Chapter 4

Tomographic imaging of the equatorial and low-latitude ionosphere in the Indian longitudes

4.1 Introduction

The concept of ray tomography for the two dimensional imaging of the electron density distribution in the ionosphere was first reported by Austen et al. [1986, 1988]. Since then there had been several studies on the development of proper inversion algorithms for the computerized ionospheric tomographic (CIT) inversion, which is basically a highly ill posed inverse problem [for example, Raymund et al., 1990, 1994; Na and Lee, 1991; Fremouw et al., 1992; Kunitsyn et al., 1995; Fehmers et al., 1998a,b; Howe et al., 1998]. All these algorithms have been explained in detail in Chapter 3. In the past, there had been several tomography experiments, mainly in the high and mid latitude regions, which provided information about the large-scale structures of the ionosphere. The first preliminary experimental tests by Pryse and Kersley [1992] using TEC measurements from a single satellite pass at two stations in Scandinavia, followed by MACE (Mid-America Computerized tomography Experiment) and the RATE (Russian American Tomography Experiment) and the experimental campaigns carried out at UK. Andreeva et al., 1990, 1992; Raymund et al., 1993; Kunitsyn and Tereshchenko, 1994; Foster et al., 1994; Kersley et al., 1997 are to list a few.

All these studies demonstrated that CIT techniques could be effectively used for imaging ionospheric structures with horizontal scales of the order of tens to hundreds of kilometers. Subsequently, it was established that these techniques are also useful for studying the Equatorial Ionization Anomaly (EIA), which is a large-scale feature of the low-latitude ionosphere by using a low-latitude ionospheric tomography network (LITN) [Huang et al., 1999; Andreeva et al., 2000; Fränke et al., 2003]. The LITN consists of a
chain of six receivers along the 121°E longitude, from 14.6°N to 28°N geographic latitudes. However, these studies pertain only to the northern crest of the EIA, since the LITN does not have a station near the trough of the EIA. Questions regarding the development of the EIA during the course of the day, and its relationship with other ionospheric processes like EEJ and ESF still needed further systematic investigations covering both the trough and the crest regions of the EIA.

In this context, the Coherent Radio Beacon Experiment (CRABEX) has been initiated to address the aforementioned questions regarding the large-scale processes over equatorial and low-latitudes. The CRABNET receiver chain for tomography is unique as it covers the crest and trough regions of the EIA latitudinally, by far making it one of the longest receiver chains for ionospheric tomography. The details of the CRABNET stations, the CRABEX receiver system and the data processing are explained in chapter 2. In the present chapter, the tomographic images obtained using CRABEX are presented. The images show the variability of the large-scale features in the equatorial and low-latitude ionosphere. It may be noted that these are the first tomographic images from the Indian longitudes. However, there have been many tomography experiments in the world, especially in the high-and mid latitude regions, which are described briefly.

4.2 Development of Experimental Ionospheric Tomography

Soon after the presentation of the basic idea of ionospheric tomography at the Beacon Satellite symposium in Finland by Austen et al. [1986], an attempt was made to coordinate observations from three stations in Scandinavia, in September 1986 as a first experimental test of the application of tomographic methods for imaging the ionosphere. In the event, simultaneous measurements were made for only a single satellite pass of a NNSS satellite at the two stations Kiruna and Oulu. These two stations were separated by ~5° in longitude, thus the geometry was not appropriate for tomography. The experiment was coordinated with a run of the European Incoherent Scatter Radar (EISCAT) to yield independent measurements of electron density. Comparison of the tomographic image and radar observations revealed that both showed a gradual, large-scale northward gradient in electron density over the common latitude range [Pryse and Kersley, 1992].

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Despite many experimental limitations, the study demonstrated the potential of tomographic methods in bringing out the large-scale features of the ionosphere.

After this preliminary experimental test, another campaign was carried out in Scandinavia, with four stations covering almost 10° in latitude, along a meridian in Norway and Sweden. This campaign was also coordinated along with a continuous 48 hr run of the EISCAT radar. The results of this campaign have been described by Raymund et al. [1993]. In general, comparison of features such as enhancements and depletions show reasonable agreement and the reconstructions were able to reproduce the gradient in the height of the layer peak. However, the tomographic images had low peak heights, and the shape of the topside profiles differed significantly. Both factors resulted from the poor ability of the IRI-90 model, which was used as the initial guess. Similarly, there was another tomography experiment in UK, in December, 1990. The images obtained could depict the mid-latitude trough, quite well. A sequence of tomograms obtained over a 12-hr period could be used to understand the development and motion of the mid-latitude trough [Pryse et al., 1993]. The location and depth of the trough minimum, the width of the feature, and the horizontal gradients in electron density associated with the trough walls and the characteristics of the trough during geomagnetic disturbances were studied using tomographic imaging [for example, Kersley et al., 1997]. Apart from the studies on troughs (seen in the sub-auroral to polar latitudes) tomographic imaging was also used to study the polar cap ionosphere [Pryse et al., 1997].

