

From April 1995–1997, the GPS/MET low Earth or- biter gathered, at 740 km approximately, the dual-frequency codes and phases of GPS satellites offering a valuable source of information for atmospheric sounding and in particular for ionospheric tomography. Works like Hajj et al. (1994) or Leitinger et al. (1997) used the ionospheric delay (propor- tional to the slant TEC) measured by GPS/MET to provide tomographic models with vertical information of electron density distribution. In this section, this observable will be used for validation purposes of the proposed approach. In this scenario, densities using ground GPS and all avail- able ionosondes have been computed. Afterwards, each ray from each GPS satellite to GPS/MET has been divided ac- cording to the cells it crosses. Once this has been done, a re- constructed STEC is generated by means of multiplying the length of each portion of the ray by the corresponding elec- tron density. Once all occultations have been reconstructed, they are compared with actual GPS/MET measurements. As is known, an occultation consists of a group of con- secutive rays seen with negative elevations. Fig. 6 shows a single ray of an occultation (upper) and the corresponding projection on a 2-D map of all rays that form an occultation (lower) using the same color coding. In the lower map of Fig. 6, the range of latitudes/longitudes covered by a com- plete occultation can be seen as well. The study of the oc- cultations provided by GPS/MET reTects that a great deal of rays go through the height where there is a maximum of electron density, thus providing valuable data to test the performance of its estimation in these regions. In Fig. 7, an example of reconstruction is given, the STEC (in TECU) is plotted against the minimum distance between 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 Estimated Electron density (*10^12 e/m^3) NeQuick Electron density (*10^12 e/m^3) Comparison for Slough, Low and High Geomagnetic Activity Slough, Low Geomag. Activity Slough, High Geomag. Activity 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 Estimated Electron density (*10^12 e/m^3) NeQuick Electron density (*10^12 e/m^3) Comparison for Rostov, Low and High Geomagnetic Activity Rostov, Low Geomag. Activity Rostov, High Geomag. Activity ray and earth surface (impact parameter D, see Fig. 6). The peak corresponds to the rays affected by the NmF2. To give a more general impression in Fig. 8 the mod- elled STEC against the observed STEC for all occultations considered on October 18th is shown (30 occultations, 1641 points to compare). It can be seen that the agreement is bet- ter for the reconstructions under the hmF2. This is due to the fact that under this height there are more resolutions in height (check the configuration of the height layers centers) and the constraints are built from a model anchored with ionosonde measurements (better constraint), leading to bet- ter estimations of electron density. This point can be seen in Fig. 7 as well, where for impact parameters above the max- imum there is a coarseness in the estimation. This is due to the fact that the upper layers are large in height and this implies worse resolution in the estimations.

3.2.1. Comparison with Abel Inversion

The observations gathered by GPS/MET have led to the use of inversion techniques such as Abel Inversion (Hajj and Romans, 1998; Schreiner et al., 1999) to perform vertical profiling of the ionosphere. Hernández-Pajares et al. (2000) showed that it is possible to retrieve profiles with Abel In- version from GPS occultations with a confidence of 10% on foF2 and FoE with respect to raw ionosonde data. This fact suggests that an equivalent way to check the

results obtained in this paper is to compare the vertical profiles obtained with Abel inversion techniques with those computed with the proposed method. Note that the results are obtained with different data, that is: Abel Inversion uses only GPS/MET data while the proposed method uses ground ionosonde and ground GPS receivers. Although both methods are indepen- dent, they give similar results (see Fig. 9 for an example of690 -20 0 100 200 300 400 500 600 700 800 STEC (TECU) Minimum distance Ray-Earth Surface (D in km) GPS Met occultation for GPS PRN 31 at 05hUT,October 18th, 1995 Observed STEC (GPS/MET) Reconstructed STEC(ground GPS+NeQuick prof.) 0 20 40 60 80 100 120 140 160 180 Reconstructed STEC (TECU) Observed STEC (TECU) +25% 0% -25% Under HmF2 Above HmF2 Regression lines Error lines comparison between both techniques). This shows how the technique explained in this work can give relevant informa- tion about topside ionosphere.

