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# Ionospheric Electron Content in Subtropical Regions

Y. V. SOMAYAJULU, TUHI RAM TYAGI & N. K. NEGI NPL
Space Research Section, Radio Science Division, National Physical Laboratory, New Delhi 12

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**The observational studies on the ionospheric electron content in the subtropical regions over the past decade are reviewed. It is found that the gross features of the equatorial anomaly in electron content, viz. its structure and diurnal development, are consistent, in all longitude sectors, with the anomaly in electron density in the topside and the bottomside. The general features of the diurnal and seasonal variations of the electron content as a function of latitude and solar activity are discussed. The electron content variations at Delhi and Hawaii, which have almost the same geomagnetic latitude and dip, but differ in geographic location by 7° of latitude, are compared. It is further noted that the annual variation in the electron content is pronounced whenever the seasonal anomaly is absent and the semiannual component dominates when the seasonal anomaly is present. The electron content distributions in northern and southern hemispheres are also compared. Electron content contours have been generated and presented for use as ionospheric inputs for estimating errors in satellite navigation systems.**

ONE of the simplest and earliest techniques used for studying the topside ionosphere has been the study of the Faraday rotation of radio beacons aboard orbiting satellites as observed on the ground. The technique enables the measurement of the electron content, i.e. the total number of electrons in a column of unit area of cross-section extending from the observer to the satellite. Data on electron content using this technique have been accumulating for more than a decade now. In the early years use was made of low orbiting satellites, such as Sputnik III or Cosmos V, which had an eccentric orbit with the satellite height ranging from 200 to about 1400 km. The more suitable satellites are the geodetic satellites, such as Transit IV or the polar orbit ionospheric beacon satellite Explorer-22, which have a nearly circular orbit. The polar orbit is very convenient for these studies, because the satellite height is nearly constant so that measurements over a long period can be directly compared to study long-term effects, and pole-to-pole scans can be made within a very short time. However, the disadvantage of the low orbiting satellites is that they are visible to an observing station only a few times a day and for 10-15 min during each pass. With the launching of the geostationary satellites it has become possible to monitor the electron content continuously, as the satellite appears stationary to an observer on the ground and this provides a ready estimate of the diurnal variation of the electron content and also enables one to identify and study transient phenomena, day-to-day variations, etc. At the present time, the global coverage of these geostationary satellites is limited. The satellite ATS-F proposed to be launched shortly will provide coverage over the missing Asian, African and European zone, so that almost complete global coverage would be available.

With the increasing use of satellites for communication and navigation, it is of great interest to evaluate and correct for the degradation in service and errors in navigational systems introduced by the ionospheric electron content. In this paper, we attempt to review the morphology of the electron content in the subtropical regions in general and the Asian sector in particular. It is hoped that such studies would be useful in providing the necessary ionospheric inputs for the evaluation of errors, etc., in satellite applications.

## Electron Content in the Equatorial Anomaly Belt

A characteristic feature of the equatorial ionosphere is the well-known equatorial anomaly in $f_0F_2$ (or $N_mF_2$), viz. the existence of a trough in values of $f_0F_2$, during day-time centred on the magnetic equator with peaks located at approximately 30° dip in the northern and southern hemispheres. The anomaly is present in the bottomside ionosphere as well as in the topside, and has been the subject of extensive studies[1-10]. These studies show that the topside anomaly is an extension of the bottomside anomaly. King *et al.*[11] have shown that usually all the anomaly crests at different heights lie on a magnetic field line referred to as the ' anomaly field line '.

In general, the anomaly structure shows asymmetry with respect to the magnetic equator in the location and magnitude of the anomaly crests. The maximum asymmetry is present during solstices, the closest to symmetry occurring at equinoxes. There are also longitudinal dependences and three sectors are distinguished, viz. the Asian, African and American sectors. For sunspot minimum condition, Rastogi[1] has shown that the bottomside anomaly structure is symmetrical in all seasons and in all the longitude sectors. For sunspot maximum conditions during the IGY, Rao[2], Lyon and Thomas[4] and Thomas[5] observed marked asymmetries about the magnetic equator during solstices. Thomas[5] found that such asymmetries are observed only in the American sector during the June solstice period and in the African and Asian sectors during the December solstice period, the winter crest being larger than the summer crest. At these times, the subsolar point is farthest removed from the magnetic equator. Asymmetries are also observed in the topside anomaly structure. For the period of 1962, King *et al.*[6] reported pronounced asymmetries in the Asian sector, the summer crest being greater than the winter crest. Similar asymmetries were reported for the American sector during the years 1962-63 (ref. 8 and 9). However, Somayajulu and Mack[10] noted that during June solstice of the solar minimum period of 1965, the winter crest was greater than the summer crest in the American sector.

The development of the equatorial anomaly shows marked differences between the American sector and the Asian and African sectors. Thomas[5] noted that the anomaly in $f_0F_2$ develops by about 0800 hrs LMT in the American sector, while it develops much later in the other sectors.

The anomaly in the topside first becomes noticeable by about 1000 hrs LMT in both the Asian and American sectors, perhaps developing slightly earlier in the Asian sector[7]. The anomaly crests begin to move apart until they attain their maximum separation with the anomaly fully developed by about 1500 hrs LMT in the Asian zone and a little later in the American zone. The disappearance of the anomaly is not fully established due mainly to the occurrence of spread-F in the late evenings. It was, however, noticed that the anomaly is more strongly developed in the Asian sector compared to the American sector. This difference may be associated with the greater value of the earth's magnetic field at the magnetic equator in the Asian zone as compared to that in the American sectors[2].

Associated with the solsticial asymmetry of the anomaly structure there is a shift in the axis of symmetry of the anomaly towards the summer hemisphere. This shift is greatest in the early hours of development and it almost disappears at the time of the anomaly maximum[9]. It is also noticed that any chosen electron density contour descends in height on either side of the equator by more than 100 km at the time the anomaly disappears. All these features of the topside anomaly are considered to be consistent with what one would expect from the bottomside anomaly in $f_0F_2$.

