Tomographic imaging of the ionospheric structure and disturbances in the region of the East-Central Africa region

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Abstract. Knowledge of the ionospheric electron density distribution and its fluctuations are essential for models such as the International Reference Ionosphere (IRI) for predicting ionospheric characteristics for radio wave propagation and for other applications such as satellite tracking and navigation, etc. the Global Navigation Satellite Systems (GNSS), such as the Global Positioning System (GPS), can be used to determine the Total Electron Content (TEC) in the ionosphere. TEC is an important characteristic of the Earth's ionosphere that carries information on time and position variability of the ionosphere and has proved to be useful as a sensor of ionospheric climatology. However, such satellite to ground-based receiver measurements can only produce information about the density in the form of path-integrated snap-shots of the TEC. The challenge is to decompose its integral properly into the different values of N_e in order to generate the distribution of the N_e with altitude. In this study, we use the tomographic reconstruction techniques to successfully reconstruct the altitude structure of the ionosphere from TEC data. Using the data from the recently installed Africa Array GPS stations in the Central-Southern Africa region, we calculate three-hour average N_e profiles over this wide region using ionospheric tomography. The advantage of tomographic ionospheric N_e profiles is that they provide information of the N_e distribution up to global positioning system (GPS) orbiting altitude (with the coordination of space-based GPS tomographic profiles), and can be incorporated into the next generation of the IRI model. Since it uses real measurement data, tomographic average N_e profiles describe the ionosphere during quiet and disturbed periods. The computed average N_e profiles are compared with IRI model profiles. The study provides a good indication of the ionospheric electron density distribution and its fluctuations and how it compares with the IRI model in this region. This knowledge is essential in the adaptation of the IRI model for the locations and epochs of interest to enable data ingestion and assimilation necessary for transforming it into a real-time or near-real time ionospheric ionization N_e characterization model.

1. Introduction

Because of the wide application of the ionosphere in space science, knowledge of the ionospheric electron density (Ne) distribution is essential for several factors. For example, solar activity such as flares and coronal mass ejections often produce large variations in the particle and electromagnetic radiation incident upon the earth. Such variations can, in turn, lead to disturbances of the "quiet-time" magnetosphere and ionosphere. These disturbances, when affecting the ionosphere are known as ionospheric storms, tend to generate large disturbances in ionospheric density distribution, total electron content (TEC), and the ionospheric current system. Ionospheric storms have important terrestrial consequences such as disrupting satellite communications and interrupting the flow of electrical energy over power grids. Furthermore, irregularly structured ionospheric regions can cause diffraction and scattering of trans-ionospheric radio signals. When received at an antenna, these signals present random temporal fluctuations in both amplitude and phase. This is known as ionospheric scintillation. Ionospheric

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scintillation may cause problems such as signal power fading, phase cycle slips, receiver loss of lock, etc., and degrade the quality of satellite navigation systems.

It is therefore necessary to obtain knowledge of the ionosphere as this is a natural resource for radio wave propagation. It is essential for the purpose of error correction of GPS applications, over the horizon radar, navigation, surveying, geodesy, simplification of scientific research for Sun-Earth space physicists and so on.

Although ionospheric tomography has been introduced to provide broad spatial coverage of ionospheric density profiles, most previous tomographic campaigns were focused on determining instantaneous Ne profiles. Currently, there are not sufficient densities of ionosonde or incoherent scattering radar (ISR) facilities to make routine regional or global ionospheric Ne profiles. Therefore, global ionospheric models are used to “fill in” gaps in data coverage.

Ionospheric tomography, proposed by Austen et al. (1986), has developed from initial modeling studies to be a viable technique for monitoring ionospheric Ne profiles. The first experimental results were presented by Andreeva et al. (1990), while Pryse and Kersley (1992) presented the first observation in which a tomographic Ne profile was verified by ISR. Several experimental campaigns have been conducted since then (e.g., Raymund et al., 1993; Foster et al., 1994; Kunitake et al., 1995; Mitchell et al., 1997; Yin et al., 2004; Yizengaw et al., 2004, and the references therein). These studies have extensively validated the performance of tomographic reconstruction technique in providing accurate Ne profile of the ionosphere. However, all of these experimental campaigns were focused on extracting instantaneous or a few minute average Ne profiles using ground-based tomographic reconstruction of the slant total electron content (STEC). Therefore, tomography was not used to make average Ne profiles.

