Chapter 1
Introduction to Total Electron Content (TEC) and it’s analysis

1.1 Introduction

Ionospheric physics as an experimental subject, started in the year 1925 with the frequency change experiments of Appleton and Barnet (1925) and the pulse sounding technique of Breit and Tuve (1925). In the decades that followed the pulse sounding technique of Breit and Tuve has been used extensively as a basic tool for bottomside ionospheric measurements (Green 1946; Ratcliffe and Weekes, 1960). As a result of these bottomside-sounding experiments the detailed structure of the ionosphere was well established. Accordingly, the ionosphere is classified into different layers such as D, E and F-layers.

The satellite era of ionospheric studies started in the late fifties with the launching of the first artificial earth satellite, Sputnik I in 1957. The successful launching of the Canadian satellite Alouette in 1962 inaugurated the era of ‘topside sounding’ (Warren, 1963). The topside sounding experiments led to the understanding of a continuous decrease of electron density with height in the topside ionosphere without any distinct layers.

Total electron content (TEC) of the ionosphere is a measure of the total number of electrons in a vertical column of unit cross-section extending from the ground to the top of the ionosphere. Being weighted more than 90% by the F region peak ionisation, TEC reflects most of the properties of the peak electron density. TEC observations have yielded valuable information on many ionospheric processes and
have also helped to evaluate the gross ionospheric effects of trans-ionospheric satellite, radar and radio-astronomical measurements.

Measurements of TEC have progressed tremendously from the days when measurements were made from Faraday fading of moon echoes (Evans, 1957). Observations of radio beacon signals from satellites provided valuable information, particularly of regions well above the peak of the F-layer which were not accessible by ground based techniques. The earliest beacons were on relatively low orbiting satellites and they provided information on the horizontal distribution of Faraday content because the speed of the satellite was much larger than the movements of the ionosphere. These measurements had the advantage that the Faraday rotations were relatively easy to measure.

However, the conversion of Faraday rotation which is directly proportional to the component of the magnetic field along the ray path, to ionospheric content was hampered by the movement of the ray path with respect to the geomagnetic field. Other difficulties arose from horizontal gradients, the necessity to track the beacon and having to eliminate the integral number of half rotations along the shortest path. The distinct advantage of synchronous satellites (the satellite position being fixed relative to an observer, which eliminates the necessity of tracking and ensures an almost constant angle between the ray path and the geomagnetic field) was quickly recognised and the first geostationary satellite Syncom-3 was soon being used for ionospheric studies (Garriott and Little, 1960). The various techniques used for TEC measurements and the morphological features of TEC have been reviewed by Al’pert (1976), Evans (1977) and Davies (1980).

The radio beacon technique for measurement of electron content has made major progress with the use of geostationary satellites like ATS-6 and ETS-II which were designed specifically for the measurement of total columnar electron content between the transmitter and receiver as well as the Faraday (or ionospheric) columnar
content along the ray between the receiver and a height of about 2000 km (Titheridge, 1972; Davies, 1980). The new beacons enabled high time resolution and broad frequency coverage, which were not available with previous telemetry channels.

Recently, a suggestion has been made by the Space Environment Laboratory, NOAA, USA that a radio beacon be placed on board the polar platform orbiting at a height of about 800 km (Davies, 1988). Another concept using radio beacon signals for ionospheric research is described by Klobuchar and Hicks (1988), in which signals from small transmitters located on the ground are received on a geostationary satellite and then transmitted at a higher frequency to one or more ground locations for real time central data collection. According to Ciraolo and Spalla (1988), the future investigations of the ionosphere will require observations with high temporal and spatial resolution in order to check models and theories and to improve the statistics of the ionospheric parameters involved in broadcasting, navigation and geophysics. Recently, Foucher and Civaldini (1991) have modelled the TEC for the TOPEX-POSEIDON oceanographic satellite telemetric signals in order to correct the apparent altitude lengthening which will be brought about by ionospheric propagation.