Using the topside sounder data, King *et al.*[6] have also shown that the integrated electron content in the topside between 450 and 1000 km reveals the anomaly structure. They also found that during the development of the anomaly in the topside content, the value above the magnetic equator did not show any significant change, while the anomaly crests moved apart, the magnitudes of the crest increasing by a factor of 5.

From measurements of electron content in low latitudes by the Faraday rotation technique, several investigators reported the existence of the equatorial anomaly in the latitudinal distribution of the electron content[12-21] (Table 1).

Tyagi and Somayajulu[19] have shown that in the Indian zone in the Asian sector, the anomaly crest is present during day-time to the south of Delhi (dip 40°N). Basu and Das Gupta[15], from observations made at Calcutta, have concluded that on quiet days the anomaly is regular and pronounced, showing a crest around 33° dip; the anomaly develops in the forenoon and disappears in the late afternoon and its behaviour is consistent with that of the $f_0F_2$ anomaly. Tyagi and Mitra[20] have combined the data from Delhi and Calcutta as shown in Fig. 1 and confirmed the location of the anomaly in the afternoon at a dip value of 30°.

TABLE 1 — LATITUDINAL DISTRIBUTION OF THE SATELLITE BEACON OBSERVING STATIONS DATA FROM WHICH HAVE BEEN USED

| | Geographic latitude | Geographic longitude | Geomagnetic latitude | Computed dip |
|---|---|---|---|---|
| Asian sector | | | | |
| Delhi | 28·6°N | 77·2°E | 18·9°N | 42·3°N |
| Hawaii | 21·3°N | 202·3°E | 21·1°N | 39·2°N |
| Ahmedabad | 23·0°N | 72·6°E | 13·8°N | 32·2°N |
| Calcutta | 23·0°N | 88·6°E | 12·3°N | 31·1°N |
| Hongkong | 22·3°N | 114·2°E | 10·8°N | 30·0°N |
| Hyderabad | 17·3°N | 78·5°E | 07·5°N | 19·4°N |
| Bangkok | 13·7°N | 100·6°E | 02·4°N | 10·4°N |
| Singapore | 0·13°N | 103·8°E | 10·1°S | 18·3°S |
| Rarotonga | 21·2°S | 159·8°W | 20·9°S | 38·2°S |
| African sector | | | | |
| Addis Ababa | 09·0°N | 38·8°E | 05·4°N | 00·4°S |
| Nairobi | 01·3°S | 36·8°E | 04·4°N | 25·6°S |
| Dar es Salaam | 06·5°S | 39·2°E | 10·0°S | 38·0°S |
| American sector | | | | |
| Huancayo | 12·0°S | 75·3°W | 00·6°S | 1·3°N |
| Sao Jose dos Campos | 28·2°S | 45·8°E | 12·6°S | 23·7°S |

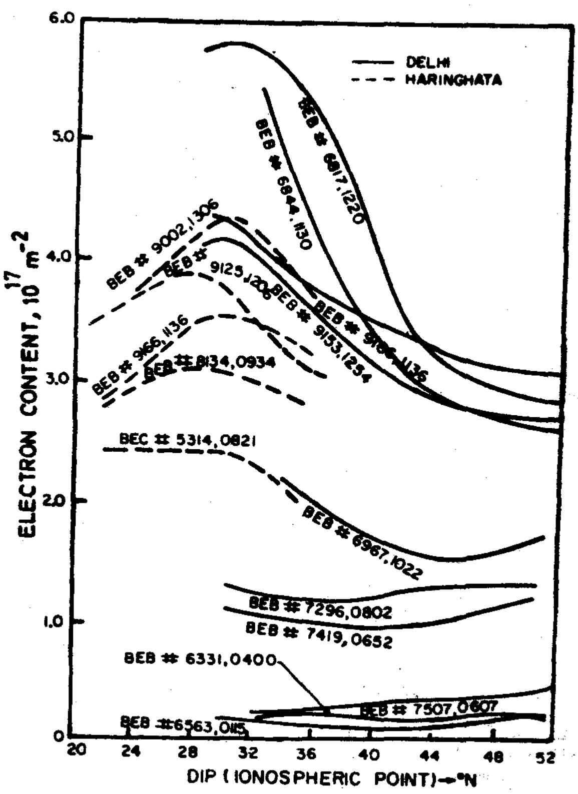


Fig. 1 — Variation of electron content with magnetic dip, derived from the satellite S-66 Faraday fadings recorded at Delhi and Calcutta

In the East Asian zone, Rufenach *et al.*[17] and Golton and Walker[21] studied the anomaly structure using the observations from Hong Kong, Bangkok and Singapore. These workers found that the equatorial anomaly begins to form around 1000 hrs LMT. Then the anomaly crests start moving apart, the anomaly reaching its maximum extent between 1300 and 1400 hrs LMT. At the time of the maximum of the anomaly, the crests are located at approximately 30° dip. They also noted that the maximum crest-to-trough ratio is about 2:1. The anomaly persists until about 1800 hrs LMT.

In the African sector, the observations made at Addis Ababa, Nairobi and Dar es Salaam have been combined by Hunter *et al.*[18] to study the equatorial anomaly in terms of the electron content. Their results for equinox are shown in Fig. 2. The development of the equatorial anomaly is much more regular and is much closer to that expected from $f_0F_2$ during equinoxes. There are some significant differences compared to the Asian zone in both the African and the Asian sectors. There is considerable day-to-day variation, much greater than is observed in $f_0F_2$, in summer and winter.

In the American sector, de Mendonca *et al.*[13] found that the anomaly crest begins to form around 1000 hrs LMT at a dip value of −10° and subsequently moves further south, reaching the southernmost position at about 1400 hrs LMT in spring and summer and at 1500 hrs LMT in winter. The anomaly crest at its southernmost position is located around −20° dip, moving south in summer and north in winter. The extent of this movement is about ±5° of dip. This behaviour is found to be consistent with the $f_0F_2$ anomaly.