Currently, there are several models that provide a monthly mean value of ionospheric Ne distributions over an extended region of latitudes. Among these ionospheric models the international reference ionosphere (IRI)-2001, (IRI)-2005 and (IRI)-2007 models are the most particular. However, calculating the average Ne over an extended region of latitude from real measurements has been restricted to areas where ground-based ionosonde and ISR facilities are located. Therefore, average Ne profiles in the area where those instruments are not available are needed to develop and test model mean Ne profiles.

This paper introduces a technique that can be used to calculate average Ne profiles over a wide area of coverage, using real data measurements from ground-based GPS receivers. GPS receivers have a broader and denser global distribution than ionosondes and ISR. By applying the tomographic reconstruction approach to the GPS STEC, we calculate 3-h average Ne profiles over a wide area of coverage. These average Ne profiles are compared with IRI model Ne profiles and average Ne profiles obtained from available ground-based ionosonde observations.

2. Data and method

The GPS constellation currently consists of 29 satellites orbiting at ~ 55^0 inclination in six distinct orbital planes and at ~20,200 km altitude (~4.2L). Each satellite broadcasts two L-band signals at frequencies f_1= 1.57542 GHz and f_2=1.2276 GHz. Owing to the dispersive nature of the ionosphere, dual frequency GPS measurements can provide integral information about the ionosphere and plasmasphere by computing the differential phases of the code and carrier phase measurements recorded at the ground-based GPS receivers (Klobuchar, 1996).

For this study we use the algebraic reconstruction technique (ART) to invert the GPS STEC into two-dimensional (altitude and latitude) average density profiles.

The results presented in this paper are obtained from measurements made during experimental campaigns using GPS stations in the East-Central African region. The geographical locations of the GPS stations used are zamb(-15.42, +28.31), mong(-15.25, +23.15), tezi(-15.73, 26.02), mzuz(-11.43, +34.01), maua(-19.90, +23.53), ulub(-11.63, +27.48), dodm(-6.19, +35.75) and zomb(-15.38, 35.33).

We have taken all TEC data obtained in a single 3-h period on two particular days. A day that is relatively “quiet” (Kp <1) and the other a day that is relatively “disturbed” (kp > 5) and used them to derive tomographic images for each 3-h period on the respective days. The density values for individual pixels are then obtained from all STECs traversed through each pixel. This provides an averaged description of the ionospheric Ne distribution in a two-dimensional plane covering substantial spatial sections of the ionosphere. These images are then used to observe how the kp index affects the ionization and structure of the ionosphere. We observe the level of electron density, the structures in the ionization and so on. This describes what effect geomagnetic disturbance has on electron density and ionization of the ionosphere. Before 2009 tomography was not a viable technique in Africa as at the time only the IGS was present. Since then, AFREF and the Africa Array Networks have been brought into the picture. Those including the IGS have made tomography a plausible technique as it requires large densities of receivers. An example of a location with recently installed GPS stations is Zambia. With the new density of GPS stations, we have the ray path of the Array network looking more efficient. And now a comparison drawn between IRI simulations and tomography show distinctly that tomography reveals more structure and is denser in its findings.

