Development of Computerized Ionospheric Tomography Technique and its application to study the Equatorial Ionization Anomaly over the Indian region

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Abstract

The paper explores the development and validation of latest ionospheric monitoring technique known as computer added ionospheric tomography (CAIT) for its application in understanding the dynamics of ionosphere. The Total Electron Content (TEC) is derived from the differential Doppler method by receiving the two coherent radio signals from beacon receivers aligned in the same meridian. The estimated TEC is then further used to generate the 2-dimensional (2D) tomographic image with the help of the conventional Algebraic Reconstruction Technique (ART). The results show that the technique can be successfully utilized to study the 2D structure of electron density and Equatorial Ionization Anomaly (EIA) which is one of the most crucial phenomenons of equatorial and low-latitude region.

Keywords: Ionospheric tomography; Beacon Experiment; Equatorial Ionization Anomaly.

Introduction

The characterization and parameterization of equatorial and low latitude ionospheric media is difficult and needed more instruments with less spacing. This problem can be overcome by using a latest developed technique, known as computer added ionospheric tomography (CAIT). This technique has its own advantages and covers a wide as well as remote area with less number of instruments. The computerized ionospheric tomography technique has an advantage to give a snapshot picture of latitude-altitude variation of ionosphere by using the data recorded with the help of chain of simple and inexpensive beacon receivers. The chain of beacon receivers must be aligned along a common meridian and capable to record simultaneously the coherent signals from the low-earth orbiting (LEO) satellite. The snapshot ionospheric tomographic image would correspond to the electron density (Ne) projections in a given direction. The technique is also very useful for the study of the spatial structure and temporal development of even the large-scale features in electron density present on any given day. The concept of ionospheric tomography is introduced by Austen et al., (1988) for two dimensional study of the ionosphere which is further improved by many researchers (Yeh and Raymund, 1991; Fremouw et al., 1992; Raymund et al., 1994; Sutton and Na, 1996). The 2D ionospheric tomographic images are deduced from the one-dimensional ionospheric total electron content measurement along the satellite to ground based receiver ray path.

The present work deals with the development and validation of the computerized ionospheric tomographic technique derived from the ionospheric STEC (Slant total electron content), which is the integral of the electron density in the line-of-sight. The above tomographic technique has been performed over equatorial and low-latitude region of the Indian zone which is highly dynamic and unpredictable and thus needed to be investigated. The time series latitudinal profile of Total Electron Content (TEC) and the tomographic images are employed to investigate the spatial and temporal variation of EIA over the Indian region.

Methodology

It is well known that the ionosphere is a dispersive media, hence it offers a group delay and phase advancement, when these two coherent frequencies travels through it. The group delay and phase advancement in ionosphere is proportional to the ionospheric TEC between the transmitter and the receiver. Here, in the present study, the Differential Doppler method is used to deduce the ionospheric total electron content. The phase difference ΔØ of both the frequencies is then calculated by using the following equation

$$\begin{aligned} \Delta Ø &= (Ø_2/q_2) - (Ø_1/q_1) \\ &= (40.3N_T/f_0c)\,[(1/q_2^2) - (1/q_1^2)] \text{ in cycle} \text{ ------------- (1)} \end{aligned}$$

By using the equation 1, the initial phase values are estimated. The estimated phase values are in between 0 to 2π. By adding or joining all the phase values, it gives a cumulative phase records or relative ionospheric Total Electron Content (TEC) with a minimum value of the curve being arbitrary set to zero. The minimum value of relative TEC is zero because the initial phase is not known when the receiver starts locking the radio signal. This problem is often known as 2nπ Ambiguity. During a satellite pass, occasionally the radio signal is loss due to poor signal to noise ratio. To remove this type of discontinuities, self developed software is used to interpolate the data over this lost signal regions by using linear interpolation method. In phase measurements and in phase difference measurements, the phase counting starts when the receiver gets a phase lock to the signal. At this moment, the phase count starts from an arbitrary value. This implies that TEC is known only to an unknown offset, and hence it is only the relative TEC which is referred to as the 2nπ Ambiguity. This can be removed by adding some phase offset value. The phase offset is computed by using two station methods as described by Leitinger et al. (1975). The slant TEC (STEC) is related to the measured phase (Φ) by