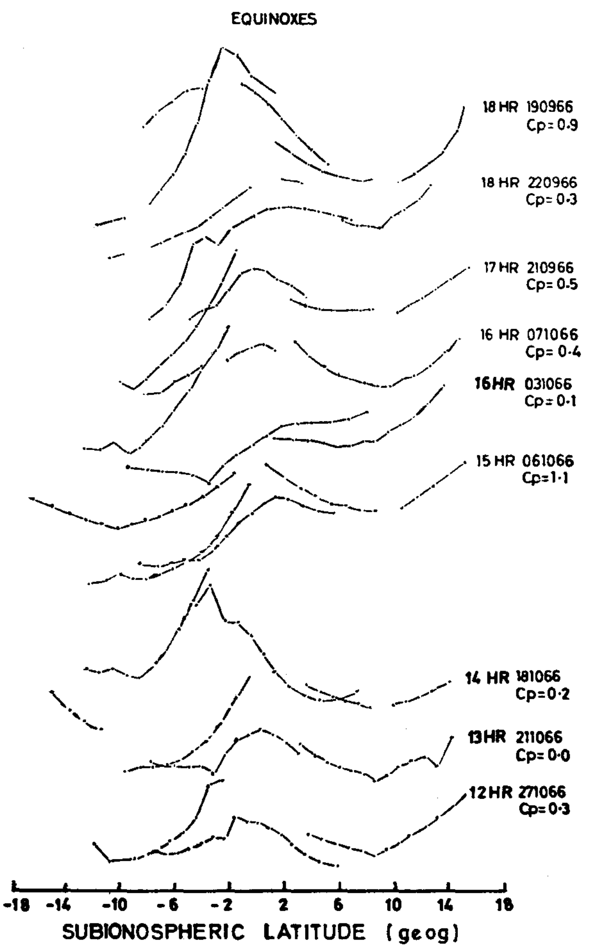


Fig. 2 — Total electron content plots for equinoxes using data from Dar es Salaam, Nairobi and Addis Ababa (left to right) (after Hunter *et al.*[18])

It may be concluded that the gross features of the equatorial anomaly in electron content, viz. its structure and diurnal development are consistent, in all longitude sectors, with the anomaly in electron density in the topside and bottomside. There are, however, significant longitudinal differences in the behaviour of the anomaly. For example, the anomaly structure and its movement during all the seasons appear regular and somewhat alike in the American and Asian sectors, while the regular structure is seen only at equinoxes in the African sector. Also a midnight peak at about 2300 hrs LMT is frequently seen in the African sector but not in the other sectors. In the American sector, in the Brazilian anomaly region, a peak in the content, ascribed to the starfish radiation belt, is observed[13].

During magnetic disturbances, the anomaly is found to be nearly absent; the peak is flattened out and shifts towards the magnetic equator[16]. On the other hand, no consistent effect with magnetic activity is found in the southern American zone[13].

## Diurnal Variation at Different Latitudes in Anomaly Belt

The diurnal variation of the electron content in the subtropical latitudes in the Asian sector for the three seasons during low and moderate solar activity conditions is shown in Figs. 3-5. For low solar activity conditions the data are essentially limited to the northern hemisphere, while for moderate solar activity, the data for southern latitudes reported by Titheridge and Smith[22] are also utilized. It is noted from Figs. 3-5 that in summer, the electron content reaches a minimum before sunrise, while in winter, the minimum is comparatively flat and is reached between 0430 and 0600 hrs LMT. For southern latitudes, Titheridge and Smith[22] note that the winter minimum occurs around 0400 hrs LMT, while the summer minimum occurs just prior to sunrise. Following sunrise, the electron content at lower latitudes increases faster. Golton and Walker[21] note that the anomaly crests begin to form between 0900 and 1000 hrs LMT in northern latitudes in the Asian sector. As the anomaly crest starts moving to higher latitudes, the content at latitudes within the belt would show in the afternoon either a flat peak or a double peak, depending on the location of the station with respect to the maximum latitudinal position of the crest. Thus, at the latitude corresponding to the position of the crest at its maximum development, the content would increase to a large value, showing a single afternoon peak. Beyond this latitude, the maximum electron content value would drop much faster than within the belt for the same latitude increment. Titheridge and Smith[22] observed (Fig. 5) that during winter, the anomaly crest in the southern latitudes is located at about 10°, while in summer at its maximum development it is located at about 17°. They also note that beyond the crest, the electron content falls off rapidly until a transition to a relatively constant midlatitude ionosphere occurs at about 21° in winter and at about 25° in summer.

It is seen from the diurnal curves in Fig. 4 corresponding to the Indian zone that for the same period (1966-67), the maximum electron content is reached at 14° (Ahmedabad), while at 20° (Delhi) and 7° (Hyderabad), the afternoon electron content is smaller. As described earlier, the anomaly crest in the Indian zone is located at about 30° dip close to the latitude of Ahmedabad. The diurnal curve for Hyderabad shows a broad maximum due to the to and fro movement of the crest past it. Either the trough is relatively shallow or the process of smoothening used in constructing the diurnal curve has wiped out a double humped structure. Again in winter, the anomaly crest at its maximum excursion is located close to 14°N (Ahmedabad) or 30° dip. The occurrence of the peak much later than at 7°, and the winter peak at 7° latitude being sharper than the summer peak are perhaps due to the later development of the anomaly during winter and also to its greater persistence. When the anomaly crest in winter starts receding in the late evening, perhaps the decay more than overtakes an increase that is caused as the crest approaches 7° latitude, so that its effect on the diurnal curve is not noticeable.