4. Conclusions

In this work, the feasibility of data combination has been shown between GPS ground data and vertical profiles com- puted from ionosonde data. The performance has been stud- ied in two different scenarios: (1) Electron density vertical profiles have been recon- structed using only one ionosonde and ground GPS data. (2) STEC profiles seen by GPS Met occultations have been reconstructed using all ionosonde and ground GPS data. 1000 0 0.1 0.2 0.3 0.4 0.5 Height (km) Electron density (*10^12 e/m^3) Profile RMS=0.08*10^12 e/m^3 Difference NmF2 = +1.6% Difference hmF2 = +47km Vertical profile using Abel Inversion Vertical profile using ground GPS + NeQuick The results obtained suggest that it is possible to recon- struct the electron density in regions where ionosonde data are not available by combining ground GPS and relatively far ionosonde data. The differences in this context are in general better than 25% in low geomagnetic activity con- ditions. Moreover, valuable information about the topside can be obtained using constraints based on ratios extracted from a certain model. Regarding the bottomside, it can be estimated using realistic data from a model like NeQuick, combined with measured ionosonde data. The estimation of GPS/MET revealed that it is possi- ble to obtain reconstructions of occultations with errors less than 25% for estimations under hmF2. To improve the ac- curacies obtained above this point more realistic plasmas- pheric models may be included. Once this topic has been studied, the validation scheme may consist of reconstructing non-occultations observations (with positive elevations) of GPS/MET or other LEO satellites. Future improvements of this model may be consid- ered. The interpolation scheme between grid centers may be improved in order to diminish the interpolation error. Moreover, new types of data such as those obtained from topside electron density information provided by iono- spheric sounders onboard satellites, 3D ionospheric models like NeQuick in its full version or UV information may be considered for further improvements on data combination. Hajj and Romans, 1998

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Figures

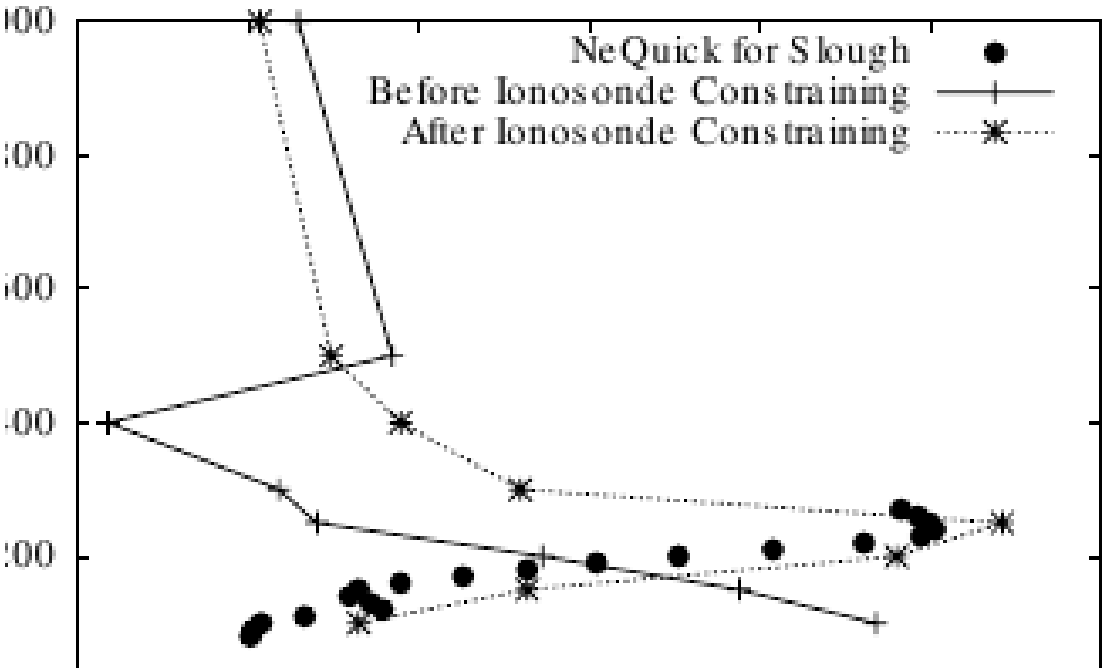
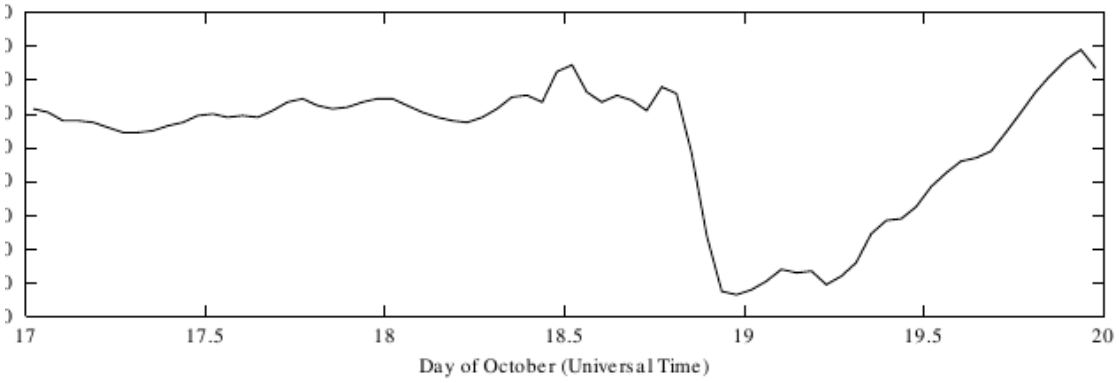