$$STEC = A\,(\Phi + \Phi_0) \text{ ------------------------- (2)}$$

Where Φ_0 is the unknown phase offset. The common formula for computing STEC value is

$$STEC = \int_S^R N ds \text{ ------------------------------------ (3)}$$

Where, N is the electron density and ds is the length of the straight line path element between the satellite S and receiver R. For TEC calibration, it is necessary to convert the above calculated STEC into vertical TEC value. For calibration it is assumed that the common latitudinal VTEC recorded by two consecutive stations must be same if the stations are align in a same longitude. But it is not same owing to the unknown initial phase problem. Therefore, for calculating the unknown initial phase value, the so called least-squares method is used suggested by Leitinger et al., (1975). This method provides us two coefficients, one each for both the stations i.e. Φ_{01} and Φ_{02}. With the help of these derived coefficients, the corrected STEC values are estimated, which is known as the absolute TEC values. This corrected or absolute STEC values is then converted into Vertical TEC value by using the equation

$$VTEC = STEC \times \cos(\chi) \text{ -------------------------------- (4)}$$

Where, χ is the satellite zenith angle at the ionospheric pierce point (IPP). This procedure is further extended for other stations. The converted VTEC values are depicted in figure 1(a).

3.1 Algorithm for Inversion

In the present work the Algebraic Reconstruction Technique (ART) is used to generate the tomographic images. This technique requires an initial approximation or guess values of the altitudinal distribution of electron density for any given location which falls under the same considered meridian. The initial approximation can be provided either by the electron density profile obtained from any of the conventional ionospheric models or from the electron density profile measured with the help of digital Ionosonde. The electron density profile observed from the digital Ionosonde is more accurate than the model derived values but Ionosonde can only give the bottom side electron density profile. The top side electron density can be obtained by using Chapman's function. The computed TEC value through the grid is subtracted from the experimental TEC measurement. Further, the calculated value is then divided by the sum of the squares of the path pixel intersection lengths for that ray path. The value is then multiplied by the length of the path in the specified pixel. After this one can get the electron density value, which may be either an increment or decrement by applying proper number of iteration. Iteration is applied till the required image is generated. This is then repeated for all of the different ray paths through the image and then applied a number of times until acceptable convergence is reached.

3.2 Validation

The foF2 values derived from the reconstructed tomographic image are compared with the manually scaled foF2 values measured with the help of Digital Ionosonde located at Bhopal.

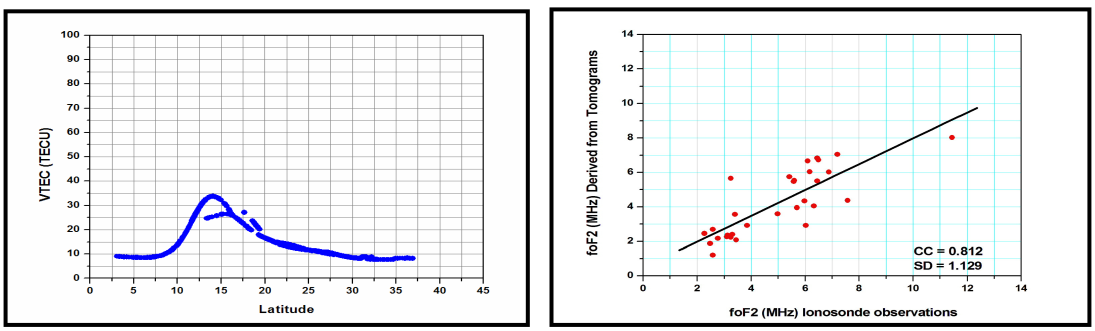

Figure 1(a) : - The Vertical Total electron content value derived from differential Doppler Method.
1 (b): Comparison between the Ionosonde measured foF2 and foF2 derived from tomogram.