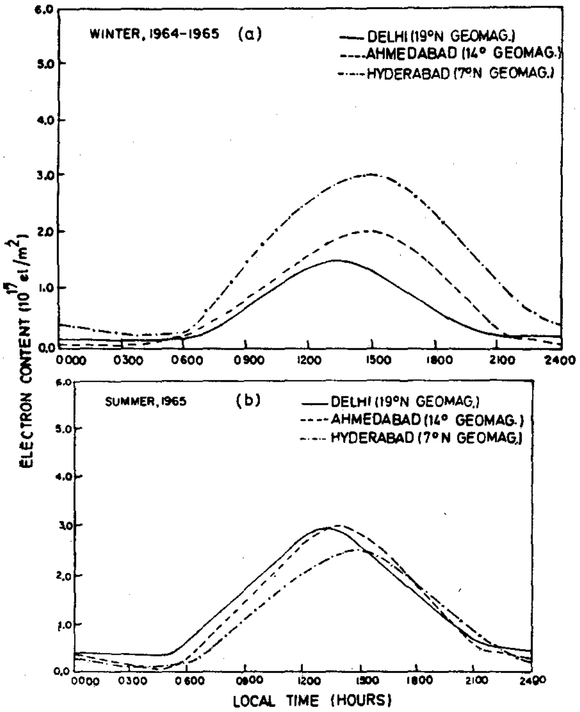


Fig. 3 — Mean variation of electron content with local time at Delhi, Ahmedabad and Hyderabad during low solar activity

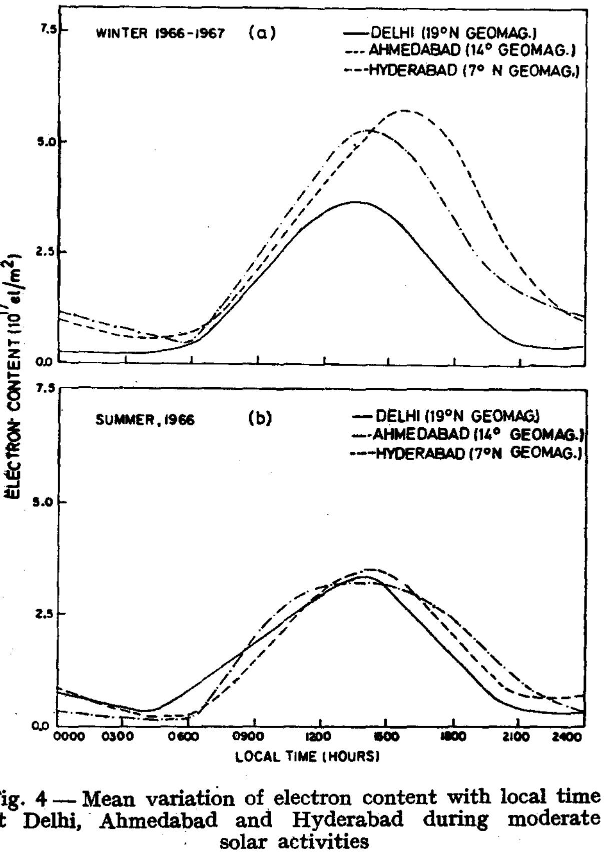


Fig. 4 — Mean variation of electron content with local time at Delhi, Ahmedabad and Hyderabad during moderate solar activities

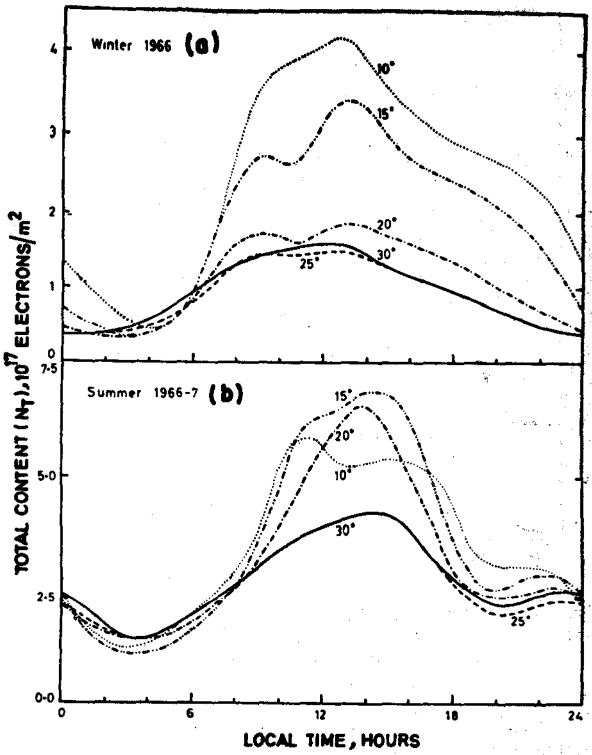


Fig. 5 — Mean variation of electron content with local time at geomagnetic latitudes of 10°, 15°, 20°, 25° and 30°S during moderate solar activities (after Titheridge and Smith[22])

The diurnal curves for the East Asian zone stations shown in Fig. 6 also show features similar to those discussed above and consistent with the formation of the anomaly at about 0900 hrs LMT and subsequent movement of the anomaly crests[21]. The variability in the diurnal curves during the periods April-May and June-July 1964 illustrates the changes from equinox to summer.

## Electron Content Variations in the Transition Region

Outside the anomaly belt, the electron content, during day-time, decreases with latitude until a transition to midlatitudes occurs, characterized by a relatively constant electron content with changing latitude. This feature was pointed out by Titheridge and Smith[22] for southern latitudes and is

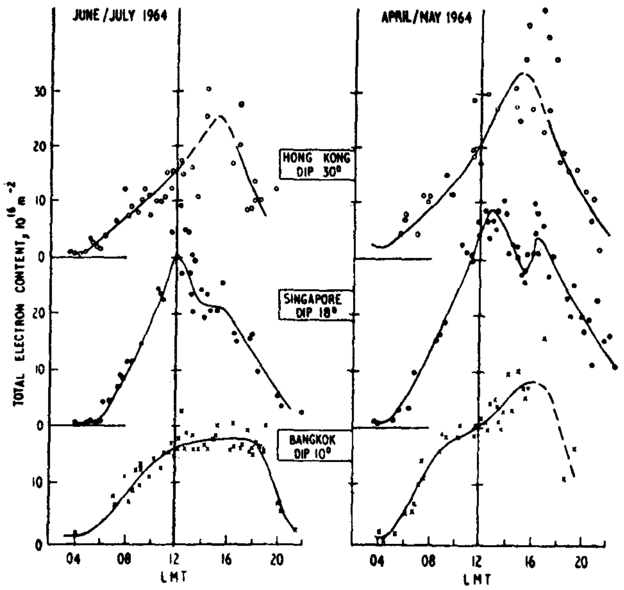


Fig. 6 — Diurnal variation of electron content at the equatorial stations Hong Kong, Singapore and Bangkok (after Golton and Walker[21])

