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# Variations in TEC & Other Ionospheric Parameters Associated with Magnetic Storms

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The stormtime variations of the ionospheric total electron content (TEC) and peak electron density ($N_m$F2) of the F-layer are studied for Kurukshetra and Gauhati using 140 MHz transmissions from the ATS-6 geostationary satellite for the period 1975-76. The results of major storms except those of the one which occurred in summer show that during early night hours following the main phase onset of the storm, a significant positive phase is observed for both TEC and $N_m$F2. It is followed by a negative phase. The positive phase is noticed more commonly during the forenoon hours on day-1 and almost throughout on day-2. Negative phase is also noticed on the afternoon of day-1 and also on day-3. As for the summer storm, the negative phase is observed simultaneously with a large negative excursion in the *H*-component of the local geomagnetic field and the positive phase observed on day-2. The effect of moderate storms is also of the same type as for severe storms. No significant changes were observed in ionospheric production as well as loss rates during the magnetic storm. The daytime storm effects in TEC and $N_m$F2 are suggested to be caused by the **E**×**B** drifts, whereas some abnormal increase in TEC is suggested to be due to the effects of thermospheric winds set up by high latitude heating during the geomagnetically disturbed periods.

## 1. Introduction

There has been considerable interest in the effects of geomagnetic storms on the ionosphere. Stormtime $f_0$ F2 (or $N_m$ F2) variations have been studied by many workers.[1-11] In recent years the ability to measure the total electron content (TEC) by utilizing the Faraday rotation of satellite radio transmissions has enabled workers[12-22] to define these effects better. It has been suggested[5,18,23] that the response of the ionosphere to an individual geomagnetic storm is determined by the local time of sudden commencement (SSC) or main phase onset (MPO) of the storm. The consensus seems to be as follows.[18] The response of the ionosphere to an individual geomagnetic storm in the cases for which SSCs or MPOs occur during daytime would be a positive phase in the afternoon of the same day followed by a negative phase. These storms would be termed as "regular". If SSC or MPO occurs after dusk, either no positive phase is seen at all and only a negative phase is seen ("No" storm) or, the positive phase is delayed and seen the next day afternoon ("Delayed" positive storms). The purpose of this paper is to examine deviations from the above mentioned average patterns for TEC and $N_m$F2 at Gauhati and Kurukshetra.

## 2. Data and Method of Analysis

The TEC data along with maximum electron density $N_m$F2 were examined during four severe storms and four moderate storms which occurred during Nov. 1975-July 1976, a low solar activity period. The details of the magnetic storms referred to in this paper are given in Table 1. The TEC data were obtained by Faraday rotation measurements of the 140 MHz signal from ATS-6 geostationary satellite (lat., 0·0°N ; long., 35·0°E), recorded at Gauhati (26·2°N ; 91·8°E) and Kurukshetra (29·9°N ; 76·8°E). The 420 km subionospheric coordinates of Gauhati and Kurukshetra for ATS-6 were (23·8°N ; 83·6°E) and (27·9°N ; 73·3°E), respectively. The corresponding peak electron density ($N_m$F2) values were derived from the published $f_0$F2 measurement from Delhi (28·6°N ; 77·2°E) and

Table 1—Geomagnetic Storm Data

| Storm | Date of commencement | Time of MPO hrs 75°E | Time of maximum depression in $H$ at Alibag |  | Recovery |  | Range in $H$ at Alibag | Type of storm |
|---|---|---|---|---|---|---|---|---|
|  |  |  | Date | Time hrs | Date | Time hrs | nt† |  |
|  |  |  | 1975 |  |  |  |  |  |
| I | 17 Nov. | 1630 | 17 Nov. | 2130 | 18 Nov. | 1530 | 217 | Major |
| II | 21 Nov. | 1330 | 22 Nov. | 2030 | 24 Nov. | 0730 | 207 | Major |
| III | 29 Nov. | 1400 | 29 Nov. | 1630 | 4 Dec. | 2330 | 140 | Moderate |
|  |  |  | 1976 |  |  |  |  |  |
| IV | 10 Jan. | 1730 | 10 Jan. | 2330 | 14 Jan. | 0430 | 238 | Major |
| V | 29 Apr. | 2130 | 30 Apr. | 1130 | 5 May | 0930 | 106 | Moderate |
| VI | 2 May | 0700 | 3 May | 1230 | 5 May | 1930 | 178 | Major |
| VII | 19 May | 0300* | 20 May | 2200 | 20 May | 0000 | 88 | Moderate |
| VIII | 10 June | 0600* | 11 June | 1500 | 12 June | 0200 | 110 | Moderate |
| IX | 30 June | 1300 | 30 June | 1630 | 1 July | 0300 | 1300 | Moderate |

*An asterisk means next day.

