[1]CONTRIBUTIONS TO IONOSPHERIC RECONSTRUCTIONS FROM LEO-GPS MEASUREMENTS

M. Materassi(1), C. Chong(2), C.N. Mitchell(3), P. Spalla(4), P.S.J. Spencer(5)

(1) Istituto di Fisica Applicata "Nello Carrara", C.N.R., via Panciatichi 64, 50127, Firenze (Italy), E-mail: maxmat@ifac.cnr.it

(2) University of Bath, Department of Electric and Electronic Engineering, Claverton Down BATH, BA2 7AY, U.K., E-mail: eepccc@bath.ac.uk

(3) As (2) above, but E-mail: eescnm@bath.ac.uk

(4) As (1) above, but E-mail: spalla@ifac.cnr.it

(5) As (2) above, but E-mail: eesps@bath.ac.uk

ABSTRACT

The MIDAS (Multi-Instrument Data Analysis System) algorithm can produce free-electron-density maps across a given ionospheric region from slant TEC values, and from ionosonde data giving local vertical profile information. However, satellite-to-ground slant TECs show a lack of horizontal and topside-crossing rays, yielding poor resolution on the vertical ionisation profile and on topside density. The addition of satellite-to-satellite slant TEC data from LEO-GPS measurements can be of help in fixing both the problems, as shown here by comparing inversions obtained with different combinations of instrumentation.

INTRODUCTION

In order to describe the electromagnetic properties of a region **H** of the sky for some continuous time interval, it would be necessary to assign the free electron density $N_e(\mathbf{r},t)$ in all the points **r** of **H** for each instant t of interest. Such maps are not obtainable by direct in situ measurements, but rather reconstructed via some inversion method.
Recently, new inversion techniques have been developed, namely the ionospheric ray-tomography techniques, that can reconstruct N_e in a certain region from the knowledge of the total electron contents (TECs)

$$d_g\left[N_e\right] = \int_g N_e(\mathbf{r},t)\,ds \tag{1}$$

along a suitable set of rays γ crossing **H**. If the region **H** is subdivided into a grid of volume elements $\mathbf{V}_1,\ldots,\mathbf{V}_N$ of constant free electron density $N_e = x_1,\ldots x_N$, there exists a matrix relationship between the collection $\underline{d} = (d_1,\ldots,d_M)$ of measured slant TECs along the paths $\gamma_1,\ldots,\gamma_M$ crossing **H**, and the collection of the unknown values $\underline{x} = (x_1,\ldots,x_N)$ of the density:

$$A\underline{x} = \underline{d}, \quad A \in \mathbf{R}^{M,N} \tag{2}$$

(where $\mathbf{R}^{M,N}$ is the set of real matrices with M rows and N columns. The coefficient A_{ij} is the length cut along γ_i within the volume element $\mathbf{V}_j$). In general, the matrix A is neither square nor invertible, and $\underline{x}$ must be found from (2) via some statistical algorithm. In our study the quantities $d_\gamma[N_e]$ are obtained by measuring the ionospheric Doppler phase shift on radio signals along their optical paths γ. The inversion technique employed here is described in [1]. It is clear that the reliability of the result depends on the number and on the geometry of the rays. The inversion algorithm used here is referred to as MIDAS, i.e. Multi-Instrumental Data Analysis System [1], and it allows for the integration of several sources of data into the inversion problem, yielding the possibility of resolving both space features and time evolution.
In the past Navy Ionospheric Monitoring System (NIMS) and Global Positioning System (GPS) signals received by ground stations have been used to construct the data column $\underline{d}$ [2], but the use of such measurements shows two important limitations to imaging N_e. First of all, the lack of near horizontal rays: the satellites always fly over the

---

[1] C.N.M. and P.S.J.S. are grateful to the UK Engineering and Physical Sciences Research Council for sponsoring the development of the MIDAS software

ground stations, and the transmitter-to-receiver paths keep being only slant. This brings into (2) very poor information about the behaviour of N_e with height, and the inversion can resolve the vertical profile only scarcely. Second, the GPS-to-ground rays are dominated by the ionospheric TEC and so the plasmaspheric and high topside information may be lacking. An attempt to obtain a better resolution of the behaviour of N_e with height is made by adding ionosonde data into the inversion. Some satisfactory improvements are obtained in this way up to the peak height. Addition of ionosonde data cannot however bring any improvement in the topside imaging.