also indicated for the northern hemisphere in the latitude *vs* electron content curves in the vicinity of Delhi[19]. Delhi is located outside the anomaly belt, but inside the transition zone. The transition to midlatitude seems to start from about 25° geomagnetic latitude. Hawaii, at the end of the Asian zone, is also located in the transition zone. It is located at the same magnetic latitude as Delhi, but geographically it is located about 7° south of Delhi. It will, therefore, be interesting to see the similarities and differences in the behaviour of the electron content at these two locations. In the following section, the features of electron content and its variations at Delhi are described and compared with those at Hawaii.

## Electron Content Variations at Delhi

*Diurnal variation of electron content* — The electron content for the period 1964-69, the increasing phase of the present solar cycle, over Delhi (28·6°N, 77·2°E, dip 42°N) is used to describe the diurnal behaviour during different seasons and the solar activity conditions.

*General features* — The general features of the diurnal variation are summarized in Fig. 7, (a)-(c). From a minimum value reached just before sunrise, the electron content starts rising rapidly, reaching a peak value between 1300 and 1500 hrs LMT. Thereafter, the electron content decreases rapidly until somewhere between 2000 and 2300 hrs LMT, when it starts decreasing very slowly until a minimum is reached just before sunrise.

The mid-day maximum value and the pre-sunrise minimum value have seasonal and solar activity dependences. The lowest value of $I_{min}$ of $0{\cdot}15 \times 10^{17}$ $m^{-2}$ is reached during equinox of solar minimum and the greatest value of $0{\cdot}96 \times 10^{17}$ $m^{-2}$ is reached in summer of high solar activity. Similarly, the lowest value of $I_{max}$ of $1{\cdot}5 \times 10^{17}$ $m^{-2}$ is reached during winter of solar minimum, while the maximum value is reached during equinox of high solar activity. The diurnal ratio, defined as $I_{max}/I_{min}$, attains its minimum value of 4·8 in summer of high solar activity, while the maximum value of 23 is reached during the equinox of low solar activity.

*Seasonal and solar activity control* — There are distinct seasonal and solar activity effects in electron content values. It is evident from Fig. 7 that the diurnal maximum is very flat during winter in the low solar activity period[23], while it is relatively sharp during summer and equinox. The winter maximum becomes sharper as the solar activity increases, while the nature of the summer peak undergoes very little change[24] (becomes flat) and the equinox peak remains sharp throughout. Thus, during high solar activity, though the equinox peak remains sharpest and greatest in magnitude, the winter peak becomes sharper and the magnitude becomes greater than that of the summer peak, showing the presence of the so-called seasonal anomaly. During night, the electron content values are almost constant from 0000 to 0600 hrs

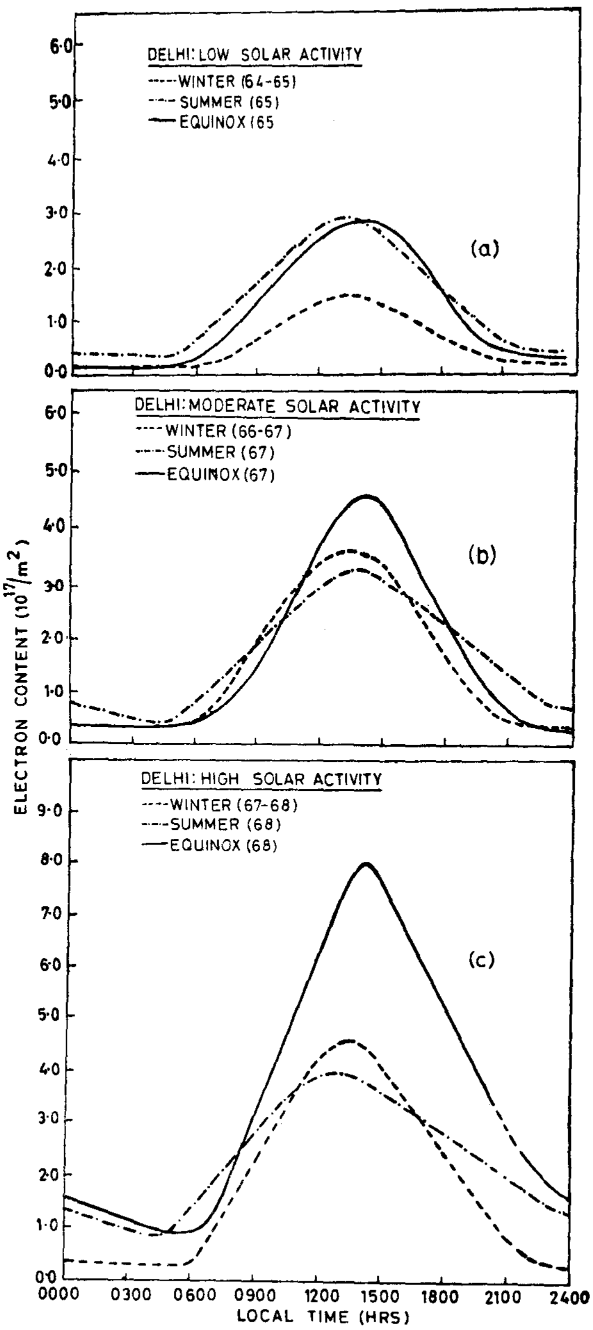


Fig. 7 — Diurnal variation of electron content over Delhi measured from Faraday fading of satellite BE-B transmissions for (a) low solar activity; (b) moderate solar activity; and (c) high solar activity

LMT in winter, and behave similarly throughout the solar cycle, from low to high solar activity; only the actual value changes from $0{\cdot}16\times10^{17}$ m$^{-2}$ during low solar activity to $0{\cdot}32\times10^{17}$ m$^{-2}$ during high solar activity. In contrast, the diurnal minimum during summer remains very sharp for all the values of solar activity and occurs around 0400-0500 hrs LMT. During equinox, the night-time electron content remains almost constant between 0000 and 0600 hrs LMT for low and moderate solar activity; the diurnal minimum is thus rather flat, but the minimum becomes very sharp during high solar activity and occurs around 0500 hrs LMT.