† 1 nt (nanotesla) = 1 gamma = $10^{-9}$ weber/m$^2$.

Ahmedabad (23·0°N ; 72·3°E), the nearest available stations to the subionospheric points. The Ahmedabad data were supplemented where necessary by data from Bombay (19·0°N ; 72·5°E). Instead of the actual data with monthly median values being plotted side by side, the deviations in TEC values were determined in the following way. For each storm, quiet days arround the day of MPO of the storm are selected (as Jain *et al.*[22]) and the average diurnal curve in TEC is determined for each of the sets of quiet days for both the stations. Then this average quiet day TEC value is subtracted from the corresponding values for the disturbed days. For $N_m$F2, the deviation is determined by subtracting the monthly median values from those of disturbed days, as sufficient number of quiet days were not available because of the gaps in the data. Thus, the derived hourly deviations of TEC and $N_m$F2 are plotted as functions of stormtime as well as local time (75°E time) to study the storm effects.

## 3. Results

Fig. 1 (for three major) and Fig. 2 (for two moderate) show the plots of deviations for field, TEC and $N_m$F2 data, respectively, against 75°E meridian time-spread over a period of 5 days commencing a day before the MPO and lasting for four days subsequent to the MPO of the storm. The top curve shows geomagnetic $D_{st}$ (Ref.24) indicating the MPO. Below this are the plots of deviations of the TEC recorded at Kurukshetra and Gauhati. For winter storms, the TEC data for Kurukshetra were not available.

The TEC and $N_m$F2 at stations in the equatorial anomaly region can be affected by variations in electrojet strength through "fountain effect". If this mechanism be dominant even on storm days we should observe a negative correlation between $N_m$F2 at an equatorial station and TEC at an equatorial low midlatitude station. To examine this effect we have also plotted in Fig. 1 (a,b) the $N_m$F2 for Thumba (lat., 8·5°N ; long., 76·9°E) values for time advanced by 2·5 hr to account for the diffusion time taken by the plasma. In the discussion that follows, the day of MPO will be denoted by day-0 and the subsequent days as day-1, day-2, etc. for convenience of expression.

### 3.1 Storm of 17 Nov. 1975

For this storm the TEC data for Gauhati and corresponding $N_m$F2 data from Ahmedabad and Thumba [Fig. 1 (a)] have been plotted for a five-day interval 16-20 Nov. 1975. The storm MPO occurred on 17 November at 1630 hrs LT and lasted for about eight hours. According to the consensus evolved from the study of earlier workers,[18] if MPO occurs in the daytime (local sunrise to local sunset), the ionospheric electron content is supposed to be enhanced in the afternoon or dusk period. In this case TEC remained enhanced throughout the night till the next day (day-1) forenoon hours. Then there was decrease in TEC in the afternoon on 18 November (day-1) which lasted only for about 5-6 hr before coming to its normal values on 19 November (day-2). But there was again a large negative phase on 20 November (day-3). The $N_m$F2 values also varied almost similarly.

From Fig. 1 (a) it can be seen that corresponding to negative values of TEC such as these in the afternoon of 18 November (day-1) and 20 November (day-3), there were corresponding positive values of $N_m$F2 (Thumba). However, corresponding to positive values of TEC on 16 Nov. 1975 (day before MPO and forenoon of 18 Nov. 1975) significant negative values of $N_m$F2 (Thumba) were not noticed.