The advent of LEO (Low Earth Orbiting) satellites is very promising both for imaging the topside ionosphere, and for improving the vertical behaviour of N_e reconstruction. Indeed, LEO orbital data provide with LEO-GPS slant TEC values along many paths across the topside; on the other hand, LEO occultation data, obtained as phase shifts along rays passing near planet's limb, provide with important information concerning the vertical profile of the ionosphere, since these paths are nearly horizontal [3]. CHAMP is a LEO satellite that started operating in July 2000, and is orbiting at an altitude of about 400 km; it is equipped with GPS receivers that collect both orbit and occultation data. Studies of CHAMP-MIDAS compatibility have already given encouraging indications for the use of CHAMP data in this field.

In this paper we make a comparison between different electron-density distributions obtained with different combinations of data in the imaging: NIMS, GPS, ionosonde and CHAMP orbital and occultation data.

DATA ANALYSIS

In the present study we have obtained ionospheric images from differential Doppler phase shift analysis on GPS-to-ground and NIMS-to-ground radio signals; in these inversions we put ionosonde data too, carrying some local information about the vertical profile of N_e. We studied the ionosphere over Europe and the northern part of the Mediterranean Sea from June to December 2001, and obtained the values of $N_e(\mathbf{r},t)$ for many days in this interval. The maps studied here are restrictions of the field N_e along a vertical plane of geographic longitude (λ) at 11.2°E, as shown in Fig. 1, Fig. 2, Fig. 3 and Fig.4, where the electron density is in units of 10^{11}electrons/m^3. In these figures, the time is UT. The vertical plane is roughly that containing the orbits of NIMS satellites passing over the chain of the four NIMS receivers of IFAC in Florence, L'Aquila, Gibilmanna and Lampedusa [2].

The solution of (2) is constructed assuming that the field N_e results from a combination of mathematical-model ionospheres. Then, the coefficients of such combinations become the unknowns of the problem, determined using SVD or similar statistic techniques. In the maps presented here we modelled the free-electron density by combining 3 orthogonal profiles (in the vertical), 40 latitudinal harmonics and 3 longitudinal harmonics. Then we assumed that every coefficient of the combination has a linear dependence from time and obtained one snapshot of the ionosphere per hour:

$$N_e(\mathbf{r},t) = \sum_{a=1}^{3}\sum_{b=1}^{40}\sum_{c=1}^{3}(\alpha_{abc} + t\beta_{abc})E_a(h)P_b(\cos\varphi)[\cos(c\lambda)+\sin(c\lambda)] \quad (3)$$

(in (3) the E_as are a set of empirical profiles, h is the height, φ is the geographic latitude. The functions $P_b(\cos\varphi)$ are Legendre polynomials). When (3) is put into (2) the αs and the βs become the unknowns.

An extended version of (3) would read

$$N_e(\mathbf{r},t) = \sum_{a,b,c}(\alpha_{abc} + t\beta_{abc})E_a(\mathbf{r})P_b(\cos\varphi)[\cos(c\lambda)+\sin(c\lambda)], \quad (4)$$

where the orthogonal profiles E_a ($\mathbf{r}$) are functions of the three space coordinates of the position $\mathbf{r}$. In our study the assumption (3) is applied.

The further step was the addition of data taken from CHAMP-GPS measurements. In doing this, the model combination setup was kept the same. Here two orientations of CHAMP data are used: orbit (off vertical) and occultation (near horizontal) data. Orbit data give the differential Doppler phase shifts along the paths connecting CHAMP and those GPS satellites orbiting above it. From these orbit data one gets the d_γs defined in (1) for the γs crossing the space between CHAMP and the GPS orbiting over it, and carrying useful information about the topside density. Occultation data give the ionospheric phase shifts affecting the CHAMP-GPS rays passing nearby the Earth's limb, and since these rays are almost horizontal occultation data hold information of help in the determination of the behaviour of the ionosphere with height. Then CHAMP data were included, and the problem (2) is solved again for the same time intervals, which gave N_e as a product of GPS, NIMS and ionosonde data merging only. New maps of the free electron density and the vertical TEC over Europe were obtained.

EFFECTS OF CHAMP DATA ADDITION

A comparison between the maps obtained without the use of CHAMP-GPS data, and those in which they are involved, renders it possible to get an idea about the net contribution given by adding the CHAMP-GPS data.

Here we compare the reconstruction of N_e obtained without CHAMP-GPS data, in Fig.1, and Fig.3, with that obtained involving them, in Fig.2 and in Fig.4. In Fig.1 and in Fig.2 only satellite-to-ground data are used, while in Fig.3 and in Fig.4 ionosonde data are used too. Fig. 5 shows the vertical TEC map obtained from the inversion that used all four types of data. The TEC map shows the increase to the south-west as expected for this time of day during quiet geomagnetic conditions.