Subsequently, there was another campaign in Scandinavia, during March 1992, in which ionosonde information was used in the reconstruction, with independent EISCAT run for verification. Ionosonde information in the form of layer peak density and height from three stations were incorporated into the background formed by IRI-90 model. In addition to this, topside shapes selected from a large database of normalized topside profiles provided by the Malvern and EISCAT radars were also used. The results of this campaign were summarized by Kersley et al. [1993]. A sample case is shown in figure 4.1a. Broadly similar features were seen in the tomographic image and the corresponding EISCAT scan. The absolute magnitudes of the electron densities in the central part of the region agreed well, particularly near the peak.
Fig. 4.1a Tomographic image of electron density for a satellite pass at 1818 UT on 23 March 1992 with background ionosphere based on IRI-90 model with ionosonde input (top panel). Tomographic image of electron density for the same pass; background ionosphere based on IRI-90 model and ionosonde input, with topside shape selected from a large data base of normalized topside profiles provided by the Malvern and EISCAT radars (middle panel) electron densities measured by EISCAT between 1810 and 1829 UT on 23 March 1992 (bottom panel) [after Kersley et al., 1993]
However, the discrepancies were again found on the topside, reflecting the inadequacy of the IRI-model to reproduce the topside ionosphere at auroral latitudes. All these experiments demonstrated the potential of tomography to image ionospheric features such as troughs in electron density found at auroral and sub-auroral latitudes, [Kersley and Pryse, 1994], and Traveling Ionospheric Disturbances (TIDs) [Pryse et al., 1995], and the importance of complementary ground-based data inputs for improving the accuracy of reconstruction [for example, Kersley et al., 1993]. Mitchell et al. [1998] have shown the tomographic measurements showing a narrow, field-aligned enhancement in electron density in the post-noon sector of the dayside auroral zone, which are also observed as a temporal increase in the plasma concentration by the EISCAT Svalbard incoherent scatter radar in the region. Apart from these, there were tomographic experiments from other parts of the world also. The most important of them include the Russian Tomography Experiments, Russian-American Tomography Experiment (RATE) and the Mid-America Computerized Ionospheric tomography Experiment (MACE).

In the RATE, the spatial distribution of ionospheric electron densities was observed by the MIT Millstone Hill incoherent scatter radar and an array of four receiving stations was set up along the northeastern United States and eastern Canada to obtain data for the tomographic reconstruction. The first results were reported by Foster et al. [1994] followed by a number of other publications [for example, Kunitsyn and Treshchenko, 1994; Kunitsyn et al., 1995; Fougere, 1997, Aladjev et al., 2001]. In this experiment, both the phase and phase difference tomography methods were followed and the images were inter-compared. There was a severe geomagnetic storm during this campaign period, with Ap values reaching 77 on 4 November 1993. The images obtained during this period revealed to be highly structured, with an enhancement of lower F-region ionization at mid-latitudes caused by low energy particle precipitation [Foster et al., 1994].

Another important experiment was the Mid-America Computerized Ionospheric Tomography Experiment (MACE-93). This experiment was conducted over a period of five months, with a network of nine NNSS receivers extending from south Texas to
South Dakota (a distance of \( \sim 2000 \) km). The CIT reconstructions were compared with the data from two digisondes, and a single site locator (SSL) system, co-located with the NNSS receivers. The results were presented by Vasicek and Kronschab [1995]. The TEC data as well as tomographic reconstructions obtained during MACE showed the presence of TIDs, even though with a 'smearing' effect, due to the movement of the TIDs [Cook and Close, 1995]. Apart from this, experimental campaigns for tomographic studies were conducted to study the mid-latitude ionosphere in Japan with four receiving stations covering the 140°E meridian [Kunitake et al., 1995], along the Eindhoven meridian (5°E), with five receiving stations covering 43°N to 53°N [Fehmers et al., 1998]. All these experiments in the mid-latitude and high latitude region showed the potential of ionospheric tomography in bringing out the large-scale features of the ionosphere.

Reviews outlining the development of the method with discussion of the potentials and limitations of this method are published [special issues- *International Journal of Imaging systems and technology* 5(2), 1994 and *Annales Geophysicae*, 13(12), 1995]. Presently also there are tomographic chains operational in the high-latitude region. Most important of them being in the region of Alaska, which is maintained by the North West Research Associates (NWRA) as part of the High-frequency Active Auroral Research Program (HAARP), jointly directed by the U.S. Air Force Research Laboratory and Office of Naval Research. Two sample tomograms obtained from this ongoing experiment is shown in figure 4.1b (obtained from http://www.haarp.alaska.edu/).

### 4.3 Low-Latitude Ionospheric Tomography Experiments

As we have seen in the previous section, most of the ionospheric tomography experiments were pertaining to the high- and mid-latitude regions of the ionosphere. Later, it was realized that the tomographic techniques could be used to image the large-scale features of the low-latitude ionosphere also. The first network of six receivers, from 14.6°N to 31.3°N (geographic latitudes) along the 121°E meridian, namely the Low latitude Ionospheric Tomography Network (LITN), was established, and the chain is operational since June 1994. The initial results were reported by Yeh et al.
Fig. 4.1b The upper panel in each column shows the images (receiving stations indicated by triangles along the abscissa). The middle panel shows the latitudinal distribution of TEC obtained from the image. The lower panel shows the latitude distribution of $f_0F_2$, which has been derived from the image. The lower panel (right) also shows spot measurement (arrow) of $f_0F_2$ provided by local ionosonde near the time of the satellite pass [from http://www.haarp.alaska.edu/].

