Indian Journal of Radio & Space Physics
Vol. 20, October 1991, pp. 351-355

Two generations of progress in ionospheric research*

John A Klobuchar
Ionospheric Physics Division, Air Force Geophysics Laboratory, Hanscom AFB, MA, USA

Many of the great advances in ionospheric research in the last 40 years have come about because of improvements in technology, especially through modern electronics and optical and computational advances. The advent of the space age, with satellite and rocket capability, has provided a major improvement in our ability to measure the upper atmosphere and the ionosphere. The construction of realistic theoretical models of the upper atmosphere and the ionosphere have made great strides in our understanding of the relative effects of various driving forces on the ionosphere. These are discussed in some detail along with prospects for future breakthroughs in technology which will benefit ionospheric research. One particularly significant example to be described in detail is the improvement of knowledge of the now well known equatorial anomaly, briefly described in S.K. Mitra's book [*The Upper Atmosphere* (The Asiatic Society, Calcutta, India), 1947, 1952]. During the course of the 1950s, and even to the present date, the anomaly in F2-region electron density has been an active area of study, with much of this research being done by Indian scientists. Despite the many experimental results from both ground-based and satellite-borne sounders, and total electron content measurements, clearly showing the variability of the equatorial anomaly, it was not until the 1980s when a model of the low latitude ionosphere derived from first principles was able to reasonably well reproduce the observations discussed in Mitra's book. Other examples of areas still needing additional experimental and theoretical research are also described.

1 Introduction

In about forty years since the publication of editions of Prof. S K Mitra's book[1], many advances have occurred in ionospheric physics research which he could have only vaguely predicted at that time. The largest impetus to a better understanding of the ionosphere came about due to the beginning of the artificial satellite age in late 1957, with the launching of the first Sputnik.

From the radio signals transmitted from that very first satellite and many of the early satellites to follow, the effects of the ionosphere on those radio waves were of primary importance and were studied by many workers. With the advent of the satellite age the possibilities for advanced research on problems in the ionosphere became much greater.

In this paper many of the new techniques and results are mentioned with an emphasis on those involving the effects of the ionosphere on the radio signals transmitted from satellites, as they have been studied in a major way by ionospheric research groups all over the world. Especially in India much excellent scientific work has been done using radio signals transmitted from satellites to study the ionosphere. It is fortuitous that India lies under an extremely important part of the earth's ionosphere—the equatorial region and the equatorial anomaly region.

2 Some ionospheric observational techniques

Listed below are several of the more popular techniques for making ionospheric measurements. Some of these have been in use since the early 1950s, while others were developed later and only now are being exploited to their fullest extent. These techniques can be grouped into the categories given below.

(A) Direct (*in situ*)

(i) Langmuir Probe
(ii) Impedance Probe
(iii) Mass Spectrometer
(iv) Other direct satellite or rocket-borne instruments

(B) Satellite drag

(C) Remote optical

(i) Lidar (Laser radar)
(ii) Optical emissions

*This paper was presented at the International Symposium on Optical & Radio Remote Sensing of the Atmospheric Environment, held during 24-26 Oct. 1990 at NPL, New Delhi 110 012, India.

(D) Radio propagation

(i) Ionosondes, bottomside, topside, vertical, oblique
(ii) Partial reflection
(iii) Riometer
(iv) VLF, whistlers, transmitters, ground-based and satellite-borne

(E) Sound propagation

(F) Incoherent scatter radar (Also coherent scatter radar mode)

(G) MST radar

(H) Trans-ionospheric propagation

(i) Satellites of opportunity
(ii Dedicated beacon satellites

While many of these techniques have been used in studies of the ionosphere and, indeed, most are still in use in various places in the world today, one technique, from the post first Sputnik satelllite launch which has had a large impact on our knowledge of the equatorial and low latitude ionosphere, is that of monitoring ionospheric effects on signals from beacon satellites. Many research groups in India have used this technique to make studies of the ionosphere in the Indian subcontinent. A review of the Indian work in this area has been given by Somayajulu[2].