Fig. 1. E;ect of including ionosonde data to GPS electron density estimations. In crosses the electron density in the voxels have been estimated using only ground GPS data and this nonrealistic profile gives an account of the high correlations when this data are used alone. The solution with asterisks is obtained after constraining the "ground GPS alone" solution with ionosonde (in this case only the data from El Arenosillo ionosonde have been constrained). Circles are the reference values corresponding to Slough ionosonde. The epoch for this plot is October 18th, 1995 10 hUT. Locations of GPS and ionosonde stations are depicted in Fig. 3.



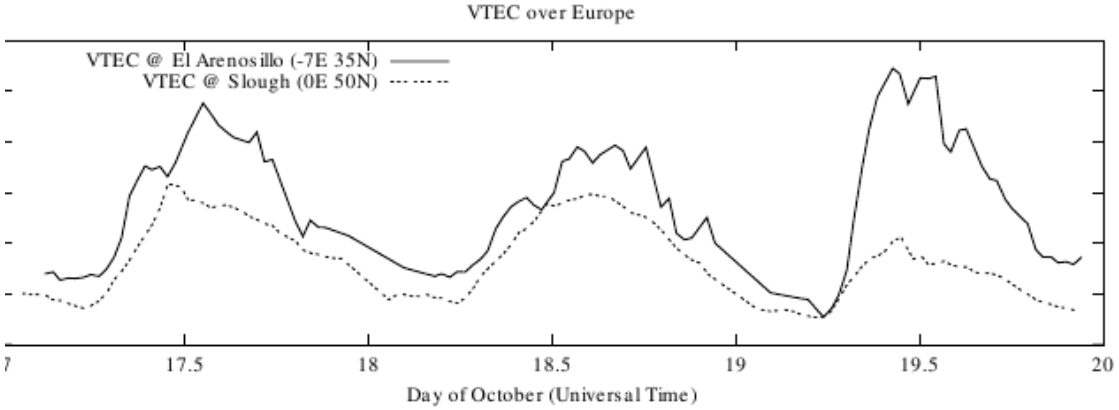


Fig. 2. Evolution of the DST parameter and VTEC during the study days of October 1995, 17th, 18th and 19th.