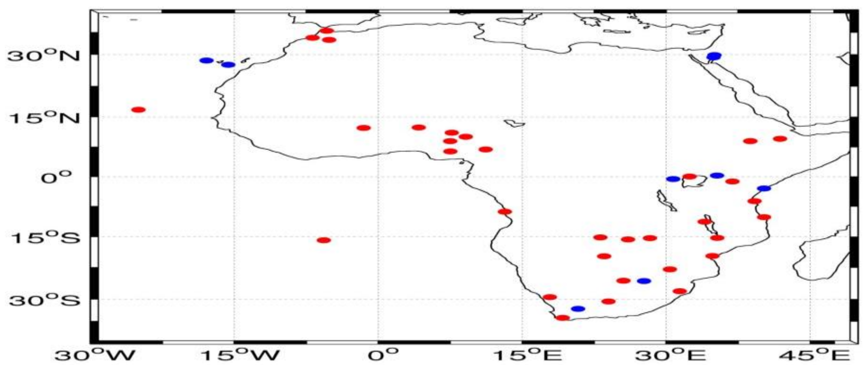
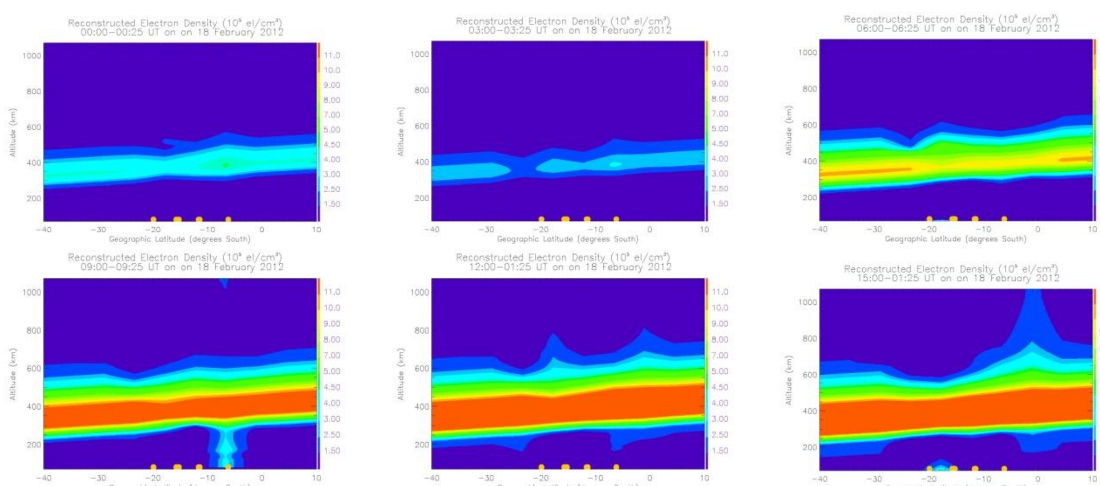


Figure 1 - Africa satellite stations (IGS in blue)

3. Results

Although we have presented the 3-h models for only two days, we have analyzed several case studies and extensively validated that the technique works.



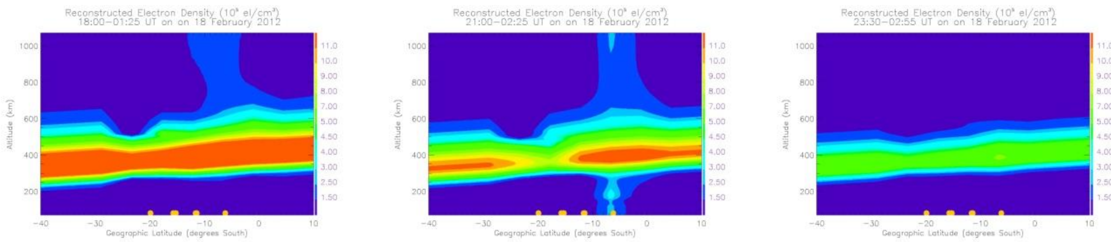


Figure 2 (a – i)

The quiet time period shows for the most part undisturbed structure, while the disturbed period shows different kinds of structure. We see in Figure 2 that the general structure is linear with very little disturbance showing.