The solar activity control over electron content can be clearly observed by studying the variation of $I_{max}$ and $I_{min}$ with solar 10·7 cm flux. These values are given in Table 2.

The solar activity control of the electron content is presented in Figs. 8 (a)-(b) and 9 in terms of

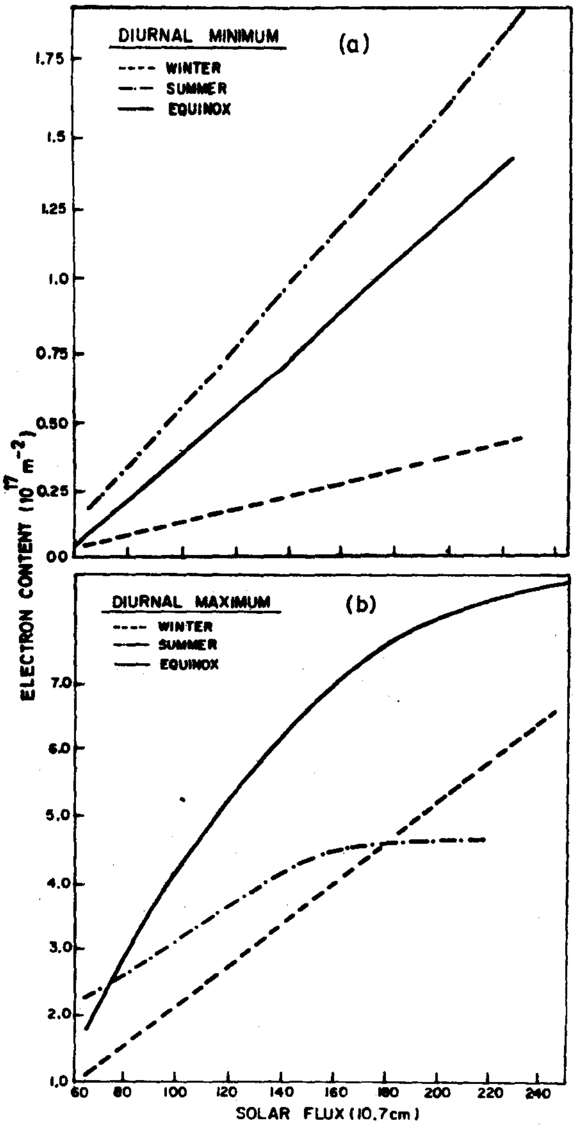


Fig. 8 — Variation of average diurnal minimum electron content ($I_{min}$) with 10·7 cm solar flux; (a) and variation of average diurnal maximum electron content ($I_{max}$) with 10·7 cm solar flux (b)

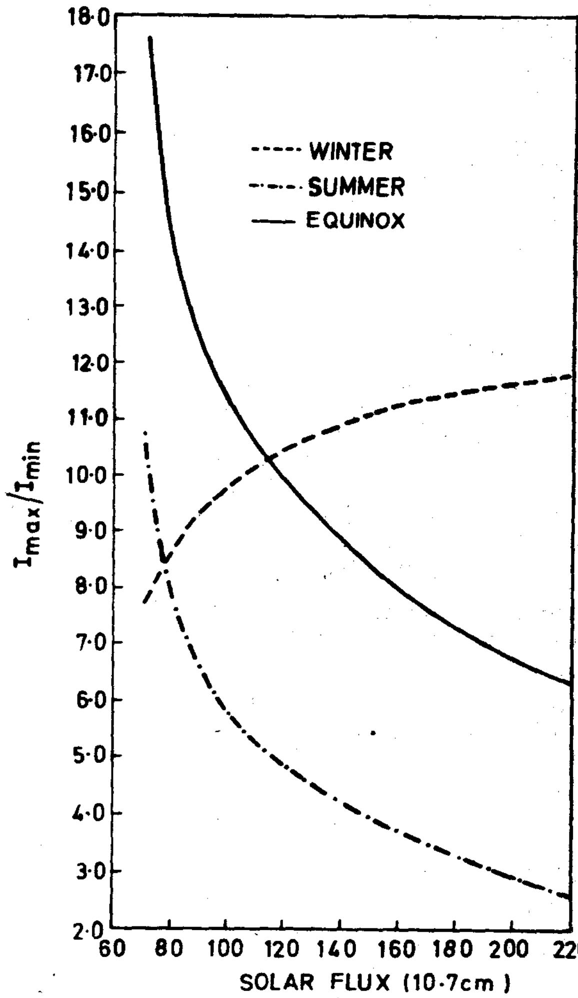


Fig. 9 — Variation of ratio of average diurnal maximum to minimum electron content ($I_{max}/I_{min}$) with 10·7 cm solar flux

TABLE 2 — AVERAGE MAXIMUM AND MINIMUM ELECTRON CONTENT VALUES FROM SATELLITE DATA WITH THE CORRESPONDING SOLAR FLUX VALUES

| Season | Solar activity | $I_{max}$ ($10^{17}$ m$^{-2}$) | 10·7 cm solar flux | $I_{min}$ $10^{17}$ m$^{-2}$ | 10·7 cm solar flux | $I_{max}/I_{min}$ |
|---|---|---|---|---|---|---|
| Winter | Low (1964-65) | 1·50 | 75 | 0·16 | 75 | 8·3 |
| | Moderate (1966-67) | 3·70 | 145 | 0·24 | 110 | 17·4 |
| | High (1967-68) | 4·70 | 190 | 0·32 | 150 | 14·8 |
| Summer | Low (1965) | 2·90 | 80 | 0·24 | 75 | 11·0 |
| | Moderate (1966) | 3·40 | 105 | 0·44 | 100 | 7·0 |
| | High (1968) | 4·4 | 150 | 0·96 | 160 | 4·8 |
| Equinox | Low (1965) | 2·8 | 75 | 0·12 | 75 | 23·0 |
| | Moderate (1966) | 4·55 | 102 | 0·3 | 100 | 15·1 |
| | High (1968) | 8·0 | 135 | 0·8 | 160 | 10·0 |