Still another new technique as applied to ionospheric studies is the use of computerized tomography to reconstruct two-dimensional electron density profiles against latitude, from one-dimensional TEC data. A typical theoretical model output of electron density contours versus height and latitude, using the Anderson[3] model, is illustrated in Fig. 1. Making measurements of differential carrier phase using satellite radio signals from satellites of opportunity, the tomographic technique[4] can be used to reconstruct similar two-dimensional profiles. Thus far, the tomographic technique has only been used with simulated ionospheric data, but its application to day-to-day variability studies of the actual equatorial ionosphere is likely to be attempted soon.

3 Ionospheric research using beacon satellites

Since the advent of radio signals from beacon satellites of opportunity, many ionospheric studies have been done. Evans[5], has reviewed many of the research results up to the mid-1970s. Davies[6], also has reviewed progress in satellite radio beacon research, emphasizing results from the ATS-6 radio beacon experiment, and Somayajulu[2] has reviewed the quarter century of the work done in India on satellite beacon studies.

Table 1 highlights the ionospheric research performed using beacon satellites. It is noted that there are many areas in which the beacon satellite technique has made major contributions to our knowledge of physics of the ionosphere.

In the low latitudes, perhaps, the two most important areas in which ionospheric studies by means of beacon satellites have made major contributions are in defining the day-to-day behaviour of the equatorial anomaly and in studying the seasonal and geographic dependence of equatorial spread-F as evidenced by amplitude

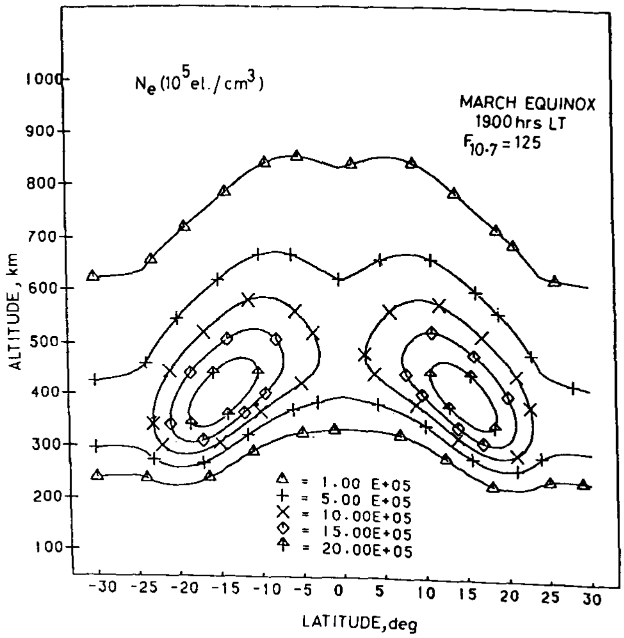

Fig. 1—Contours of electron density versus height and latitude over the equatorial region, clearly showing the equatorial anomaly

Table 1—Highlights of ionospheric research using beacon satellites

(i)	Solar eclipse effects on the F-region
(ii)	Better undestanding of magnetic storm effects
(iii)	Source and propagation mechanisms of TIDs
(iv)	Day-to-day variability of the F-region
(v)	Electron content of the earth's protonosphere
(vi)	Refilling time of the earth's protonosphere
(vii)	Development, drift and decay of irregularities
(viii)	Association of irregularities with background electron density
(ix)	Morphology of scintillation, TEC and slab thickness
(x)	TEC and scintillation changes from chemical releases
(xi)	TEC and scintillation effects of high powered HF heating
(xii)	Variability of the equatorial anomaly
(xiii)	Variability of the polar cap and auroral ionospheres

scintillation on beacon satellite signals. Because of the great importance of the equatorial anomaly to the electron density distribution over a wide range of latitudes, it has been discussed later in this paper.

4 Equatorial anomaly in the F2-region

In the second edition of Professor S K Mitra's book in 1952, more than five years before the beginning of the space age and the International Geophysical Year (IGY), there are sections on the behaviour of the so called "equatorial anomaly", in which it was shown that the maximum experimentally obtained values of electron densities from ionosondes were not found at the equator, but at latitudes $\sim \pm 15°$ from the equator. Further hints that this anomaly could be explained by electrodynamics came from the observational fact that the ordering of the experimental results from various stations was best against geomagnetic latitude, rather than against geographic latitude. Though during the years beginning in the late 1940s and continuing even to today, much has been learnt about the cause, active work is still being done on aspects of the equatorial anomaly.