[1994] and Huang et al., [1997]. This experiment provided important information about the motion of the crest of the EIA [Yeh et al., 1994, 2001], the structure and symmetry of its core [Andreeva et al., 2000] the low-latitude ionospheric response to magnetic storms [Ji-Sheng et al., 2000]. A series of tomographic images showing the time-evolution of EIA presented by Yeh et al., [2001] is shown in Fig. 4.1c. The development and motion of EIA crest and tilt of the ionization contours with the approximate alignment with geomagnetic field lines are clearly seen.
Fig. 4.1c Sample tomograms showing the development and motion of the EIA crest from LITN [after Yeh et al., 2001]
It may be noted that the tomographic reconstruction was performed using the phase difference method and the final images were obtained after averaging an assembly of images, for improving the accuracies. Another important study conducted using the LITN data was on the variability of the EIA crest region during a solar eclipse [Huang et al., 1999]. They have shown that during the eclipse day the ionosphere experienced some large-scale changes. The day-to-day and seasonal variability of the northern crest of the EIA has been studied using tomographic images obtained from the LITN [Franke et al., 2003]. They have reported that the fully developed anomaly crest is aligned along geomagnetic field lines, resulting in the existence of strong and directional gradients in the EIA crest region. Another chain of receivers for tomography is deployed in the 11-13°E meridian in the EIA crest region [Materassi et al., 2003]. A series of tomographic images showing the time-evolution of ionosphere reported by Materassi et al. [2003] is shown in figure 4.1d. All these experiments have shown that tomographic techniques could be used to study the phenomenon of EIA. However, these tomography networks covered only the northern crest of the EIA. None of them have an equatorial station, and hence the EIA trough could not be imaged accurately.

In this context, the Coherent Radio Beacon experiment (CRABEX) was envisaged to image both the trough and crest of the EIA in the Indian longitudes. This chain is unique as it covers both the trough and northern crest of the EIA and goes well beyond, by far making it the longest tomography chain of the world. The locations of the receivers, the details of the receiving system, data processing etc. have been presented in Chapter 2. The feasibility of the network of stations to image the equatorial ionospheric features is assessed using simulations, as described in Chapter-3. In the present chapter, the first tomographic images from this experiment are presented, signaling the addition of a new dimension to the investigation of equatorial ionosphere. These images show the temporal evolution as well as the day-to-day and seasonal variability of EIA. Apart from this the images also show the imprints of ESE Traveling Ionospheric Disturbances (TIDs) etc. on various occasions. These are explained in detail in the next sections.
Fig. 4.1d Images of electron concentration ($\times 10^{11} \text{ m}^{-3}$) for a succession of satellite passes recorded at (a) 01:12 UT (almost no ionization); (b) 08:40 UT (morning enhancement); (c) 12:30 UT (maximum ionization along the day); (d) 14:13 UT [after Materassi et al., 2003]

4.4 Tomographic Reconstruction Using the CRABNET Data

As mentioned in Chapter 2, the CRABNET consists of a chain of receivers located in the 77°-78° E meridian. The satellite passes simultaneously observed at three or more stations having direct elevation angles $>50^\circ$ are used for tomographic reconstruction. Figure 4.2 shows the slant TEC data obtained from three stations on September 30, 2004 ($\text{Ap} = 3$), used for the tomographic imaging. The total latitudinal coverage obtained using these three stations is $\sim 28^\circ$, i.e., from $\sim 20^\circ$N to $\sim 8^\circ$S (geomagnetic).
The data with reasonably good intersecting ray paths are only used for imaging. The accuracy of the image will be less at the edges, because of the less number of intersecting ray paths in that region, as explained in chapter 2. The altitude extent for reconstruction is from 100 to 700 km. The resolution is 0.5°(horizontal) x 50 km (vertical), for all the images. As mentioned in chapter 2, the geocentric circular grids are constructed in the region, and the geometry matrix is computed. The initial guess which is fed into the iterative algorithm (ART in the present case) is shown in Fig. 4.3. This has been generated using a single profile at off-equatorial latitude obtained from the IRI-90 model. Since we do not know the exact location of the EIA crest, the EIA was not incorporated into the initial guess at this point.
Fig. 4.3 The initial guess used for the reconstruction. The white dotted lines are the magnetic field lines (dipole approximation). The black dotted lines are the radial grid-lines.

The reconstruction was performed using ART algorithm, and it was seen that after 10 iterations the solution converged. Figure 4.4 shows the reconstructed image obtained. It can be seen that the magnitude of the electron density values have changed from the initial guess, and the signature of the EIA crest has appeared between $-5^\circ$ and $10^\circ$N geomagnetic latitudes. Even though the EIA crest is obtained, the image shows in addition, some sharp structures at the Nmax altitude near $-1^\circ$ - $2^\circ$N and $4.5^\circ$N latitudes.