The satellite radio beacon techniques which are usually used for electron content measurements are (1) Faraday rotation technique and (2) Group delay technique. The Faraday rotation technique gives the electron content up to an altitude of about 2000 km (Titheridge, 1972) while the delay technique gives the content up to the satellite height. The difference between the group delay content and the Faraday content gives a measure of the plasmaspheric content. The basic principles of the Faraday rotation and group delay techniques are described in section 1.2. The applications of TEC and its general morphology are described respectively in sections 1.3 and 1.4. The latitudinal variations of storm time ionospheric response, ionospheric response on local time of SC and intensity of geomagnetic storms, the dependence of night-time enhancement in TEC on SC storm, storm dusk effect and an
empirical model for TEC by harmonic analysis, which form the subject matter of this thesis are given respectively in sections 1.5 and 1.6. Finally, a statement on the scope of the present study is given in section 1.7.

1.2 Satellite beacon techniques for measuring TEC

1.2.1 Faraday rotation technique:

The polarisation angle of a plane-polarised radio wave rotates as it traverses the ionosphere by an amount which depends on the number of free electrons along the ray path. Measurements of the angle of rotation known as Faraday rotation, therefore, gives a direct measure of total electron content along the line of path between the satellite transmitter and the receiving ground station. At frequencies $f$ much higher than the plasma frequency $f_p$ and under quasi-longitudinal (QL) approximation, the one way rotation $\Omega$ of the plane of polarisation is given as (Evans, 1977):

$$\Omega = \left(\frac{K}{f^2}\right) \int_0^h B_h \cos \theta_h \sec \chi_h N_h \, dh \, \text{rotations}$$

(1)

where $K = 3.75 \times 10^3$ in MKS units

$h$ = height of the satellite

$B_h$ = flux density of Earth's magnetic filed at height $h$

$\theta_h$ = angle between the ray and the magnetic field direction

$\chi_h$ = local zenith angle to the ray

$N_h$ = local electron density (el/m$^3$).

Equation (1) holds provided that the ray path at no point becomes exactly normal to the magnetic field. In practice the measured amount of polarization, $\Omega$, is converted into an equivalent total vertical electron content $\int N_h \, dh$ by removing $B_h \cos \theta_h \sec \chi_h$ from the integral sign and replacing it with a mean value $M$. This is justified by the fact that while $N_h$ is a rapidly changing function over the region where most of the
electrons are distributed, \( B_h \cos \theta_h \sec \chi_h \) changes very slowly over the same height range.

\[
\Omega = \int_0^{h_t} N_h \, dh
\]

Then

\[
\Omega = (K/M/c^2) \int_0^{h_t} N_h \, dh
\]  

where \( M = B_h \cos \theta_h \sec \chi_h \)

Computations of the correct value of \( M \) are made by assuming a typical \( N-h \) profile and by equating

\[
M = \frac{\int_0^{h_t} B_h \cos \theta_h \sec \chi_h N_h \, dh}{\int_0^{h_t} N_h \, dh}
\]  

Intercomparison of total electron content measurements made using satellite beacon observations and incoherent scatter observations allowed \( M \) to be determined empirically (Smith, 1970; Kersley and Taylor, 1974). It was found that \( M \) is given quite accurately by the actual value of \( B \cos \theta_h \sec \chi_h \) at a height 50-100 km above the height of the layer peak. Any resultant error due to the choice of a constant \( M \) rather than a diurnally changing \( M \) factor has been estimated to be not greater than 5% and the resultant TEC is considered to be a measure of the TEC to a height of approximately 2000 km (Titheridge, 1972). Even though many researchers (Titheridge, 1972; Davies et al., 1976) have used different approaches to estimate the height at which \( M \) is to be computed, it is to be noted that their results are in general agreement.