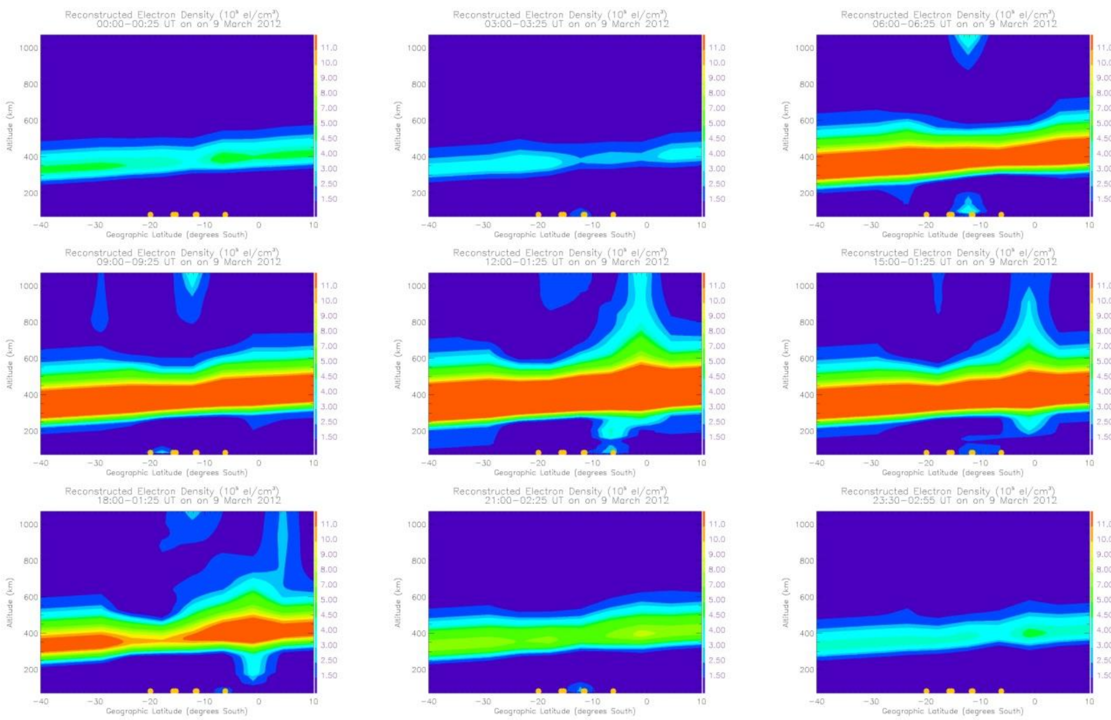


Figure 3 (a – i)

The disturbed period has a lot more structure and shows a lot more ionization. The evolution of ionization of the disturbed period is shown in Figure 3. The Ionosphere is ionized by solar radiation. The diagrams 2(a – i), show the evolution of ionization during the quiet day in the 3-h intervals and the diagrams 3(a – i), show the evolution of ionization during the disturbed time. We see that at night we have very little ionization, and this slowly changes as the night turns into day. We see a gradual formation of ionization in the shown structures. The regular variations that affect the extent of ionization in the ionosphere can be divided into four main classes: daily, seasonal, 11-year, and 27-day variations. The reason for the evolution we see in the images is clearly the daily variations. Daily variations in the ionosphere are a result of the 24-hour rotation of the Earth about its axis. Daily variations of the different layers are summarized as follows: The D layer reflects vlf waves; is important for long range vlf communications; refracts lf and mf waves for short range communications; absorbs hf waves; has little effect on vhf and above; and disappears at night. In the E layer, ionization depends on the angle of the sun. The E layer refracts hf waves during the day up to 20 megahertz to distances of about 1200 miles. Ionization is greatly reduced at night. Structure and density of the F region depend on the time of day and the angle of the sun.

This region consists of one layer during the night and splits into two layers during daylight hours. Ionization density of the F1 layer depends on the angle of the sun. Its main effect is to absorb hf waves passing through to the F2 layer. The F2 layer is the most important layer for long distance hf communications. It is a very variable layer and its height and density change with time of day, season, and sunspot activity.

We also see large scale structure such as the mid latitude trough (figure 2.h and 3.g), the equatorial anomaly (figure 2.c and 3.a), we also see a rise in ionization at the latitude 15^0S geomagnetic in both the quiet and disturbed times. It can also be clearly seen that the ionization during the disturbed period is a lot more evident than the quiet period even at night. The disturbed period is a lot more structured as well.