Fig. 4.4 The tomographic image for September 30, 2004 1455 IST
These could be due to the insufficient number of intersecting rays in these regions. Hence, it was conjectured that a better initial guess could improve the image. As we know from this image that the location of the EIA crest is between 5° and 10°N magnetic latitudes, the initial guess was modified accordingly. However, since we are not sure about the exact magnitude of the EIA, we have incorporated only a very small enhancement in the initial guess. The EIA intensity in the new initial guess is actually much lower than the intensity of the EIA obtained in the tomographic image (Fig. 4.4). This is to ensure that we are not providing any unwanted amplification of the EIA crest intensity through our initial guess. Figure 4.5a shows the new initial guess (top panel), and result after the first (middle panel) and third (bottom panel) iterations. It can be seen that as in the previous case, the magnitude of the electron density values change at each iteration, according to the input data and the presence of the EIA crest becomes clearer after each iteration. In this case also the solution converged after 10 iterations. Figure 4.5b shows the tomographic image obtained after 10 iterations.

It can be seen that the presence of artifacts has reduced in the new reconstruction. The EIA crest has become better-defined around 5°-10°N geomagnetic latitude, with crest to trough ratio ~1.2 at the Nmax altitude. Another important aspect, which is clearly seen, is the approximate field-aligned nature of the EIA crest.

Figure 4.6a shows the altitudinal profiles obtained from the tomographic image, for 2°S, 0°, 2°N, 4°N and 6°N magnetic latitudes. It can be seen that the electron densities are more than that at the equator, on either side and the northern crest is seen ~6°N magnetic latitude. Similarly, Fig. 4.6b shows the latitudinal profiles (at altitudes 300, 350, 400 and 450 kms) showing the presence of EIA, obtained from the tomographic image. It can be seen that at lower altitudes below the $h_mF_2$ (350 km in the present case), the EIA crest is shallower, and the crest to trough ratio is maximum near the $h_mF_2$. In the topside F-region above $h_mF_2$, the crest is again shallower. It is also seen that the EIA crest lies around 5°N to 6°N at 350 km, where as it is around 4°N to 5°N at 450 km. It should be noted that even though our horizontal resolution is ~0.5°in latitude for the reconstruction, in the latitudinal profiles of electron density, the average value for each latitude is shown.
Fig. 4.5a The improved initial guess used for the reconstruction (top panel). The solution after the first iteration (middle panel) and the solution after 3 iterations (bottom panel).
Fig. 4.5b The final image after 10 iterations for September 30, 2004 1455 IST. The white dotted lines are the magnetic field lines

Fig. 4.6a "Vertical cuts" obtained from the above tomogram
This has demonstrated the potential of the CRABNET to obtain the spatial variability of the low-latitude ionospheric electron densities. Similar procedures are followed in generating the other images also. In the next section, the temporal evolution of the equatorial ionosphere is shown using a series of images.

**4.5 Temporal Evolution of Equatorial Ionosphere**

Figure 4.7a shows the temporal evolution of equatorial and low-latitude ionosphere obtained using data from different satellite passes during 29 September 2004 (Ap=4), and 30 September 2004 (Ap=3). The start time of the satellite passes are given in the figures. The data from three stations, Trivandrum, Bangalore and Hyderabad were used in the reconstruction, since during this period, only three receivers were operational. There are four images, the first one on 29 September, at 2120 IST and the other three images at different times of the next day (03 30 IST, 09 25 IST and 1455 IST). These images (at ~ 6 hour interval each) show the typical temporal evolution of the low-latitude ionosphere during the autumnal equinox season of the solar minimum epoch, for magnetically quiet days. The image at 0920 IST shows the EIA at the beginning stage of
its development, whereas the tomogram obtained at 1455 IST shows the well-developed EIA crests. These images corroborate with the behavior of equatorial ionosphere reported earlier [for example, Sastri, 1990].

The first tomographic image (top panel in Fig. 4.7a), is obtained at 2120 IST, on 29 September, 2004. On this night, ESF was observed (onset at 1915 hrs IST), in the ionosonde located at Trivandrum. The image revealed a clear-cut signature of plasma depletion in the entire latitudinal region. It may be noted that this is the first radio tomographic image during an ESF event, and this is explained in detail later (section 4.8). The next image is at 03 30 IST, on 30th September (i.e., ~6 hours later), which shows that the electron densities are less than the daytime values, as expected. The altitude profiles obtained at 0°, 2°N, 4°N and 6°N magnetic latitudes (figure 4.7b) clearly shows this decrease in electron density.

The ionization densities enhance with sunrise, and in the next image (third image shown in figure 4.7a, for 09:25 IST), we can see that the EIA has started developing. The anomaly trough is located at the geomagnetic equator, and a broad crest is seen from 5°N-10°N geomagnetic latitude. The crest to trough ratio at Nmax height is ~1.1.

The last image in the series (Figure 4.7a) is obtained at 14.45 IST, on the same day, where the EIA has intensified with crest to trough ratio ~1.2 (at Nmax). However, the crests are seen as centered at ~6°N magnetic latitude. It is known that the anomaly crest locations have a poleward motion within the low-latitude region after its generation in the morning hours. However, in the tomographic images presented in this study this kind of a motion is not very evident. This may due to the ‘edge effect’, as there were limited number of intersecting rays beyond 9°N geomagnetic latitude. since only three receivers along the meridian (Trivandrum, Bangalore and Hyderabad) were operational during this observation period. As a consequence, the accuracy of the images is limited in the region beyond 9°N geomagnetic latitude.
Fig. 4.7a Temporal evolution of equatorial ionosphere and the EIA
Later on, two more stations (Bhopal and Delhi) were also added to the receiver chain. Hence, the images obtained during the later phase of CRABEX show the latitudinal extent of EIA better. This can be seen from the image shown in figure 4.8, obtained on 10 March 2005, 1045 IST, which corresponds to vernal equinox. On this day, all the stations up to Delhi (28°N geographic latitude) were operational and the region between 5°S to 19°N geomagnetic latitudes was having good number of intersecting rays. The image clearly reveals the EIA crest to be beyond 12°N geomagnetic latitude. However, this image represents the EIA in the developing stage as the time of the fully developed EIA crests is expected to be around 1400 IST during this period. It should also be noted that even though these tomographic images show the different instances of the development of EIA, the temporal resolution is not very high. This is due to the fact that the CRABNET can track only 3-4 NIMS satellites, and only the high elevation satellite pass with good latitudinal coverage from all the stations could be used for tomographic reconstruction.
Fig. 4.8 Tomographic image obtained at 10 45 IST, on March 10, 2005.