The main sources of error in the Faraday rotation method are those due to the choice of a fixed height for \( M \), vertical motions of the source and horizontal gradients in the electron content (Titheridge, 1972). Other sources of error include quasi-
longitudinal approximation, height-frequency approximation, neglect of corrections in the Appleton-Hartree formula for refractive index, low zenith angle approximation and geometry of the magnetic field used for M calculation.

The main difficulty in analysing Faraday rotation data arises from the ambiguity problem, ie, the fact that a radio receiving system cannot normally distinguish between one cycle and the next. A variety of techniques have been developed to estimate the integral number of cycles or half cycles in the case of Faraday rotation (Checcacci and Giorgio, 1976). Such methods usually require peak electron density (Nm F2) information obtained from a suitable ionospheric sounding location. At some locations, particularly at low geomagnetic latitudes, at night, the Faraday rotation falls below or near to one rotation and there is little doubt about the number of half cycles. Then the usual procedure for obtaining the total Faraday rotation is to count the half cycles one by one as the electron content builds up after sunrise. This requires continuous beacon operation as well as a careful counting of half cycles. The ambiguity in the measurement of \( \Omega \) can be removed if observations are made simultaneously at two frequencies separated by a small amount, \( \Delta f \) (Evans, 1977). In this case, the difference \( \Delta \Omega \) in the rotation at the two frequencies may be determined. \( \Delta \Omega \) is related to \( \Omega \) as:

\[
\Omega = (2f / \Delta f) (\Delta \Omega)
\]

To obtain the best possible TEC values from the observations, conversion tables have also been prepared for converting the values of polarisation read off raw data in chart divisions to the final TEC values.

1.2.2 **Group delay technique**

This technique uses the variation of phase path with frequency and it is essentially independent of the geomagnetic field, at least to a first approximation, so
that it gives the total columnar electron content between transmitter and receiver. Of the several different versions of this technique, the one used in ATS-6 (Davies, 1980) which was designed to provide both high sensitivity and cycle resolution, is described here. The method is based on the fundamental relationship that the time of flight \( t_\phi \) of a wave group is the frequency derivative of the phase (Brillouin, 1960):

\[
\frac{\partial \phi}{\partial f} = \frac{\Delta \phi}{\Delta f} \quad \text{sec}
\]

where \( \Delta \phi \) is the phase difference (in cycles) between waves with a frequency difference of \( \Delta f \) Hz.

For frequencies normally used with radio beacons, the anisotropy of the ionosphere is negligible and in the absence of ray refraction, the phase difference between transmitter and receiver is

\[
\delta \phi = (f/c) S \int \mu ds \quad \text{cycles}
\]

where \( \mu \) is the phase refractive index and \( ds \) is an elemental surface area.

It is customary to use the non-derivative and quasi-longitudinal approximation for the refractive index, viz.,

\[
\mu = 1 - kN/2f (f \pm f_i)
\]

where + and - refer to ordinary and extraordinary waves respectively. Since \( f_i \) is of the order of 1 MHz whereas \( f \) is of the order of 40 MHz or greater, generally, the effect of the geomagnetic field is small. Substituting (7) in (6), we can see that there is a term, which depends on the transmitter-receiver path length. In the modulation phase method this term is removed by taking two sets of frequencies separated by the
same difference $\Delta f$. Let $f_2$ and $f_i$ be the arithmetic average of these two frequency sets. Then the difference $\Delta \phi$ between the two-phase differences is

$$
\Delta \phi = \frac{-k \Delta f}{2c} \left[ \frac{1}{(f_2 + f_L)^2} - \frac{1}{(f_i + f_L)^2} \right] \int_r^s Nds \text{ cycle} \quad (8)
$$

where $f_L$ is the average of the electron gyro-frequency. The minus sign arises from a sign convention. Hence, from the measured $\Delta f$ and the wave frequencies the total electron content $N_T = \int Nds$ can be determined.