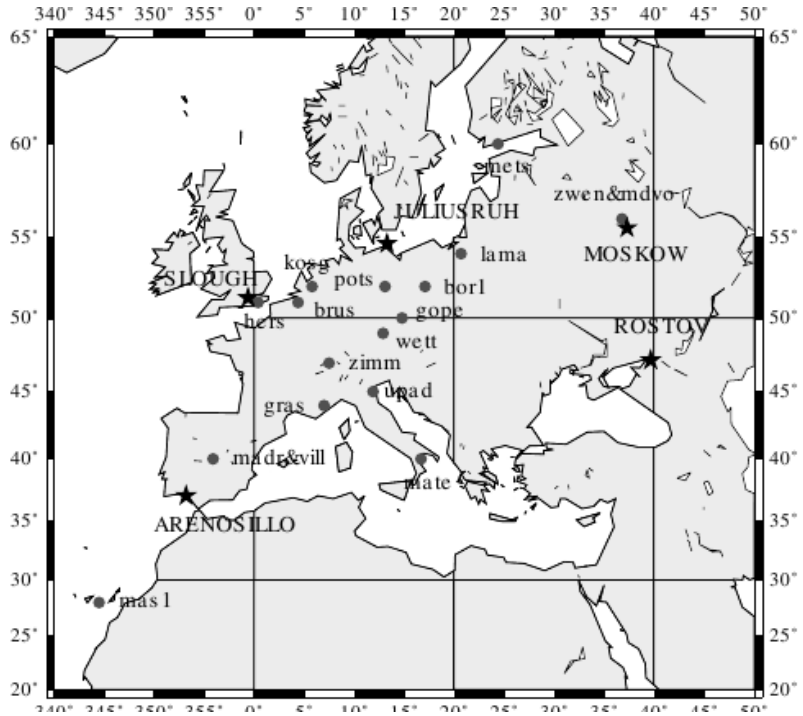


Fig. 3. Figure depicting GPS network and ionosonde stations where vertical profiles were obtained. Circles