An important aspect which is seen in these images is the almost field-aligned nature of the EIA crests. It may be noted that the field lines are plotted with a simple dipole approximation which is valid in these ionospheric heights at low latitude, especially in the Indian longitudes. Another important aspect which needs to be considered here is that apart from the EXB drifts, the plasma density at a given latitude region is governed also by the production (which is having a solar zenith angle dependence) and loss processes, and also by the prevailing neutral winds. The latter processes lead to the stratification of the ionospheric plasma with a latitudinal distribution which is not completely field-aligned. The resolution (0.5° x 50 km) for the tomographic reconstruction would also smooth out the variations within a grid.

Figure 4.9a shows a tomographic image obtained just as the EIA starts evolving. The image is obtained on 1 October 2004 (Ap = 3), at 0830 IST. Figure 4.9b shows the corresponding altitude profiles obtained at 0°, 2°N, 4°N and 6°N magnetic latitudes. It can be seen that the EIA has not started developing yet, and the peak of electron density is near the geomagnetic equator, and the densities at 0°, 2°N, and 4°N are nearly the same, and the densities at 6°N is slightly less than these values. It should also be noted that the prevailing magnetic conditions on this day are nearly same as that on the previous day (30 September, 2004), Combing the tomograms shown in Figures 4.7a and
4.9a, we can see that the EIA develops rather quickly, and within ~50 minutes, well-defined crests are formed ~5° away from the dip equator.

**Fig. 4.9a** Tomographic image obtained at 08 30 IST (before the development of anomaly), on 1 October, 2004

**Fig. 4.9b** Altitude profiles obtained from the tomogram shown in fig. 4.9a
Figure 4.10 shows another example of the temporal evolution of the low-latitude ionosphere, during winter season. There are four images, which are at 1830 IST on 29 January, 2005 (Ap=20), and at 0115 IST and 0700 IST and 1315 IST on 30 January 2005 (Ap=17). The data from three stations, Trivandrum, Bangalore and Hyderabad were used the reconstruction, since during this period also only these three receivers were operational.

The first image shows only a weak signature of the EIA crest centered around 4.5° magnetic latitude. The EIA crest amplitudes have already decreased substantially from the noontime values. This is quite expected, as the observation is in the solar minimum epoch. The next image is at 0115 IST on the next day (~7 hours later). Similar to the observation on 30 September 2004 at 03 30 IST, one can see a drastic reduction in the electron densities with distribution being almost horizontally stratified. The next image in this series is obtained at 0700 IST, before the development of EIA. As in the previous case (October 1, 2004), the peak of electron density is near the geomagnetic equator, showing that the EIA has not started developing yet, as expected at this local time. The last image on this series is at 1315 IST on the same day, which reveals the presence of a broad EIA crest at ~10°N magnetic latitude. The maximum intensity is around ~10°N geomagnetic latitude. It should be mentioned here that this is a moderately disturbed day, and the presence of such broad crests is a common feature of disturbance effect (this aspect is discussed in detail in the next section).

As we do not have reliable reconstruction beyond this region, we cannot obtain the complete latitudinal extent of EIA crests. Another feature commonly observed during the solstice period is the north-south asymmetry of the two EIA crests. However, we do not have much overlapping data in the southern hemisphere, and hence the southern crests of the EIA could not be reconstructed. This important aspect of EIA asymmetry is studied using the latitudinal profiles of TEC measurements obtained from Trivandrum, and is explained in detail in the next chapter.
Fig. 4.10 Temporal evolution of equatorial ionosphere and EIA during winter
4.6 Variability of EIA

Another striking feature of the EIA is its day-to-day variability. It is seen that the tomographic reconstruction is able to bring out this particular aspect, though we do not have the satellite passes at exactly same local time on adjacent days. Nevertheless, the images obtained in a time interval of one hour on different days can give a reasonably good picture of the day-to-day variability of EIA. Figure 4.11a shows three tomographic images obtained within 1445-1515 IST on three different days in the equinoctial season. The reconstruction is performed for September 30 (Ap= 3) and October 2 (Ap= 11) and October 3, 2004 (Ap= 12). It can be seen that the EIA characteristics differ significantly on these days. On 30 September and 3 October 2004, the EIA is seen to be well developed with crests beyond 9°N and crest to trough ratio of ~1.2 and 1.3, whereas on 2 October 2004, the anomaly is not very clear. On this day there is a broad maximum from ~2°N geomagnetic latitude with electron density only slightly higher than at equator. Even on days of well-developed EIA, there are differences in the intensity and extent of EIA from one day to another. In contrast to the case on September 30, (which was discussed in detail in the previous section), we can see that the crest is weaker and broader on October 3, 1515 IST.