The main driving force for the establishment of the equatorial anomaly (Fejer, 1991; Mikhailov et al, 1994) is the east west electric field, which is westward during night-time. Therefore, the corresponding resultant **E** x **B** motion is downward. This is opposite of that required to produce the anomaly; so such vertically extended density features would not normally be present at night.

4. Conclusion

Although tomographically reconstructed density profiles have been extensively validated for the case of instantaneous Ne profile and documented in (e.g., Raymund et al., 1993; Foster et al., 1994; Kunitake et al., 1997; Yin et al., 2004; Yizengaw et al., 2004, and the references therein), comparisons of tomographic and directly measured ionosonde Ne profiles with the IRI-2001 model presented in this paper show that tomographic profiles describe the averaged behaviour of the ionosphere very well. This is important to single-frequency GPS users who depend on ionospheric models to achieve optimal positioning accuracy because the ionospheric signal delay is the largest error source for positioning and navigation with error source for positioning and navigation with GPS. However, since there is a reasonable agreement between tomographic and ionosonde profiles and that tomography goes on to give more information at the epoch of interest we see a validation of the technique. Tomography provides Ne profiles at specific epoch owing to the fact that it uses calculated GPS – TEC. Even though TEC being an integrated parameter is hard to incorporate, an ionospheric tomographic reconstruction routine using the algebraic reconstruction technique has made it possible. Other than that the technique being in this paper shows how the kp index of geomagnetic storms affect the characteristics of the ionosphere. Furthermore, tomography has an advantage over the relatively sparse ionosonde networks because it can be used to readily provide details of ionospheric structure over large regions. It also has the potential to provide a more accurate description of the average Ne of the ionosphere. This is especially true regarding the topside ionosphere since current models have to rely on density profiles obtained from the sparsely located ground-based instruments that provide mainly bottom side Ne profiles. The tomographic Ne profiles, which describe Ne distribution from ground up to GPS satellite altitude up to the GPS satellite altitude, can be used for the next generation of IRI models, enabling them to model the topside ionosphere more accurately. Once the technique is extensively validated and as long as dense arrays of GPS receivers are available, tomographic imaging can be used to augment sparsely located ground-based instruments, such as ionosonde and incoherent scatter radar.

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References

Andreeva, E.S., Galinov, A.V., Kunitsyn, V.E., Mel'nichenko, Yu.A., Tereshchenko, E.D., Filimonov, M.V., Chernykov, S.M., 1990. Radotomographic reconstructions of the ionization dip in the plasma near the Earth. Journal of Experimental and Theoretical Physics Letter 52, 145 -148.

Austen, J.R., Frnake, S.J., Liu, CH., 1986. Application of computerized tomography techniques to ionospheric Research. In: Tauriainen, A. (Ed.), Radio Beacon Constributions to The Study of Ionization and Dynamics of The Ionosphere and tp Corrections to Geodesy and Technical Workshop. Ouluensis Universitas, Oulu, Finland, pp.25 – 35.

Bilitza, D., 2001. International reference ionosphere 2000. Radio Science 36, 261 - 275.

Kersley, L., Pryse, S.E., Walker, I.K., Heaton, J.A.T., Mitchell, C.N., 1997. Imaging of electron density trough by tomographic techniques. RadioScience 32, 1607-1621.

Klobuchar, J.A., 1996. Ionospheric effects on GPS. IN: Parkinson, B,W., Spilker, J.J. (Eds), Global Positioning System: Theory and Application, vol. 1. American Instiute of Aeronautics and Astronautics INC.

Yisengaw, E., Dyson, P.L., Essex, E.A., Moldwin, M.B., 2005a Comprehensive ionosphere dynamics study over the Souther Hemisphere during the severe magnetic storm on 32 March 2001. Annales Geophysicae 23, 707-721.

Yizengaw, E., Wei, H., Moldwin, M.B., Galvan, D., Mandrake, L.L., Mannucci, A., Pi, X., 2005b. The correlation between mid =-latitude trough and the plasmapause. Geophysical Research Letters 32, L10102.