1.3 Applications of TEC

1.3.1 Geophysical applications

TEC measurements have provided valuable information on various ionospheric processes. They have been used to (a) study the ionosphere-plasmasphere coupling including the maintenance of the night-time ionosphere and the occurrence of night-time enhancements (Titheridge, 1968; Young et al., 1970; Mendillo and Klobuchar, 1975; Buonsanto et al., 1979; Tan 1982); (b) determine the reasons for the day-to-day variability in the F-region (Kane, 1980; Dabas et al., 1984), (c) calculate the production and loss rates of ionisation (Garriott and Smith, 1965; Titheridge, 1974; Bhuyan et al., 1983), (d) study the F region dynamics with particular reference to travelling ionospheric disturbances as a manifestation of atmospheric gravity waves (Soicher, 1988) and (e) check theoretical and empirical models of electron density distribution (Minakoshi and Sinno, 1986; Bhuyan et al., 1987). Two areas in which fruitful studies could be conducted using TEC data were suggested by Evans (1977) and they are: (1) measurements of TEC and peak electron density in conjunction with realistic models for the ionosphere should permit some parameters (such as solar EUV flux) to be monitored inexpensively and (2) measurements of the total content
by a network of stations surrounding the auroral oval in conjunction with the incoherent scatter measurements should permit the study of the transient manner in which the energy input into the upper atmosphere by Joule heating is redistributed to other latitudes by planetary waves, acoustic gravity waves and winds.

1.3.2 Communication applications

TEC data have direct applications in communication links. Some of the applications for which TEC data are used are (a) refraction correction (b) time delay correction and (c) margins of allowance for amplitude fades. Some of the engineering parameters such as range error, phase deviation, group delay and differential phase shift between the centre frequency and the different frequencies in a band can be computed using TEC as input data. As the demand on the number of channels increases, the band width of the transmission also has to be increased. With the increase of bandwidth, the propagation through the ionosphere gets affected in terms of phase dispersion. Calla (1971) has calculated the relative phase distortion for a 100 MHz communication band extending over 790-890 MHz. Brookner (1965) and Rao et al. (1980) have studied the ionospheric effects on pulse modulated signals and derived maximum usable bandwidths on trans-ionospheric communication links. The above calculations for characterising a communication channel are based on TEC as an input parameter. Satellite tracking algorithms for correcting ionospheric refraction effects require real time TEC data from a network of stations as a basic input for updating the predictions. Models for TEC based on observational data have been developed which could be used for satellite tracking applications (Somayajulu and Ghosh, 1976; Klobuchar et al., 1977).
1.4 General morphology of TEC

Among the several factors that affect the columnar electron content of the ionosphere, the most important are (a) variations of the solar zenith angle (b) semi-annual and annual variations (c) solar cycle variations (d) latitudinal variations (e) erratic variations associated with enhanced geomagnetic activity, particle precipitation and atmospheric disturbances. The earlier studies conducted using TEC observations and its dependence on the above factors are dealt with in this section.

1.4.1 Diurnal variations

The variation of TEC under different geophysical conditions have been studied by many investigators for low (Yuen and Roelofs, 1966; Rastogi and Sharma, 1971; Bhuyan et al., 1983; Modi and Iyer, 1988) as well as mid- and high-latitudes (Hibbered and Ross, 1966; Klobuchar and Allen, 1970; Tyagi, 1974; Buonsanto et al., 1979; Soicher, 1986). From these studies it is found that some of the diurnal features are more or less common irrespective of season, level of solar activity and location of the observing station. One observed common feature is the steady increase in TEC values from about sunrise to a mid afternoon peak and then a decline to a predawn minimum. While certain diurnal features like noon bite out (Bandyopadhyay, 1970; Prasad et al., 1987; Jakowski et al., 1988) and post sunset enhancements (Young et al., 1970; Das Gupta et al., 1983, 1985; Balan et al., 1986) are more commonly observed for low latitudes, more frequently during winter and equinox, other features like the post midnight enhancements during winter (Tyagi, 1974; Mendillo et al., 1977; Soicher 1986) and the delayed occurrence of daytime peak during summer (Klobuchar and Allen, 1970; Tyagi, 1974) are observed for mid- and high-latitudes. The diurnal ratio of electron content which is defined as the ratio of the maximum to minimum electron content of the day, is found to vary with season, solar activity and latitude. Titheridge (1973) consolidated the diurnal ratios obtained by various authors for different latitudes and concluded that the ratios are smaller in the polar region and
higher near the equator with an asymmetry between northern and southern hemispheres; the northern hemispheric values being significantly higher. The ratios are found to be higher in winter than in summer. Generally, the summer ratios remain more or less constant while the winter ratios tend to increase with solar activity.