These differences may be due to the fact that September 30 was a quiet day (Ap= 3) where as October 3 was slightly disturbed (Ap=12). However, the image obtained on October 2, 2004 (Ap=11) shows a marked difference from these two days. It can be seen that the overall electron densities are higher in all latitudes in comparison to the other days. Fig. 4.11b shows the foF2 values obtained at these times from the co-located ionosonde at Trivandrum. It is clear that the foF2 value on 2 October was higher than the other two days, during this time. This could be ascribed to the effect of the magnetic disturbance.
Fig. 4.11a  Tomographic images showing the day-to-day variability of EIA
**Fig. 4.11b foF2 values for the three days, obtained from Trivandrum**

Another tomographic image on a geomagnetically disturbed period is shown in Fig.4.12a. This is for 6 April 2006 (Ap=8). This is on the beginning of the recovery phase of a very moderate geomagnetic storm with main phase on the previous day (Ap =29). Both the northern and southern crests of the EIA are seen close to the equator, and with significant north-south asymmetries. This can also be seen in the TEC measurements (Fig. 4.12b).

**Fig. 4.12a Tomographic image on 6 April, 2006 at 14 30 IST**

**Fig. 4.12b Northern and southern gradients in TEC observed on different days in April 2006**
Figure 4.12 b shows the latitudinal gradients in TEC in the northern and southern directions on different days in April 2006 during the time interval 1350 to 1450 IST, obtained from Trivandrum, which is located at the trough of EIA. (The details of the estimation of gradients are discussed in detail in the next chapter). It can be seen that the EIA crests show significant asymmetry during the disturbed period. This substantiates the asymmetry seen in the tomographic reconstruction shown in Fig. 4.12a. These images show the effects of the geomagnetic disturbance on the development of EIA. Unfortunately, we do not have TEC data during the main phase of this storm.

The EIA response to different types of disturbance electric fields and disturbance winds has been reviewed by Abdu et al. [1991]. It was shown that the equatorial plasma fountain responsible for the EIA formation could undergo significant enhancement or inhibition under the action of disturbance electric field, depending on the nature of the electric field. Trans-equatorial winds can produce an asymmetric fountain, and hence asymmetric EIA crests [Abdu, 1997]. The degree of the asymmetry would however depend on the competing forces of the wind velocity and the eastward electric field. Observations have shown that the most striking characteristic of the EIA response to the disturbance electric fields is its expansion/contraction in latitude depending upon the polarity of the disturbance electric field. In some events, the disturbance fountain seems to cover a much wider latitudinal region than the normal fountain, resulting in the formation of latitudinally expanded crests of EIA [Abdu et al. 1991; Batista et al., 1991]. These are similar to what is seen in the tomographic images for October 2 and 3, 2004, even though the disturbance levels were only moderate. Figure 4.13 shows the tomographic image obtained on 29 January 2005 (Ap=20). The electron densities are shown with the same scale as that of Fig. 4.11a. The presence of a wide EIA crest is seen in this case also, which may be attributed to the disturbance effect. However, detailed investigations with more number of tomographic images along with other ionospheric and thermospheric parameters are required to fully understand the complex 'storm-time response' of the equatorial and low-latitude ionosphere.
A comparison of Figs. 4.11a and Fig. 4.13 brings out another interesting characteristic of EIA, i.e., its seasonal variability. It can be seen that the magnitude of the electron densities are much lower in the winter solstice than the equinoctial period, for the entire region. Since some of these days were moderately disturbed the differences cannot be fully attributed to seasonal effect.

Figure 4.14 shows the tomograms obtained on September 29, 2004 (Ap=3) and January 5, 2006 (Ap=3). It can be seen that the magnitude of the electron densities are much lower in the winter solstice than the equinoctial period, for the entire region. However, we do not have many tomograms to substantiate this aspect, and hence the latitudinal profiles of TEC obtained from Trivandrum have been used to investigate this. It was seen that the seasonal variability of EIA is clearly manifested in the latitudinal profiles of TEC also. The results concerning this particular aspect of the study are discussed in detail in Chapter 5.

Apart from the EIA, tomographic imaging can be used to study features like the traveling ionospheric disturbances (TIDs) and ESF. In the next sections the examples of such events are discussed.
Fig. 4.14 Tomographic image on 30 September, 2004 and 05 January, 2006 showing the seasonal variability

4.7 Wave-like Perturbations in the Nighttime Ionosphere

Traveling Ionospheric Disturbances (TIDs) have been studied extensively ever since they were first identified as ionospheric signatures of atmospheric gravity waves [Hines, 1960]. They have been monitored by a variety of techniques, most of which could only give temporal information. Single station TEC measurements have also been used to investigate the structure, characteristics and propagation of TIDs [Bertin et al., 1975; Kersley and Rees, 1982]. The CIT methods allowed a direct acquisition of the TID parameters, especially the spatial information, that were previously difficult to obtain. The MACE’93 experiments gave important results regarding the propagation of TIDs
Reconstructions using the data from the tomographic chain over UK also showed the presence of TIDs. Pryse et al., [1995] showed that these structures showed typical characteristics of medium scale waves.