### 3.2 Storm of 22 Nov. 1975

Fig. 1 (b) shows the plot of deviations in TEC for Gauhati and $N_m$F2 for Ahmedabad and Thumba, respectively. The MPO occurred on 22 November at about 1338 hrs LT. During early phase onset on 22 November there was a negative phase in TEC values, then it recovered to its normal value and remained so throughout the night. Next morning at about 0600 hrs LT there appeared a positive phase lasting during forenoon hours before going to the negative phase in the afternoon on 23 November (day-1). There was again a positive phase on 24 November (day-2) during daytime;

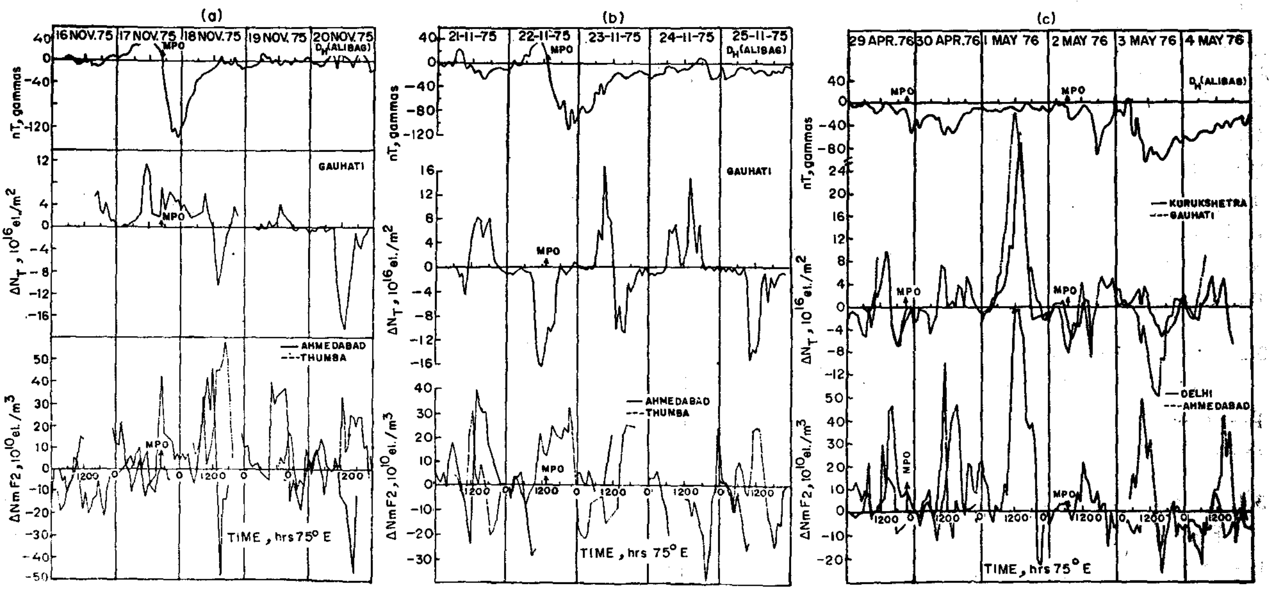

Fig.1—Stormtime variation of $D_H$, $N_T$ and $N_m$F2 for three major storms [In Figs. 1(a) and 1(b) the plots of $N_m$F2 (Thumba), the deviations for the monthly median values at equatorial station, are also shown (dotted line) for comparison. For $N_m$F2 (Thumba) plot, the time is advanced by 2·5 hr for taking into account the diffusion time.]