It has been known for years that the electrojet controls this anomaly, but it has only been in the last approximate ten years that theoretical models have been successfully compared with actual equatorial latitude ionospheric F-region data. One of the easier F-region measurements to make is that of Faraday rotation of 136 MHz linearly polarized radio waves, provided suitable radio waves are being transmitted from an appropriately placed geostationary satellite of opportunity.

5 Model results compared with TEC observations

The amount of Faraday polarization rotation can be related to the equivalent total electron content (TEC) along the path from satellite to ground observer. In India, during the solar minimum period of 1975-76 when the geostationary satellite ATS-6 was located south of India, several stations covering a latitudinal chain from the magnetic equator to north of the typical latitude of the equatorial anomaly made continuous measurements of the TEC parameter. The day-to-day variability of the latitude of the anomaly peak has been discussed by Rastogi and Klobuchar[7], where they have shown contours of TEC versus latitude and local time for several different days as examples during the ATS-6 period.

Figure 2 illustrates such an example during the two magnetically disturbed days (1 and 2 Dec. 1975). Note that, even though both days were magnetically disturbed having ΣK_p values of 35 and 32,

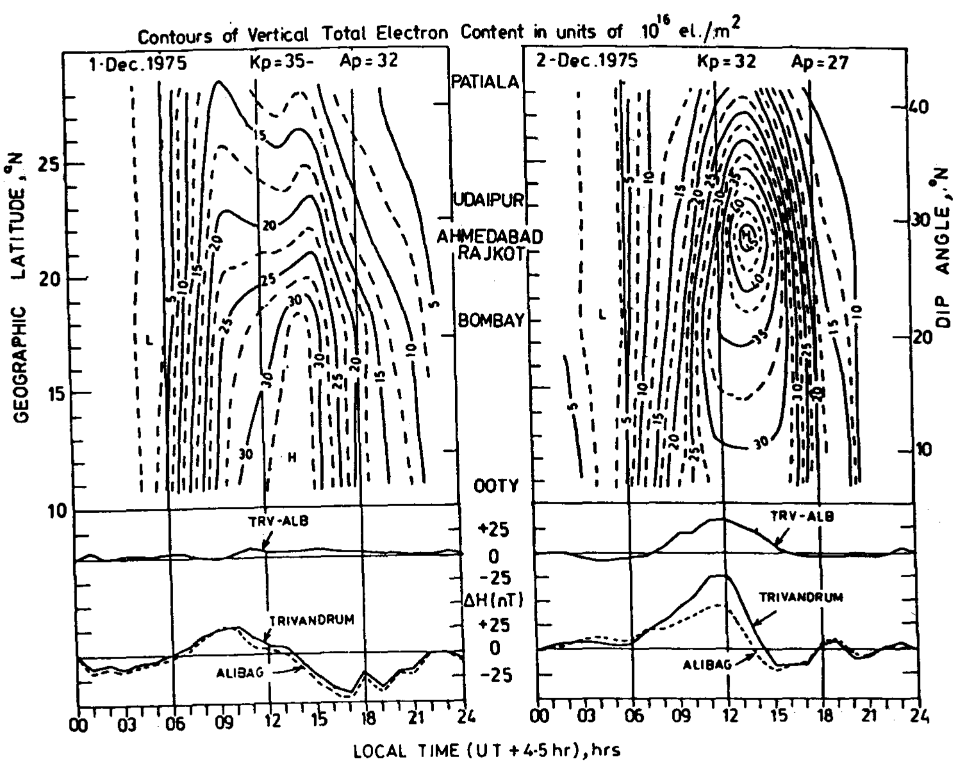

Fig. 2—Contours of TEC over the Indian sub-continent for two magnetically disturbed days (1 and 2 Dec. 1975)

respectively, the first day showed no latitudinal anomaly, while the second day has a typical anomaly in TEC. For reference, the equatorial electrojet, as obtained by the difference between the *H* component of the earth's magnetic field at an equatorial station, and that at a station located outside the electrojet, is also shown in Fig. 2. The lack of the electrojet, indicated by the TRV (Trivandrum) minus ALB (Alibag) curves at the bottom of Fig. 2, clearly shows the reason for the difference in the anomaly for the two days.

The theoretical model developed by Anderson[3] has been used to compare with this actual TEC data. Figure 3 shows the Anderson model compared against the TEC contours for 1 December, a day having no electrojet. Note the reasonably good comparison; neither the model nor the actual data has evidence of an anomaly on this day. The theoretical model was run for this case with no vertical drift at the equator, which gives rise to the anomaly.