The tomographic reconstruction using the CRABNET data has also shown the presence of TIDs on few occasions. Figure 4.15a shows such an event on March 31, 2006 2210 IST.

Fig. 4.15a Tomographic image on 31 March, 2006 at 2210 IST during ESF, showing the presence of wave like structures indicative of TID

On this day, ESF was observed in the ionograms obtained from Trivandrum. However, the TEC data (as well as the tomographic image) does not show any clear signatures of density depletions associated with ESF. However, the TEC data from Trivandrum showed small-scale fluctuations (±0.1 TECU), and amplitude scintillations. The co-located 18 MHz radar also showed a clear plume only up to 2130 IST. (These features are discussed in detail in Chapter 5). The important point to be mentioned here is that even though there was ESF on this night, the signal remained locked without any phase scintillations and hence we could obtain uninterrupted TEC data for tomographic imaging. It could be that the small-scale fluctuations in the TEC got smoothed out in the tomographic reconstruction, due to poor spatial resolution. However, the signature of the TID is clearly seen, with a group of electron density enhancements and depletions occurring over 10°N to 2°N, and the propagation is equatorward. This is quite expected, as the TIDs are usually set up by high latitude heating. It may be noted here that the
presence of such fluctuations in electron density is also manifested in the 630nm airglow intensity, measured at Trivandrum (not illustrated here), during evening hours. Figure 4.15b shows the variation of $h'F$ obtained from Trivandrum, showing the presence of wave-like oscillations on this day.

![Graph showing the variation of $h'F$ with time.](image)

**Fig. 4.15b** The $h'F$ variation obtained from Trivandrum ionosonde

This result also brings out the potential of tomographic techniques to successfully image the TIDs, even though their strength at the low-latitude region is much lesser compared to that in the high-latitudes. The image presented here shows the characteristic of typical medium-scale TIDs, propagating equatorward. However, it should be noted that there could be some 'smearing' effect, as the structures are actually moving and the tomographic image gives a snapshot of this moving structure.

### 4.8 Tomographic Images of ESF

As mentioned in chapter-1, the equatorial nighttime ionosphere often becomes turbulent, with the presence of irregularities of a wide spectrum of scale sizes. It is generally believed that ESF evolution is driven by the gravitational Rayleigh-Taylor (R-T) instability [e.g. Sultan, 1996], where plasma density gradients in the post-sunset ionosphere are gravitationally unstable. The growth rate of ESF bubbles is dependent on the height of the F layer and the steepness of the vertical density gradient. Some types of ESF events are termed Equatorial Plasma Bubbles (EPBs), which describes regions of depleted plasma density that typically originate in the bottomside post-sunset ionosphere and, while longitudinally thin, extend latitudinally along magnetic field lines. EPBs can
extend vertically to altitudes above 1000 km. Recently, the Global Ultraviolet Imager (GUVI) onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite has detected far ultraviolet (FUV) images of plasma depletions in the low-latitude and equatorial ionosphere [Comberiate et al., 2006]. Figure 4.16 shows an image of plasma depletion reported by Comberiate et al., [2006] showing the East-West extent of plasma bubbles.

![Figure 4.16](image)

**Fig. 4.16** Observations of ESF with GUVI tomographic reconstructions. Each pixel is approximately an area of 20 km in altitude by 40 km in longitude [after Comberiate et al., 2006]

However, these images could only give the longitudinal picture of the EPBs. So far only airglow cameras have provided a means of effectively imaging the structure and development of EPBs from the ground. By observing an optical emission as a proxy for electron density, these cameras can provide high-resolution movies of plasma bubble formation over a small area of the globe [Kelley et al., 2002; Sridharan et al., 1997].

The tomographic imaging using the LEOS satellites, which are in the polar orbit, can in principle give the north-south extent of these ESF irregularities. So far there had been no tomography receivers covering the dip-equatorial region. Another difficulty that often arises during ESF lies in obtaining uninterrupted TEC data without loss of lock. Often, severe scintillations and complete loss of lock happen as a result of ESF irregularities. Hence, it becomes extremely difficult to obtain a tomographic image during an ESF event.
In the present investigation, however, we could obtain uninterrupted data from the three stations for few minutes on two occasions. The images reconstructed using these data are presented here. The first image obtained on 29 September 2004 21 30, IST shown in figure 4.17a, is for a strong ESF event. Figure 4.17b shows the altitudinal profile of electron density at 2°S, 0°, 2°N, and 4°N latitudes. It can be seen that there are altitudinal structures in electron density which have large latitudinal extend. For example, the depletion extends in the whole latitudinal region (from 1°S to ~7°N) at an altitude near 400 km. There are also regions of enhanced densities at off-equatorial latitudes.

![Tomographic image on 29 September, 2004 at 2130 IST showing the presence of plasma depletions.](image1)

**Fig. 4.17a** Tomographic image on 29 September, 2004 at 2130 IST showing the presence of plasma depletions.

![Altitude profile of electron density obtained from the tomogram shown in figure 4.17a, showing depletions near 400 km](image2)

**Fig. 4.17b** Altitude profile of electron density obtained from the tomogram shown in figure 4.17a, showing depletions near 400 km

These images are the first of its kind showing the characteristics of ESF in the latitudinal plane. However, it should be noted that the resolution of the structures in these images are largely restricted by the resolution of the reconstruction (50 km in this case).
The ionograms from Trivandrum during this ESF event are shown in figure 4.17c. These ionograms show that the onset of ESF was ~ 1915 IST and the ESF was quite strong at 2130 IST, which is the time of the tomographic reconstruction.