1.4.2 Seasonal variations

TEC exhibits a distinct dependence on season. In general TEC attains its maximum values during equinox and minimum during solstices. This semi-annual TEC variation, reported for low- (McNamara and Smith, 1982; Bhuyan et al., 1983) as well as mid- and high-latitudes (Huang, 1978; Buonsanto et al., 1979), is found to exhibit latitudinal and solar activity dependence. This seasonal variation is attributed to changes in the neutral atmosphere as well as to vertical plasma drifts (Titheridge, 1973; Bhuyan and Tyagi, 1985). Another important aspect of TEC variations is the existence of a seasonal anomaly with higher TEC values during winter compared to the corresponding summer values (Torr et al., 1980; Jakowski and Paasch, 1984). It is found that this phenomenon is most pronounced in the years of higher solar activity, but becomes less distinct during lower solar activity conditions. The anomaly seems to increase with latitude and is distinctly asymmetric between the northern and southern hemispheres; it is considerably weaker in the latter (Titheridge, 1973; Besprozvannaya, 1987).

1.4.3 Solar activity variations

A close correlation between solar activity and the electron content of the ionosphere has been established for low-, mid- and high- latitudes. Bhonsle et al. (1965), using TEC observations at mid-latitudes during 1958-1962 showed that the noon time values of the electron content plotted against smoothed sunspot numbers, were distributed about a straight line indicating the linear nature of the TEC dependence on solar activity. However, the straight lines have progressively
decreasing slopes for equinox, winter and summer. Titheridge (1973) observed that for low- and mid-latitudes in the southern hemisphere, the average TEC values were nearly proportional to the 10.7 cm solar flux ($F_{10.7}$) during the ascending phase of the 20th solar cycle. The study of da Rosa et al. (1973), to determine the influence of solar activity on the ionospheric electron content has also revealed the existence of a linear relationship between the daily mean content and the $F_{10.7}$ solar flux. Huang (1978), from his study of the solar cycle variations in TEC for the mid-latitude station of Sagamore Hill, found a good positive correlation between the 12 month running mean of TEC and the corresponding sunspot numbers. Jakowski and Paasch (1984), using radio beacon transmissions of geostationary satellite in Neustrelitz (53.3° N, 13.07° E) during the years 1976-1980 observed that the long-term variations are well correlated with solar activity. However, the results obtained using geostationary satellite data at Delhi during 1975-1980 indicate that the linear relationship between TEC and $F_{10.7}$ exists only up to about 200 units more or less, for all three seasons and that there is a decrease in electron content with further increase in solar flux (Bhuyan et al., 1983). Rao et al. (1988) have reported the saturation effect of $T_{\text{EC, max}}$ for $F_{10.7}$ values exceeded 220 units for the low latitude station, Hawaii. Recently Balan et al. (1993) have reported saturation daytime TEC in all latitudes when $F_{10.7}$ exceeded about 200 units. In another paper Balan et al. (1994) through modelling work have reported the above observed saturation of TEC with solar flux. They have shown that the saturation is the result of the saturated production of ionisation due to the saturated solar EUV flux. Based on theoretical considerations, Serafimov (1986) has suggested the possibility of a saturation effect in TEC for sunspot numbers higher than about 120 units.