Figure 4 shows a comparison of the model with the actual TEC data for 2 Dec. 1975, a day with a normal electrojet. Note the excellent agreement with the magnitude of the anomaly in the model against the actual data, but with slightly lower latitude, and somewhat later occurrence time. The model output can be refined by using a diurnal variation of electric field at the equator, driving the plasma upwards to higher latitudes, which more closely corresponds to the diurnal shape of the equatorial electrojet curve (again shown in the bottom left of Fig. 4).

6 Conclusions

Many advancements have occurred in ionospheric research since Prof. S K Mitra published his book in 1947, and then the second edition in 1952. While we can excuse Prof. Mitra for not seeing the tremendous achievements in experimental knowledge brought about by the space age, can we hope to be any better in our predictions of the need for future research in the upper atmosphere than he was?

Today we are still grappling with many issues in upper atmospheric physics. Among them are: (i) the thermal balance in the ionosphere, namely, the relative heat input from magnetic storms versus that directly from the sun, the variability of the neutral winds, electric fields, and even solar flux, all of which contribute to the day-to-day variability of the ionosphere; (ii) the causes for the variability of the equatorial electrojet, and its unknown role in the development of plumes of irregularities in the early

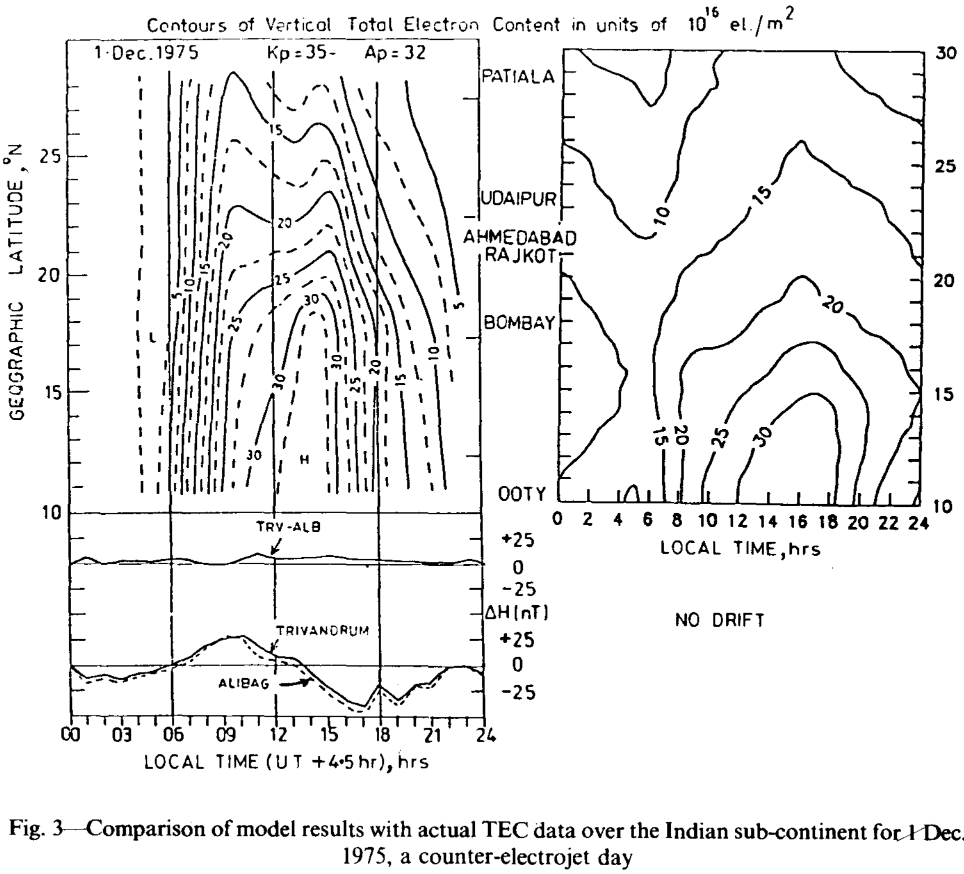

Fig. 3—Comparison of model results with actual TEC data over the Indian sub-continent for 1 Dec. 1975, a counter-electrojet day