The images obtained with or without CHAMP-GPS data are very similar to each other in the global structure, since they essentially show a thick and complex horizontal region of maximum ionisation between 200 km and 500 km height. Nevertheless, important differences appear. The region of higher density looks more richly structured in the reconstruction without CHAMP-GPS data, where the N_e contours form discrete features. When CHAMP-GPS data are involved a “simpler” ionosphere is viewed. For example, in Fig. 1 some local maximum of ionisation is seen between 65° N and 70ºN latitude at a height of say 290 km height, while there is no such maximum in Fig. 2. This can be thought of as a result of adding the occultation data: in fact, since N_e is reconstructed as a combination of many models, MIDAS sets it equal to some interpolated value of the models where no little or no data are present. Such oddities are hopefully removed adding new independent data from across these regions.

An improvement in the same sense seems to be gained also in the region above the peak, between 600 km and 1000 km height. In Fig. 1 this region is structured both with height and latitude gradients, while the same region appears basically stratified in Fig. 2.

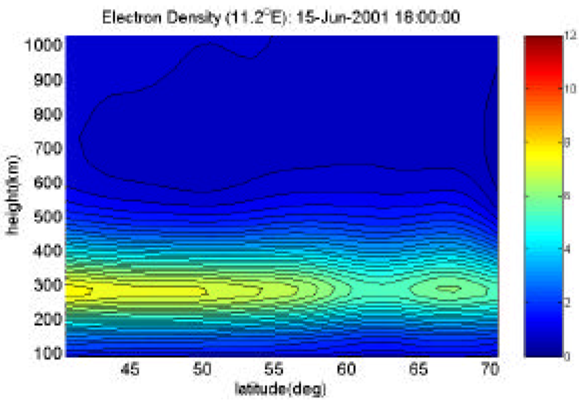

Fig. 1. Electron density (x10^{11} m^{-3}) from NIMS+GPS

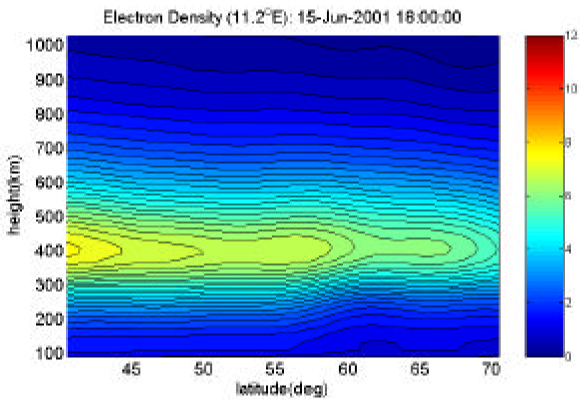

Fig. 2. Electron density from NIMS+GPS+CHAMP

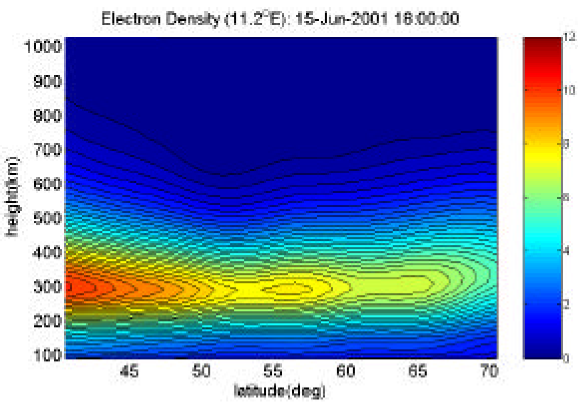

Fig. 3. Electron density from NIMS+GPS+ionosondes

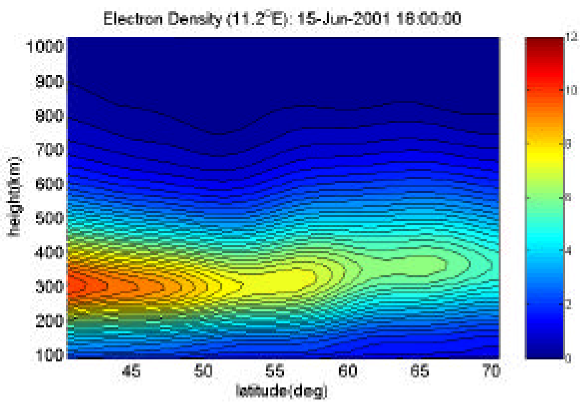

Fig. 4. Electron density from NIMS+GPS+CHAMP+ionosondes

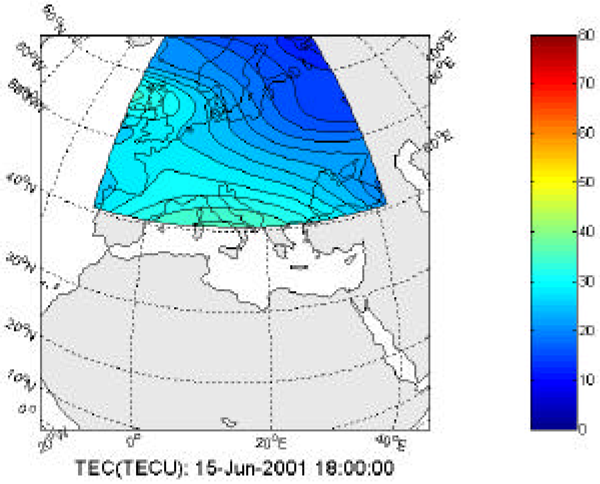

Fig. 5. Vertical TEC (TEC units) using all four data types

Let us consider the effect of adding ionosonde data in Fig. 3 and in Fig. 4: we have to compare Fig. 3 with Fig. 1, Fig. 4 with Fig. 2, and Fig. 3 with Fig. 4. Comparing Fig. 3 and Fig. 4 with Fig. 1 and Fig. 2 respectively, one can say that adding ionosondes magnifies the peak concentration of ionisation, and lowers its height in some regions when CHAMP-GPS data are involved. Latitudinal gradients also become higher when the ionosonde contribution is used.
Comparing Fig. 3 with Fig. 4 there appears a simplification in the pattern of N_e-constant levels around the peak at about 56º N, due again to the information enrichment given by occultation data. In the upper region the vertical gradients are reduced: this is probably a contribution due to CHAMP orbit data.

CONCLUSIONS