correspond to IGS GPS stations and stars to ionosonde stations.

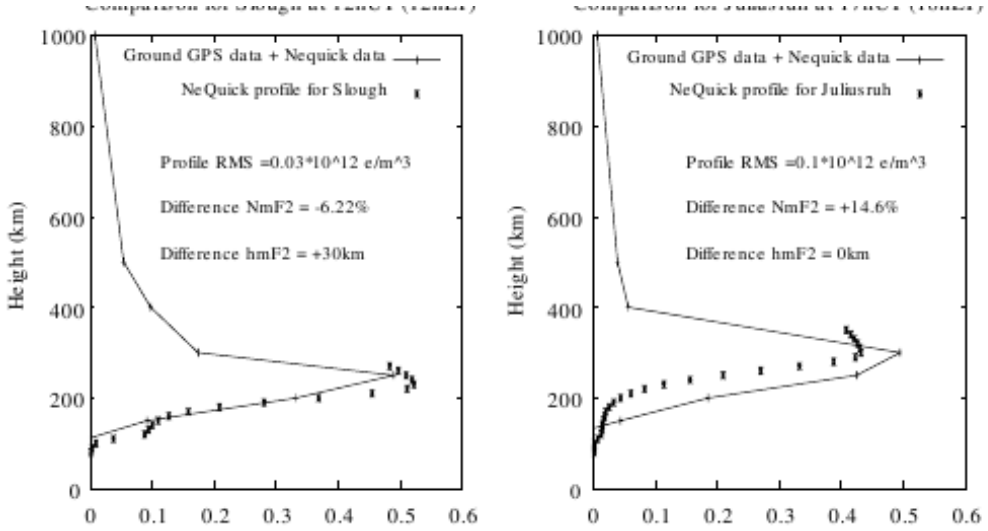
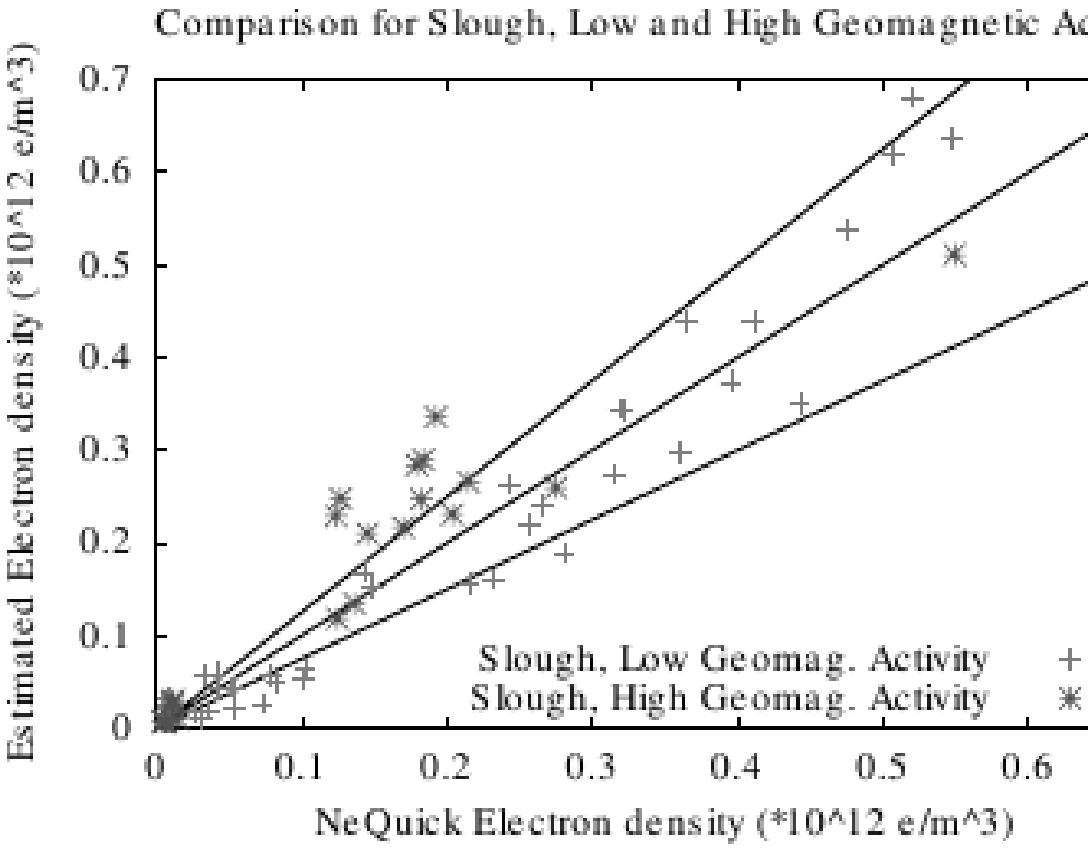