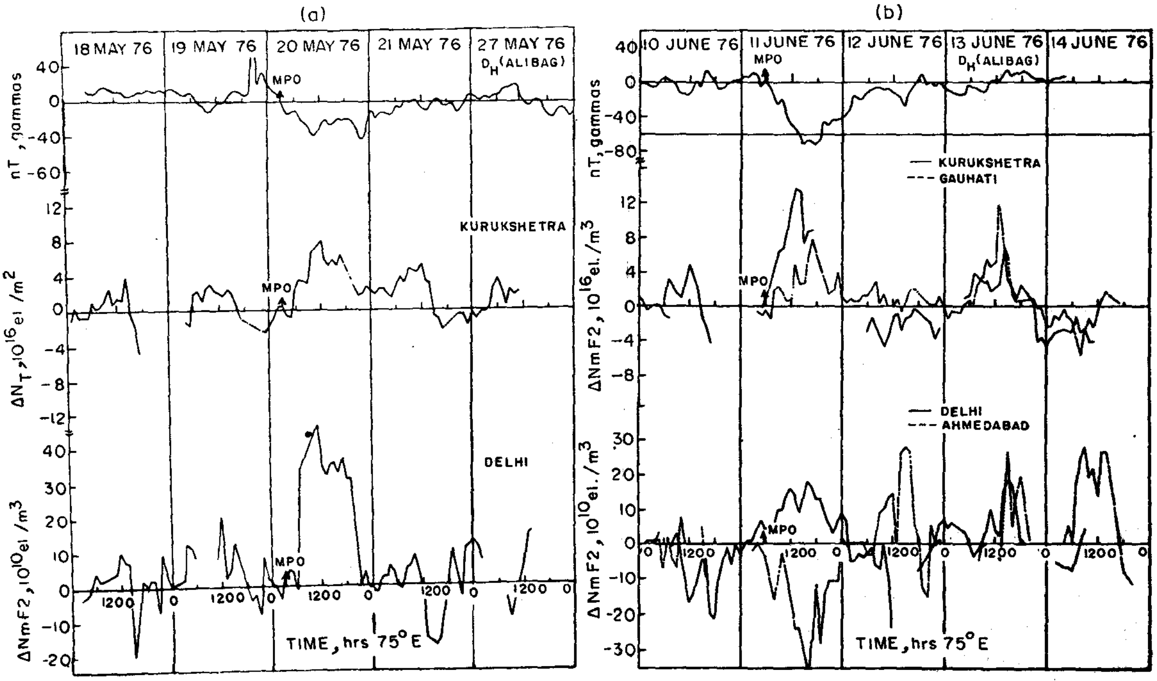

Fig.2—Stormtime variation of the $D_H$, $N_T$ and $N_m$F2 for two moderate storms

it was again followed by negative phase on 25 November (day-3) as in the case of storm of Nov. 17 1975. For this storm the $N_m$F2 data available were not continuous, yet it seems to follow the same trend as TEC except on 24 November when $N_m$F2 seems to have decreased although the TEC was above normal on that day.

As in the case of 17 Nov. 1975 storm, for this storm [Fig. 1 (b)] also, we notice a negative correlation between the changes in $N_m$F2 (Thumba) and TEC (Gauhati) on the afternoons of 22 Nov. 1975 (day-0) and 25 November (day-3). But this is not significant during forenoon of 23 November (day-1) and afternoon of 24 Nov. 1975 (day-2). Hence, it can be said that corresponding to negative TEC (Gauhati) there occurs positive $N_m$F2 (Thumba). The position in the forenoon hours in this regard is not clear ; a positive correlation in Fig. 1 (a) (day-1) and a negative correlation in Fig. 1 (b) (day-1) are noticeable.

### 3.3 Storm of 10 Jan. 1976

This storm had many features similar to those of previous two storms of 17 and 22 Nov. 1975 (Figure is not shown here).

### 3.4 Storm of 2 May 1976

Fig. 1 (c) shows the plots for a six-day interval (29 April to 4 May 1976) for both Kurukshetra and Gauhati with corresponding $N_m$F2 values for Delhi and Ahmedabad, respectively. Before the major storm on 2 May 1976 a moderate storm preceded with its MPO on 29 April at about 1230 hrs LT. For the major storm on 2 May, large $D_{st}$ changes started at about 0700 hrs LT and decrease occurred near midday on 3 May 1976. In this case the main phase duration was about 15 hr and the recovery was very smooth for the next 24 hr. For the 29 April storm, after the MPO there was a slight positive phase on 30 April but a large positive phase occurred on 1 May both for Kurukshetra and Gauhati ; $N_m$F2 also showed a large positive phase on 1 May 1976. But for the great storm with MPO on 2 May at about 1230 hrs LT there was a positive phase during early night hours following the MPO, and there was a negative phase on 3 May (day-1) which coincided with the large decrease in the *H*-field. Decrease in TEC was more at Gauhati than at Kurukshetra. Kurukshetra had a small positive phase in the forenoon hours of 3 May. Then followed a positive phase on 4 May (day-2). For this, the behaviour of $N_m$F2 particularly for Ahmedabad was different from that of TEC. At Ahmedabad $N_m$F2 showed large positive phase on 3 May in the forenoon hours, whereas $N_m$F2 value for Delhi showed negative phase after the MPO.