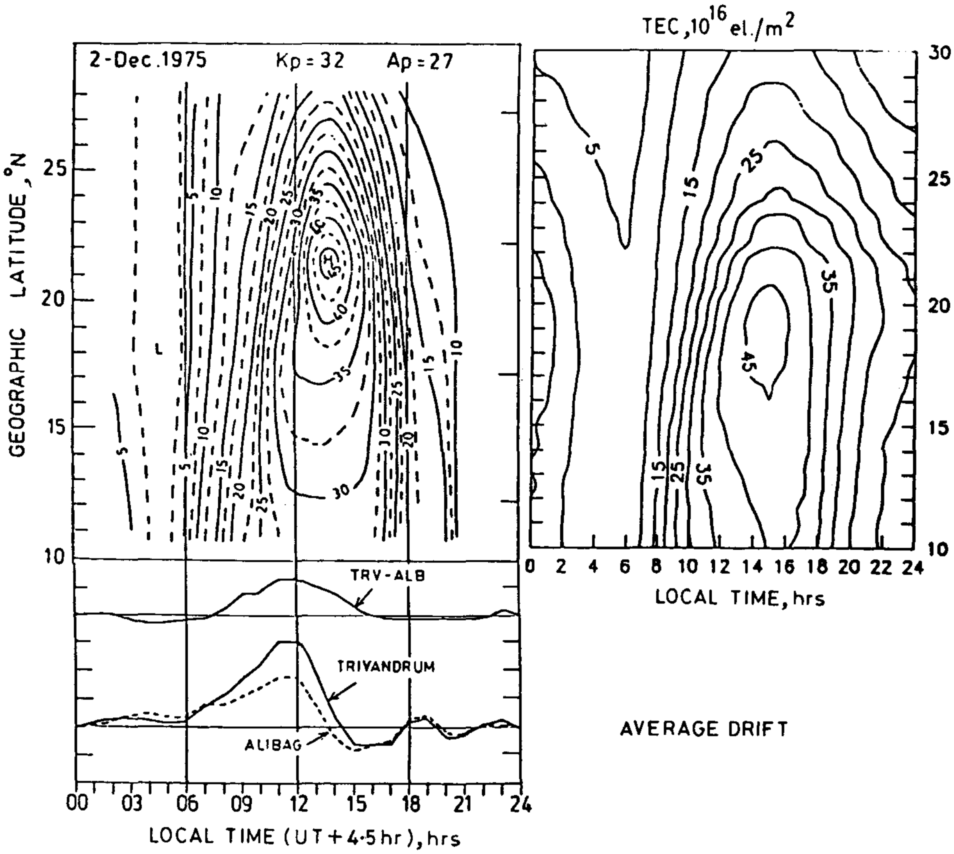

Fig. 4—Comparison of model results with actual TEC data over the Indian sub-continent for 2 Dec. 1975, a normal electrojet day

nighttime equatorial ionosphere; (iii) the full latitudinal extent of the equatorial anomaly and its effects on the lower mid-latitude ionosphere; (iv) the occurrence of magnetic storms, their prediction, latitudinal extent, persistent longitudinal effects which are unexplained. The list could go on and on.

Besides these and many other outstanding questions about the natural ionosphere there are now several methods of making actual experiments, rather than merely observations, for ionosphere. Some of these experiments use rocket or satellite-borne chemical releases, or high-power radio waves to modify the properties of the medium in small but observable ways. The future is filled with opportunity to improve our understanding of the upper atmosphere. The outstanding early work of Prof. S.K. Mitra is one of the major foundation pillars upon which much of our current research is based.

References

1 Mitra S K, *The Upper Atmosphere* (The Asiatic Society, Calcutta, India), First edition, 1947, Second edition, 1952.
2 Somayajulu Y V, *Indian J Radio & Space Phys*, 16 (1987) 136.
3 Anderson D N, *Planet & Space Sci (GB)*, 21 (1973) 421.
4 Austen J R, Franke S J & Liu C H, *Radio Sci (USA)*, 23 (1988) 299.
5 Evans J V, *Rev Geophys & Space Phys (USA)*, 15 (1977) 325.
6 Davies K, *Space Sci Rev (Netherlands)*, 25 (1980) 357.
7 Rastogi R G & Klobuchar J A, *J Geophys Res (USA)*, 95 (1988) 19, 45, 52.