Recently Jakowski et al. (1991) using TEC observations at Neustrelitz and Havana along with ionosonde observations have shown the existence of a significant solar radiation control of the ionosphere with a 27 day solar rotation period. Cross-correlation analysis indicates a 1-2 day response time of the ionosphere to the 27 day solar radiation cycle. This time lag is explained on the basis of the 2 day time lag in
the variation of atomic oxygen concentration with respect to the solar radiation variation.

1.4.4 Latitudinal variations

The two important aspects of the latitudinal TEC variations are the existence of equatorial anomaly and mid-latitude trough. During daytime, the latitudinal gradients are quite large with TEC showing distinct peaks at low-latitudes with a trough at the equator. This latitudinal variation, explained in terms of vertical electrodynamic drifts at the equator and consequent diffusion to low-latitudes is popularly known as the “equatorial anomaly”. Using satellite data, Serafinov (1986) showed that the equatorial anomaly develops both at the bottom and the top of the ionosphere. The diurnal development, latitudinal structure and day-to-day variability of the equatorial anomaly have been investigated by Huang et al. (1989). The second aspect of the latitudinal TEC distribution is the so-called “mid-latitude trough”. This marked depression in TEC lies between invariant latitudes of 55° and 75° and is primarily a night-time phenomenon but has also been observed in the pre-dusk, dawn and noon sectors. Its main morphological characteristics have been discussed by Mendillo and Chacko (1977). Putz and Leitinger (1988) using differential Doppler data collected at Uppsala (59.8° N, 17.6° E) and Sodankyla (67.4° N, 26.4° E) carried out a statistical analysis of the mid-latitude trough characteristics. They have also proposed a model, which describes the behaviour of the trough during night-time in winter and equinox.

1.5 Ionospheric response to geomagnetic storms

When the Earth’s magnetic field is severely disturbed, a “magnetic storm” is said to occur. A magnetic storm is caused by the electric current systems set up in the magnetosphere when an enhanced solar wind consisting of a stream of protons and
electrons strikes the magnetosphere or due to solar flares. Often storms begin abruptly and they are called the “sudden commencement” (SC) storms. A sudden commencement storm (SC) has 3 typical phases – initial-, main- and recovery-phases. Studies of ionospheric storm effects using the peak F region electron density and ionospheric total electron content have been reviewed by Evans (1977) and the global morphology and physics of ionospheric storms by Prolss (1997) and Fuller-Rowell et al., (1997).

Several mechanisms have been proposed to explain the storm associated ionospheric variations. They are (1) electro-magnetic drift associated with stormtime electric field; (2) enhanced thermospheric circulation (waves and winds) generated by auroral zone heating during magnetic storms and the consequent loss rate; (3) compression of plasmasphere by enhanced solar wind and (4) changes in atmospheric composition due to enhanced thermospheric circulation. Since these mechanisms have strong latitudinal effects, ionospheric response in terms of TEC variation also exhibits latitudinal dependence during storms. In fact, the storm-associated effects are complicated and depend on latitude, longitude, local time and the time elapsed from the commencement of the geomagnetic storm.

Storms are generally categorised as positive or negative according to whether the dominant deviation for a storm is on an increase or decrease. The relative deviations of TEC are not used to represent the strength of the storms because, during night-time, they may show abnormally high values due to the very low base values. Since both the peak electron density and TEC are found to vary considerably during magnetic storms, it can be inferred that the ionospheric response to geomagnetic storms is not merely a redistribution of ionisation. The maximum positive or negative deviation from the corresponding average value is obtained for each storm, which is considered as the strength of that storm. The time delay of ionospheric geomagnetic storm is taken as the time interval between the onset of SC and the time of maximum response. Maximum $A_p$ value during the storm period is used to represent the intensity
of the geomagnetic storms. Certain interdependencies exist between these storm-associated characteristics. Also time delay shows a variation in accordance with the local time sudden commencement of storm.