Figure 1(b) shows the comparison between the Ionosonde measured foF2 and foF2 derived from tomographic images. In the present case, the initial guess values provided for the reconstruction of the tomographic images were obtained from International Reference Ionosphere (IRI)-2001 model, so the reconstructed tomographic image is totally independent from the Ionosonde data. The comparison shows a good linear agreement between the two values having the correlation coefficient of 0.812. This shows that the reconstruction is very close to actual ground based measurement.

4. Results

To study the various aspects of EIA, 2D-tomograpic images during the different local times are presented in figure 2 (a), (b), (c) & (d). This provides the chance to study the two dimensional structure of electron density and the equatorial ionization anomaly over the Indian region. The temporal and spatial variation of EIA crest can be evidently seen from the figure 2.

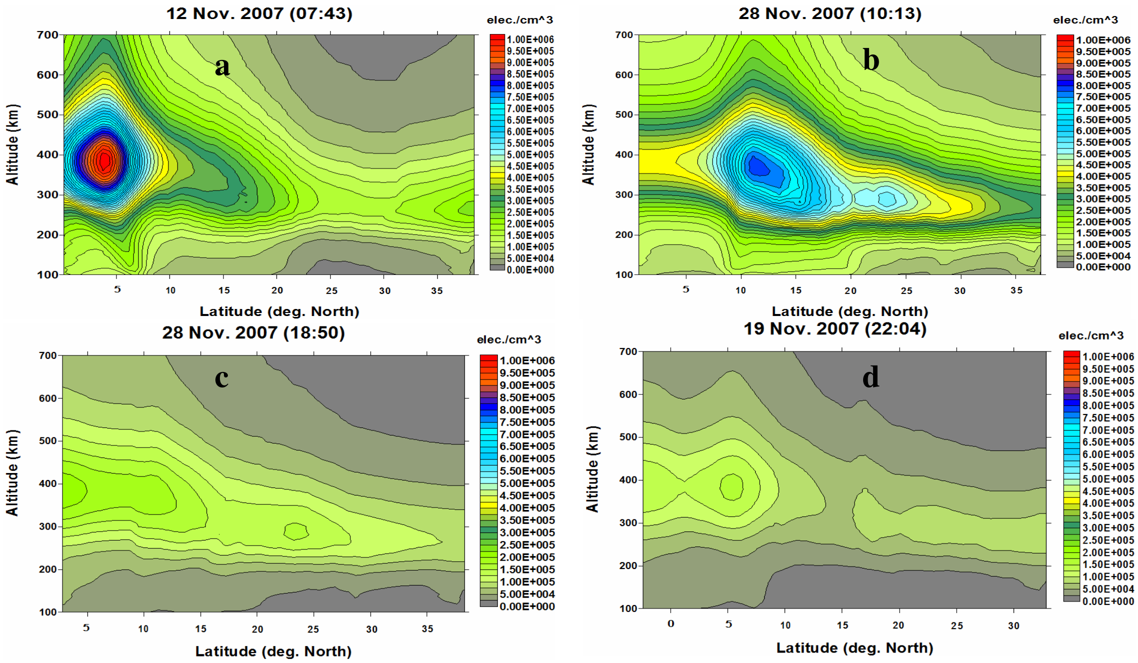

Figure 2: Spatial and Temporal variation EIA over Indian region

5. Conclusion

The present work gives the detailed description of the analysis method of the data recorded by the Coherent Radio Beacon Experiment (CRABEX). The Algebraic Reconstruction Technique (ART) which is also called as the inversion technique and is used for the generation of two dimensional image of the electron density is also described in detail. The technique is validated by using the real time electron density profile obtained by using the digital ionosonde system. Results show that the ionospheric tomograms can be successfully used to study the 2D structure of electron density and equatorial ionization anomaly which is one of the most important phenomenons of equatorial and low-latitude region.

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7. References

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