Fig. 4. Examples of performance and respective RMS for two different stations at different times when only Arenosillo ionosonde has been constrained. These plots correspond to October 18th, 1995, previous to ionospheric storm (Dst above −40).


Comparison for Slough, Low and High Geomagnetic Ac
Estimated Electron density (*10^12 e/m^3)
NeQuick Electron density (*10^12 e/m^3)
Slough, Low Geomag. Activity
Slough, High Geomag. Activity
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

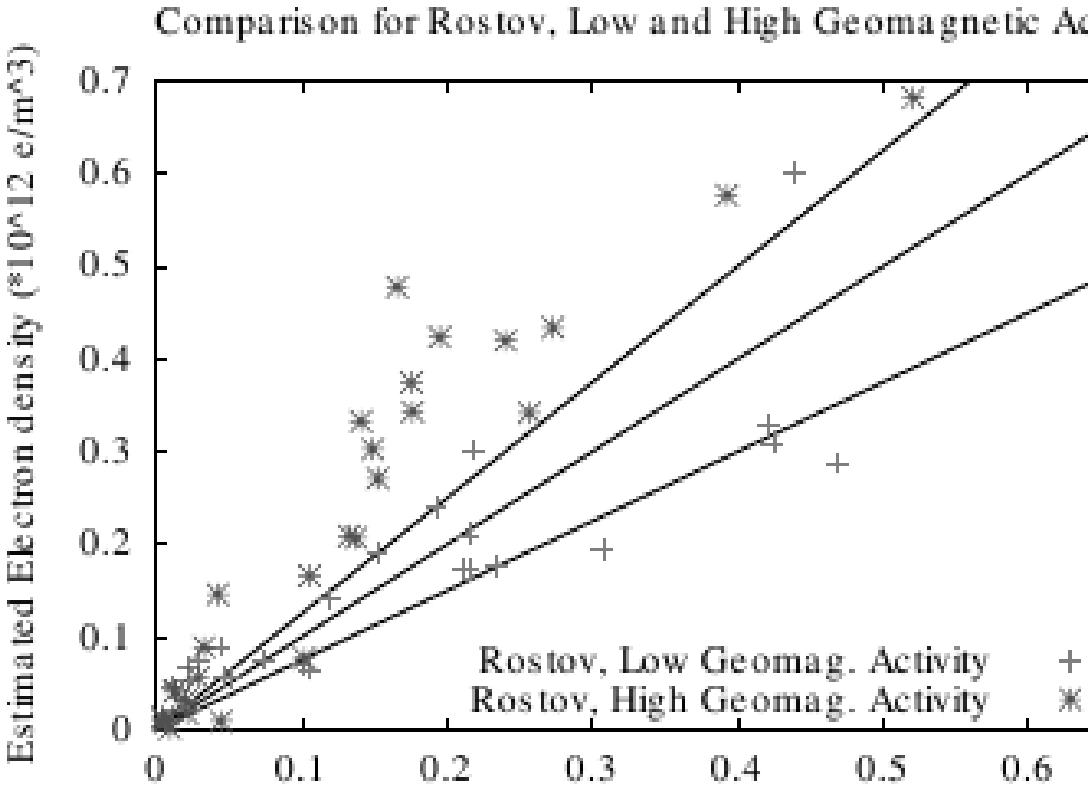

Comparison for Rostov, Low and High Geomagnetic Ac
Estimated Electron density (*10^12 e/m^3)
Rostov, Low Geomag. Activity
Rostov, High Geomag. Activity
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

Fig. 5. Comparison of estimations near hmF2 when Arenosillo and Juliusruh profiles have been constrained. The middle line cor- responds to 100% agreement while the side lines corresponds to agreement with 25% error.

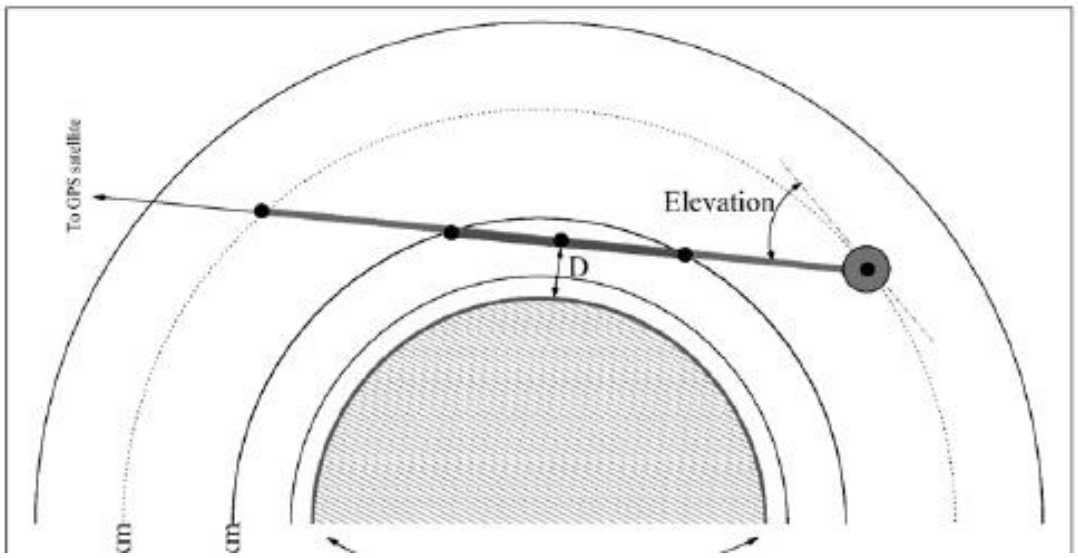


Fig. 6. Occultation of GPS/MET. Light grey lines in this figure reveal the portion of the ray comprised under the GPS/MET orbit height. On the other hand the dark grey lines indicate the portion of ray that crosses the region of maximum of electron density (under 400 km). Black line depicts the orbit of GPS/MET.