### 3.5 Moderate Storms of 20 May and 11 June 1976

Figs. 2 [(a) and (b)] show the plots of TEC and $N_m$F2 data for these two moderate storms. For both of these storms MPO occurred in the early morning hours at about 0300 and 0600 hrs LT on 20 May and 11 June 1976, respectively. According to Mendillo,[18] positive phase should occur during the afternoon hours of the same day followed by a large negative phase on the following days before the recovery phase. For 11 June storm, positive phase in TEC was observed on the day of MPO (day-0) at Kurukshetra and Gauhati. On day-1, a slight negative phase was observed at Kurukshetra but not so at Gauhati. This was followed by a positive phase on day-2 and a slight negative phase on day-3 both at Kurukshetra and Gauhati. The behaviour of $N_m$F2 at Delhi was similar to that of TEC at Kurukshetra but, surprisingly the behaviour of $N_m$F2 at Ahmedabad differed from that of TEC at Gauhati. Immediately after the MPO there was a negative phase in $N_m$F2 at Ahmedabad and then it followed a course almost in the same manner as that of TEC at Gauhati. On 14 June, $N_m$F2 and TEC variations at the above places did not agree. For 20 May Gauhati data were not available. After the positive phase which lasted till noon of 21 May, there followed a slight negative phase of TEC at Kurukshetra before arriving to its normal value. At Delhi also, the behaviour of $N_m$F2 was almost the same as that of TEC at Kurukshetra.

### 3.6 Moderate Storms of 29 Nov. 1975 and 30 June 1976

MPO for these storms occurred in the afternoon hours (i.e. at about 1300 and 1400 hrs LT on 30 June 1976 and 29 Nov. 1975, respectively). In these cases no clear storm effect was observed. The 29 Nov. 1975 storm effect was almost similar to that observed in the case of three major winter storms (Figures are not shown here).

Hence, the behaviour of TEC and $N_m$F2 during these four major and four moderate storms showed marked deviations from the expected behaviour. The general behaviour of TEC and $N_m$F2 for major storms appear to be as follows. (i) During early night hours following the MPO, increase in TEC and $N_m$F2 is observed. (ii) The increase in TEC and $N_m$F2 is more common during forenoon hours LT of day-1 and almost throughout day-2. (iii) Negative phase is also noticed in the afternoon hours of day-1 and day-3. This is opposite to the average expected behaviour.[18] This is also in contradiction with the previous observation at Kurukshetra[20] using TEC data from orbiting satellite, in which no negative phase was observed during any phase of the storm, whereas our results are in good agreement with those reported by Jain *et al.*[22] for the Indian zone.

## 4. Electron Production and Loss Rates

Two further parameters which are useful in interpreting the observations can be derived from the TEC measurements. These are $Q_0$, the apparent columnar electron production rate for overhead sun, and β, the effective columnar electron linear loss coefficient. For measurements of $Q_0$ and β, the procedure outlined by Taylor[25] and Titheridge[26] has been followed. The rate of increase of TEC at sunrise has been used to calculate the integrated rate of production of ionization for the overhead sun and corrected for the observed loss rate of TEC during the predawn hours. In this way the estimates of $Q_0$ are reasonably reliable.[26] The parameter β has been determined from the rate of decrease of TEC at local midnight assuming that electron production are negligible. The values of $Q_0$ and β calculated in this manner are plotted in Fig. 3 for the three storms (2 May, 19 May and 30 June 1976) for Kurukshetra along with the corresponding monthly median values. The values of $\Sigma K_p$ for days concerned are also plotted on the top panel of Fig. 3. Large day-to-day changes are noticed for both $Q_0$ and β but neither changes correlate significantly with stormtime. Taylor and Earnshaw[27] at a high latitude station, Jodrell Bank, also reported a large day-to-day variation for both $Q_0$ and β whereas Titheridge and Andrews[18] in southern hemisphere reported 60 per cent increase in $Q_0$ and a significant increase in β during a magnetic storm. But a decrease in $Q_0$ during periods of magnetic activity was also reported by Taylor.[25] Thus, no definite correlations have been reported. Our observations also reveal no uniformity in results of measurements of $Q_0$ and β.