$I_{max}$, $I_{min}$ and $I_{max}/I_{min}$ *vs* 10·7 cm solar flux. In the case of $I_{max}$, the solar control is clearly discernible. It is, however, seen that $I_{max}$ increases linearly with solar flux in winter, while during summer, the electron content shows a linear increase up to about 150 units; beyond this, a saturation effect is noticeable[24]. During equinox, the $I_{max}$ shows a very fast increase with 10·7 cm solar flux for low values of flux, but the rate goes on decreasing slowly with increase in flux.

On the other hand, $I_{min}$ shows a linear increase with 10·7 cm solar flux in all the seasons, the rate of increase being maximum during summer and minimum during winter. Tyagi and Somayajulu[19] reached the conclusion that below about 80 units of solar flux, $I_{max}$ is independent of solar flux. Yeh and Flaherty[25] reached a similar conclusion. It may, however, be pointed out that because of large day-to-day fluctuations it is difficult to reach any firm conclusion about the behaviour of the electron content with 10·7 cm solar flux during very low activity and this should be explored in detail in the coming solar minimum period.

It is interesting to note that during winter, the ratio $I_{max}/I_{min}$ increases in a nonlinear way from about 7·5 to 12 as the solar flux varies from about 70 to 220 units. In summer, it shows an equally regular but opposite behaviour as it decreases from a value of about 10 for solar flux of 70 units to a value of about 2·5 for solar flux of 220 units[24]. During equinox, this ratio falls in a manner similar to that in summer from a value of about 21 for solar flux of 70 units to a value of about 6 for a solar flux of 220 units.

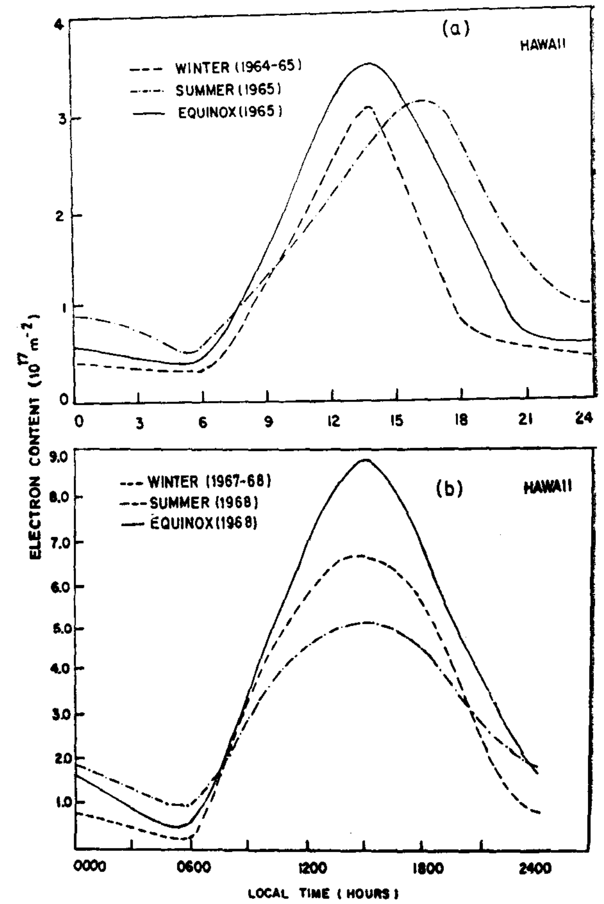


Fig. 10 — Diurnal variation of electron content over Hawaii from the geostationary satellite Syncom-3 during (a) low solar activity, and (b) high solar activity

## Comparison of the Electron Content Behaviour at Delhi and Hawaii

It will be interesting to compare the behaviour of the electron content over Delhi and Hawaii. As mentioned earlier, these two stations have almost the same geomagnetic latitude and the same dip, but Delhi is geographically 7° to the north of Hawaii. Thus, we may expect similar features in respect of the electron content controlled by geomagnetic field and ascribe the differences to the geographical factors. The diurnal behaviour of the electron content over Hawaii constructed from the curves published by Yuen and Roeloff[26] is shown in Fig. 10, (a) and (b). Comparing these plots with those for Delhi, it is seen that, in general, the diurnal behaviour at both these stations is alike both during low and high solar activities. The maximum electron content value during equinox at Delhi is $2{\cdot}8\times 10^{17}$ $m^{-2}$ for low solar activity and increases to $8{\cdot}0\times 10^{17}$ $m^{-2}$ for high solar activity conditions. The corresponding values for Hawaii are 3·5 and 9·0 respectively. The value of $I_{max}$ for summer at Delhi increases from 2·9 for low solar activity to 4·4 for high solar activity and for winter it changes from 1·5 to 4·7. The corresponding values at Hawaii are 3·12 and 5·0 for summer and 3·1 and 6·75 for winter. Thus, it may be noted that while the summer $I_{max}$ values during solar minimum are almost the same at both the stations, the winter value at Delhi is almost half of that at Hawaii. The diurnal minimum in electron content at Delhi during equinox changes from $0{\cdot}12\times 10^{17}$ $m^{-2}$ to $0{\cdot}8\times 10^{17}$ $m^{-2}$ from low to high solar activity, while the corresponding change at Hawaii is from 0·4 to 0·5 only. The $I_{min}$ value for Delhi in summer changes from 0·24 during low solar activity to 0·96 during high solar activity and in winter it changes from 0·16 to 0·32. The corresponding values for Hawaii are 0·5 and 1·0 in summer and 0·3 and 0·2 in winter. Thus, although the $I_{min}$ at Delhi changes by a factor of 2 in winter, by a factor of 4 in summer and by a factor of 6·5 in equinox from low to high solar activity conditions, the winter and equinox values remain almost unchanged and the summer value is higher at Hawaii only by a factor of 2.