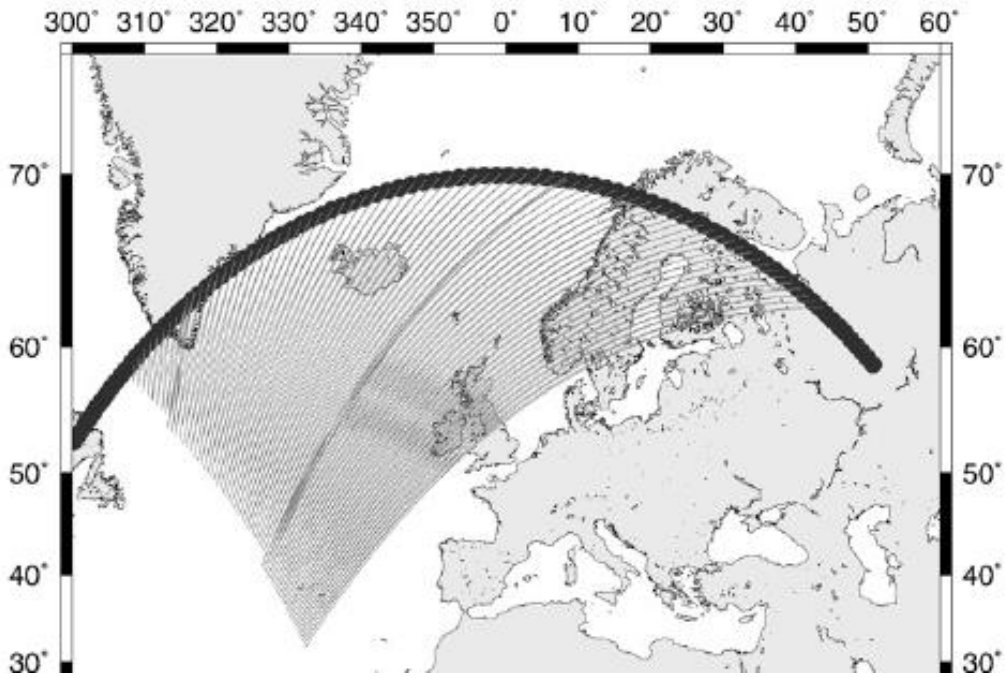
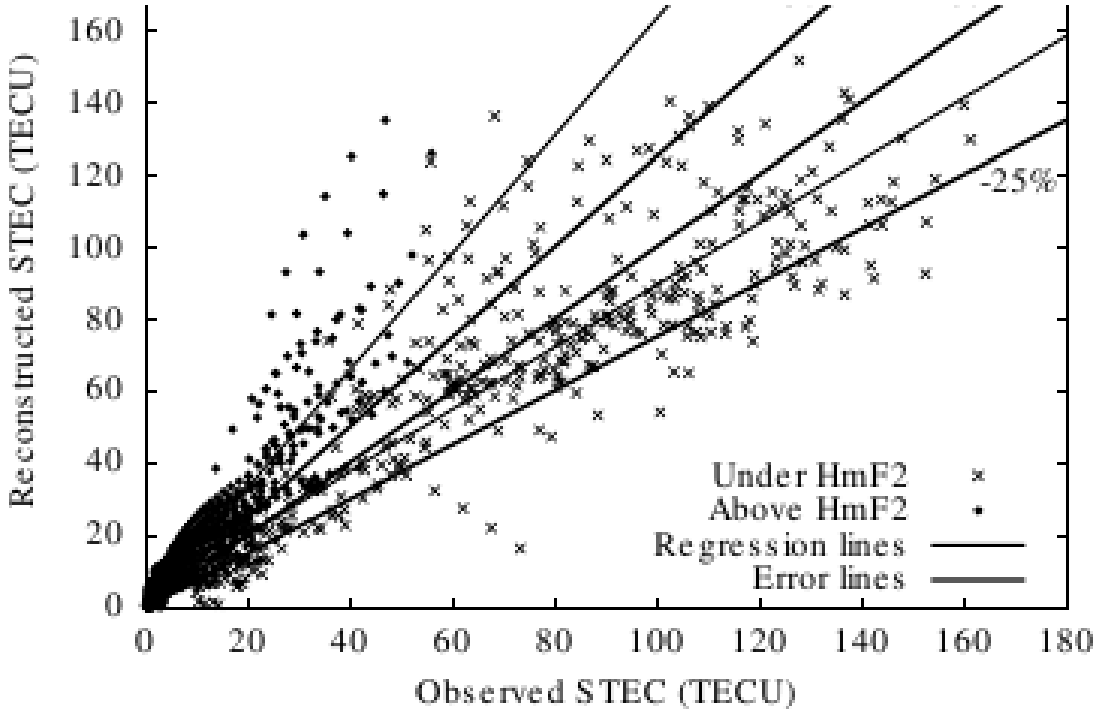