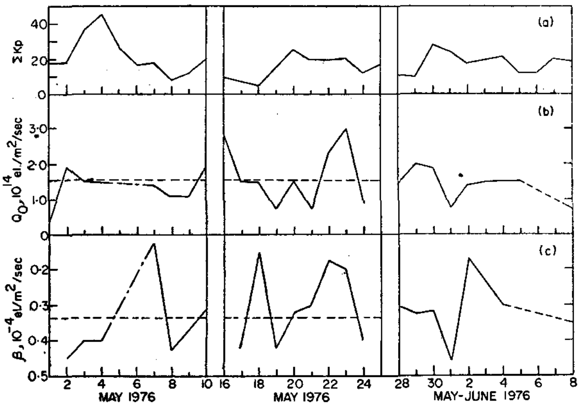

Fig.3—Plots for the three storms at Kurukshetra of: (a) integrated rates of production; (b) $Q_0$ (at sunrise); and (c) β (at local midnight)

## 5. Discussion

Though we have noticed that positive and/or negative effects may or may not occur as per the expected average pattern,[18] there is no doubt that ionospheric storm effects do have positive as well as negative effects.

The main physical mechanisms responsible for the ionospheric storm variations at equatorial and lower middle latitudes can be grouped into three types.[28] First, a stormtime electric field **E** causes the ionospheric plasma to drift at a velocity $\mathbf{E}\times\mathbf{B}/B^2$, where **B** is the geomagnetic main field. An upward electrodynamic drift for example, tends to increase the height of the F-layer and at midlatitudes it can result either in an increased electron density because of the lower loss rates at higher altitudes,[8] or a reduced density at night because of loss of plasma to the plasmasphere.[29] At the magnetic equator, the upward drift can result in a reduced electron density by virtue of the "fountain effect" whereby the uplifted ionization is influenced by gravity and diffuses down along geomagnetic field lines away from the equator.[8] A westward drift around sunset, caused by a poleward **E**, was shown by Anderson[30] to result in an electron density enhancement before sunset with a rapid density decrease after sunset. Secondly, thermospheric winds set up by high latitude heating and Lorentz forces can propagate to lower latitudes and impart motion to the ionization along the direction of magnetic field lines. Richmond and Matsushita[31] showed that impulsive thermospheric disturbance can travel away from the auroral region at speeds up to about 750 m/sec, reaching the equator in about 3 hr. Winds can result in an increase in electron density by raising the ionization to greater altitudes where the loss rate is smaller, or by compressing the ionosphere if wind shear is present.[32] Thirdly, thermospheric composition and temperature changes during geomagnetic disturbance will result in altered production and loss rates of ionization. In particular, an increase in molecular constitutents, upon which the loss process depends is thought to contribute to the main phase decrease in electron density.[8,32,33]

As we have seen from the results presented in Figs. 1(a) and 1(b) in which $N_m$F2 data (Ahmedabad) and TEC data (Gauhati) are examined in conjunction with $N_m$F2 data for equatorial station Thumba for two winter major storms, there is a significant negative correlation between $N_m$F2 (Thumba) and $N_T$ (Gauhati). Jain *et al.*[34] have also shown negative correlations (i) between TEC at stations in the anomaly region and $N_m$F2 for Trivandrum and (ii) between electrojet strength and $N_m$F2 for Trivandrum. Thus, the operating mechanism appears to be the first one discussed above according to which the increase in the electrojet strength causes more plasma uplifted from the equatorial region which after diffusing down along the field lines results in an increase in the TEC at stations in the anomaly region. A decrease in electrojet strength likewise decreases ionization at these stations and increases the same at Thumba. However, daytime occasional increase in TEC as observed on day-1 and day-2 of storms without being accompanied by corresponding decrease in $N_m$F2 at the equatorial station [Figs. 1(a) and 1(b)] cannot be explained on this basis. Therefore, some mechanism other than this may be responsible for maintaining the increase in TEC at Kurukshetra and Gauhati and in $N_m$F2 at Thumba. The second type of mechanism discussed above may be responsible for this behaviour.

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