![Figure 4.17c](image)

**Fig. 4.17c** Ionograms from Trivandrum showing the ESF event on September 29, 2004. The ionograms close to the time of the satellite pass is marked as 'CRABEX'.

The tomographic reconstruction of another ESF event on 18 March 2005 is shown in figure 4.18a. The various instances of the ESF, as seen in the ionograms from Trivandrum and SHAR are shown in figure 4.18b and 4.18c. It can be seen that the ESF onset was at ~1915 IST. ESF remained rather weak during the night, till 2330 IST at Trivandrum. Unlike this, at SHAR the ESF was very weak after ~2200 IST, and reappears later at ~2330 IST.
**Fig. 4.18a** Tomographic image on 18 March, 2005 at 22 20 IST, during a very weak ESF event.

**Fig. 4.18b** Ionograms from Trivandrum showing the ESF event on March 18, 2005. The ionograms close to the time of the satellite pass is marked as ‘CRABEX’.
Hence we expect that the spatial extent of ESF on this night should be much less, and the extent of depletion also should be much weaker than the previous day. This is in agreement with what we see in the tomogram also. We can see that the tomographic image at 2220 IST does not show any major depletion. However, the image is highly structured, with wave-like signatures both in the topside and in the bottom side. It should also be noted that these wave-like patterns are quite different from those of the TIDs (Fig. 4.15a), and hence may be associated with the weak ESF.

Here it may be noted that during ESF events, the model-generated profiles do not give a good initial guess for tomographic reconstruction. Also it is not possible to deduce accurate bottom side profiles from ionograms, and hence the accuracy of the reconstruction may be much less than that during 'no-ESF' times. This can be improved by giving profiles obtained independently, for example using rocket experiments.

Fig. 4.18c Ionograms from SHAR showing the ESF event on March 18, 2005. The ionograms close to the time of the satellite pass is marked as 'CRABEX'
However, the importance of the present investigation is that these are the first tomographic images during ESF events.

4.9 Validation of Tomographic Images

To validate the tomographic images the $N_{\text{max}}$ values obtained from the tomographic reconstructions were compared with the values derived from the ionosonde located at Trivandrum and SHAR. Figure 4.19 shows this comparison. It may be noted that in generating the tomographic images, ionosonde data were not incorporated. Usually, the ionosonde data is incorporated into the reconstruction in the form of an initial guess. Instead, we have used IRI model predictions as our initial guess. So, the images reconstructed using TEC data are completely independent of the ionosonde data.

![Graph showing comparison of $N_{\text{max}}$ values derived from tomographic images and ionosonde. The solid line shows the linear best fit.](image)

**Fig. 4.19** The comparison of $N_{\text{max}}$ values derived from tomographic images and ionosonde. The solid line shows the linear best fit.

With this limited data set, it can be seen that there is an overall agreement between these two, with correlation coefficient 0.846, which has >98% significance. It must be realized that, one cannot expect an exact agreement between these two because the peak density from tomograms is averaged over a pixel of vertical size 50 km, whereas the ionosonde signals may be scattered from a particular height. Despite these differences, our study demonstrates that the tomographic method gives $N_{\text{max}}$ values
comparable to those actually measured from ground-based ionosondes, which validates the tomographically reconstructed images.

4.10 Conclusion

The present chapter describes the development of experimental tomography using the CRABNET data. The first tomographic images from the Indian longitudes during different seasons and geomagnetic conditions are presented. These images show the potential of tomographic methods to image the large-scale features of the equatorial and low-latitude ionosphere. The effects of initial guess in the accuracy of these images are discussed. It is seen that the artifacts in the reconstructed image due to limitations in the input data can be reduced considerably by giving a proper initial guess. For this, in the absence of independent measurements of electron density profiles including the topside, a-priori knowledge about the ionospheric features could be used as discussed in section 4.4.

The temporal evolution of equatorial ionosphere and EIA are investigated using a series of tomographic images obtained on consecutive days. The images also showed the significant day-to-day variability of EIA. Apart from this, the comparison of images obtained during equinox and winter seasons showed that the electron densities are significantly less during winter than equinox. The north south asymmetry of EIA which could not be addressed using tomography due to the less intersections in the southern hemisphere, is dealt with in detail in the next chapter.

For the validation of the reconstruction, the $N_{\text{max}}$ values obtained from tomographic images are compared with that derived using ionosondes (for corresponding times) at Trivandrum and SHAR. These two independent measurements agree with each other, indicating that the images obtained from CRABEX are realistic and representative of the ionospheric variability in this region.

Apart from the images of the EIA, the first ever radio tomographic images during ESF events, showing the latitudinal extent of irregularities are also presented. It is well known that the scintillations caused by these F-region irregularities produce disruptions.
of the communication and navigation links using satellites. Hence understanding the variability of the occurrence of ESF is of considerable practical importance. This aspect is investigated in detail including the effect of background ionospheric conditions in the generation/sustenance of ESF, and presented in the next chapter.