Fig. 7. Example of single occultation modelled with the ground GPS data and the NeQuick vertical profiles compared with the observation of GPS/MET.



ig. 8. Comparison between observed and modelled STEC. Con- trained by all ionosondes, October 18th, 1995. Middle line cor- esponds to perfect agreement while the side lines correspond to

Fig. 8. Comparison between observed and modelled STEC. Con- strained by all ionosondes, October 18th, 1995. Middle line cor- responds to perfect agreement while the side lines correspond to a 25% of error. The correlation coeQcients for linear regression above and under hmF2 are 0.819 and 0.755, respectively.

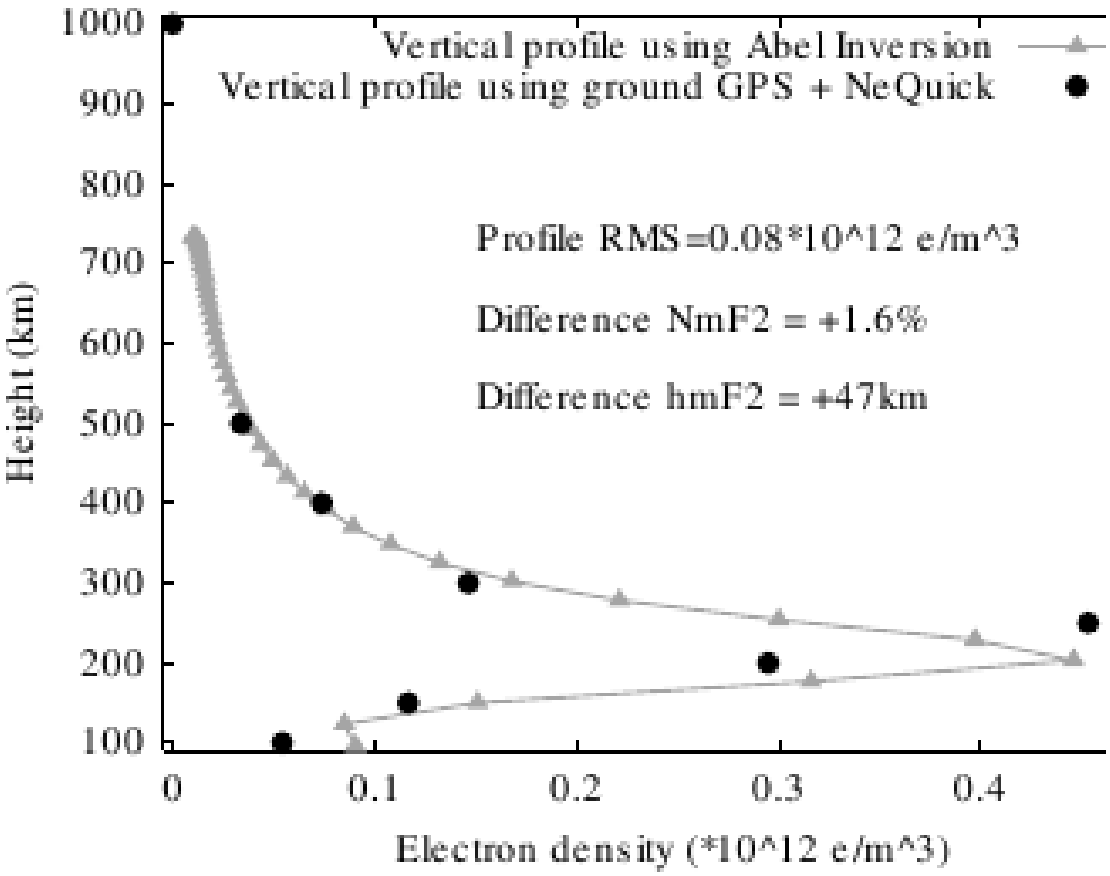


Fig. 9. Comparison between profiles obtained with Improved Abel Inversion (see Hernández-Pajares et al., 2000) and those estimated with ionosonde and ground GPS data.