The behaviour of the ionosphere during a magnetic storm is influenced by two opposing effects; one by meridional neutral air winds which causes an increase of electron content and the other by a local thermospheric temperature rise which causes a decrease of electron content. If wind effects dominate the local temperature effects, the electron content will tend to increase. If the reverse is true, the content will tend to decrease and if both effects are equal, there will be neither an increase or a decrease of electron content (Huang et al., 1974).

Short duration positive storms are caused by travelling atmospheric disturbances, which are carried along equatorward-directed winds of moderate magnitude. In response to the continuing energy injection at polar latitudes the layer height and the ionisation density remain elevated (Prolss 1997). Such prolonged increase in layer height are also attributed to meridional winds (Codrescu et al., 1992; Prolss, 1997). This may lead to long duration positive storms.

Neutral composition changes have important implications for the ionosphere. This is because a decrease of the oxygen density will decrease the production of ionisation, and an increase in the molecular nitrogen density will increase the loss of ionisation. Thus both changes combine to reduce the ionisation density (Prolss, 1997). Any station located below a composition disturbance would observe negative ionospheric storms.

It has long been realised that the total electron content (TEC) of the ionosphere does not decrease through out the night in the way predicted by simple theory but shows anomalous enhancements under a wide range of geophysical conditions (Balan and Rao, 1987). The various enhancement characteristics, such as
amplitude, half amplitude duration, frequency of occurrence and time of maximisation are found to depend upon location, season and solar activity.

The potential source mechanism for the observed night-time TEC enhancements at low-latitudes are believed to be (a) plasma transfer from conjugate ionosphere and (b) electrodynamic drifts and neutral winds. There are a few other mechanisms listed with phenomenon of night-time enhancement in TEC, such as plasma diffusion from protonosphere (Titheridge, 1968), cross-L plasmaspheric compression and consequent enhancement in plasmasphere-ionosphere plasma flow (Davies et al., 1979) and corpuscular ionisation (Titheridge, 1968) which are important only at mid- and high-latitudes.

At low-latitudes the electrodynamic $\mathbf{E}_\mathbf{\times B}$ drift is very effective in transporting ionisation in the ionosphere (Prasad and Rama Rao, 1993). It is also established that at low-latitudes atomic oxygen is enhanced by transport from higher latitudes and/or the upwelling in the auroral oval. Neutral winds and electrodynamic drifts also act as important source mechanisms especially to account for the post midnight TEC enhancements. Conjugated point transfer mechanism of ionisation (Rishbeth, 1968) can also explain certain observed facts.

Previous studies of night-time enhancements were generally conducted by selecting a particular period, which included quiet as well as disturbed nights. A study on night-time enhancement during storms will lead to a better understanding of all the possible mechanisms associated with night-time enhancements and storms.

The large increase in F2 peak density ($\text{NmF}_2$) and ionospheric total electron content (TEC) observed in the afternoon and evening hours, especially at mid-latitudes during the first storm day following a geomagnetic storm commencement is referred to as “storm dusk effect” (Lanzerotti et al., 1975). Buonsanto (1995) had conducted a study using incoherent scatter radar data collected at Millstone Hill and
total electron content data from a North-South chain of stations during the May 26-27, 1990 storm. From these he calculated the motion term in the continuity equation and used it along with wind and electric field data to assess the relative importance of the proposed mechanisms during the above storm. He observed that, in addition to travelling atmospheric disturbances (TADs), a change in neutral composition, in the form of a decrease in $N_2$ density over the course of the afternoon and evening also played an important role.

1.6 Harmonic analysis and empirical model for TEC

A modulated radio frequency signal between a satellite and ground is both reflected and refracted by the intervening ionised medium. The delay is directly proportional to total ionospheric electron content along the ray path. The disperse nature of the medium may be used to deduce the electron content from multi-frequency observations. This may be used as a real time correction for the propagation delay. Ionospheric corrections can be applied to operational systems by prediction of the expected propagation effects using numerical models. Hence models are very important because they faithfully represent the ionospheric conditions within a given time span.