This preliminary study has shown the importance of combining information from different instruments to obtain ionospheric images. The regions to the south of the images (40 to 60°N) encompassed good satellite-to-ground coverage. However, north of this area the sparseness of satellite receivers enabled improvements to the imaging by including ionosonde or CHAMP data. This highlights the importance of the new radio-occultation satellites for imaging remote regions where locating ground-based instrumentation is difficult or impossible.
While occultation data are going to have a refining role in the vertical profiles, LEO-GPS orbit data will open a window of investigation on regions which are almost unexplored by tomography, the topside ionosphere and plasmasphere. New data on this region included between LEO and GPS heights will allow a re-formulation of problem (2), based on the extension of the functions $E_a(h)$ in (3) to the topside heights. This can lead to a comparison of theoretical models of the upper ionosphere with experimental data, and start a new investigation of that ionospheric region more closely connected with the interplanetary-space dynamics. It is the case to underline that when the far topside is studied, the assumption (4) is expected to fit better than (3), because of the non spherical structure of Earth's magnetosphere which insists dynamically on the topside. The study of how outer ionosphere physical models fit our experimental data is possibly done by solving (2) with (4) replacing the functions $E_a(\mathbf{r})$ with the models under study.
Ionospheric imaging is a tool to compare experimentally reconstructed maps of the field $N_e(\mathbf{r},t)$ and theoretically predicted values of it. This is why involving LEO-GPS data in this kind of studies will open important perspectives in the investigation of ionospheric physics. What emerges from the results of ours is that the inclusion of CHAMP-GPS data will sensibly improve the ionospheric imaging via ray-tomography.
It is also to observe that a detailed imaging of the outer ionosphere will be obtained only by using data from a complete constellation of LEO satellites, since the use of one such spacecraft only cannot carry enough information, due to the sparseness of LEO-GPS rays across this region.

ACKNOWLEDGEMENTS

The authors are grateful to Geo Forschungs Zentrum (GFZ) of Potsdam for putting CHAMP-GPS data at their disposal.

REFERENCES

[1] PSJ Spencer and C N Mitchell, Multi-instument Data Analysis System, Proc. Beacon Satellite Symposium, Boston, 2001
[2] M. Materassi, L. Ciraolo, P. Spalla, C.N. Mitchell, P.S.J. Spencer, "The Effect of the Northern Crest of the Equatorial Anomaly on the Propagation Delay at GPS Frequencies", in Proceedings of the V GNSS Symposium, Sevilla, 8-11 May 2001.
[3] G.A. Hajj and L.J. Romans, "Ionospheric Electron Density Profiles Obtained with the Global Positioning System: Results From the GPS/MET Experiment", *Rad. Sci.*, vol. 33, 175-190, 1998.