An ever changing blend of sources and perturbation signatures distinguish the hour-to-hour and day-to-day variations of the real ionosphere from so called first principle models of the ionosphere. Such models appear fully capable of describing ionospheric variability if the correct blend of time dependent input parameters can be specified (Fuller-Rowell et al., 1998; Xiaoqing Pi et al., 2000).

Numerical models have significance at low latitudes because the International Reference Ionosphere (IRI) yields reasonably accurate values of electron content only at mid- and high-latitudes, while it tends to severely underestimate the daytime values at low-latitudes. Modelling also helps a lot in predicting the ionospheric response to
geomagnetic storms (Fuller-Rowell et al., 1997). To illustrate the global response at the entire thermosphere to storm time forcing, Thermosphere Ionosphere General Circulation Model (TIGMC) is highly dependable (Codrescu et al., 1992; Roble and Ridley 1994). Since TEC is an ionospheric parameter which undergoes diurnal, seasonal and solar cycle variations, suitable mathematical models can describe these variation and help to predict the data in terms of harmonic coefficients of TEC variations.

1.7 Scope of the present study

The present work is devoted to a study of the storm time ionospheric response, dependencies of its parameters on time of occurrence and strength of storm, dependence of night-time enhancements in TEC on SC storms, storm dusk effect and modelling of TEC by harmonic analysis.

In this Chapter diurnal, seasonal and solar cycle dependence of TEC were discussed. It also included the basics of stormtime variations of TEC and modelling studies.

Latitudinal, seasonal and solar cycle variations of storm time ionospheric response for low- (Ramey), mid- (Sagamore Hill) and high- (Goose Bay) latitude stations during the period 1980-'81 and 1985-'86 are described in Chapter 2.

The dependence of parameters of ionospheric response on the time of occurrence of sudden commencement and the intensity of storms at a low-latitude station Palehua, during the period 1985-'89 are presented in Chapter 3.

Though night-time enhancements in TEC were studied by many groups, little attention was paid to night-time enhancement in TEC during storms. In Chapter 4, the dependence of night-time enhancement on SC storm is examined. Here, firstly the
seasonal and solar activity dependence of characteristics of night-time enhancement are compared with those of quiet nights for a low-latitude station during the period 1980-1989. Secondly, the latitudinal dependence of night-time enhancements during SC storms are compared with those of quiet nights for a high solar active year 1989. This study also investigates whether the intensity of a storm has any influence on the characteristics of night-time enhancements. The results are discussed in the light of current theoretical understanding.

Though a few case studies were conducted on storm dusk effect, they are quite inadequate to obtain a clear picture about the dependence on the latitude, season and solar activity of the strength of the storm dusk effect. Chapter 5 mainly deals with the latitudinal, seasonal and solar activity dependence of the storm dusk effect by considering all SC storms with Ap > 20 for low- (Ramey), mid- (Sagamore Hill) and high- (Goose Bay) latitude stations. Also this study investigates the probable relation between strength of storm dusk effect, intensity of storm and local time of maximisation.

An empirical model of TEC, for all levels of solar activity, using data for the years 1980-1990 at Palehua, a low latitude station using harmonic coefficients up to four orders is developed in Chapter 6. A set of 81 coefficients of zero and the first four orders were determined which were found to be sufficient for modelling the TEC. The modelled monthly mean TEC values agree quantitatively with the measured data, the maximum deviation being limited to ±15%. The model reasonably reproduces the features observed in the diurnal, seasonal and solar cycle variations of the measured data.
1.8 References

Somayajulu Y.V. and Ghosh A.B. (1976), The geophysical use of satellite beacon observations, (ed.) Mendillo M., Boston University, 669.