## Annual and Semiannual Variations

Fig. 11, (a) and (b), shows the monthly variation of $I_{max}$ and $I_{min}$ values obtained at Delhi, Ahmedabad, Hawaii and Hong Kong. It is noted that $I_{min}$ shows an annual variation for the years 1964-68, the period covering both low and high solar activity conditions, the maximum value occurring in summer months and the minimum during winter. Though all the four stations show this variation, the maxima and minima are not always coincident. The maxima occur in the months of April-July, while the minima occur in the months of October-January.

The variation of $I_{max}$ is a little more complicated. For Hawaii, it shows a semiannual variation throughout the years 1964-68, while for Delhi, Ahmedabad and Hong Kong, the semiannual variation is clearly evident only from the year 1966 onwards. For the low solar activity period 1964-65, at Delhi, the annual component dominates, with a small semiannual component discernible.

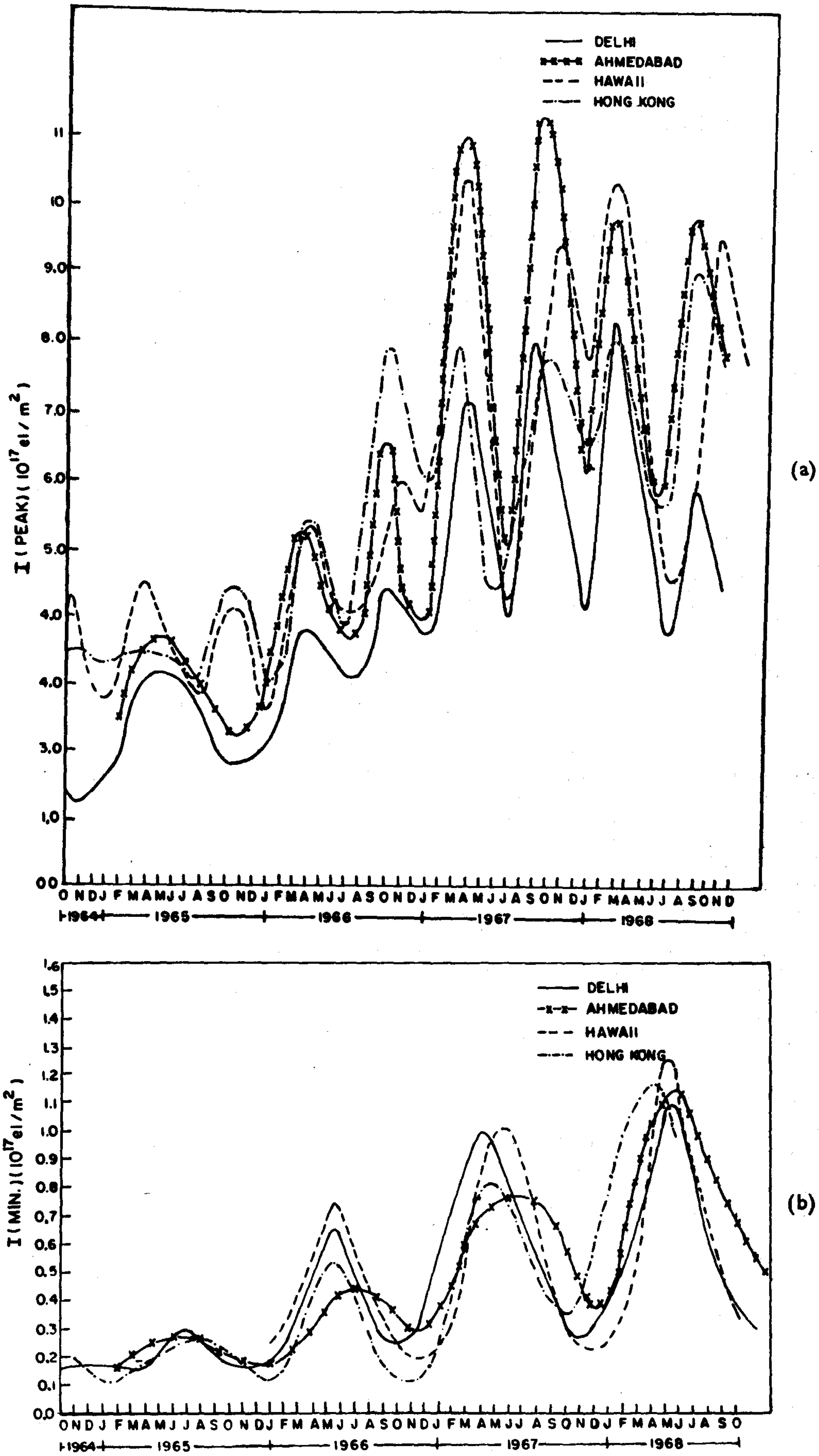


Fig. 11 — Monthly variation of average values of (a) peak electron content ($I_{max}$); and (b) minimum electron content ($I_{min}$)

The trend of variation at Ahmedabad and Hong Kong is more or less similar to that at Delhi, but the semiannual component is stronger. Further, though all the stations show semiannual variation for moderate and high values of solar activity, the maxima and minima seem to be coincident alternately. For example, the maxima in the months of April 1966, April 1967 and March 1968 are coincident at all the four stations, while they are scattered from September to November in alternate peaks. The trend is almost similar in respect of the minima.

The annual variation dominates whenever seasonal anomaly is absent and the semiannual component is pronounced when seasonal anomaly is present. Thus, during night-time and during solar minimum day-time, when there is no seasonal anomaly at Delhi, there is annual variation, while at Hawaii there is semiannual variation of $I_{max}$ throughout the years 1964-68; seasonal anomaly is also observed more or less for the entire period, the trend of variation in summer and winter being comparable in 1965.

### Seasonal Anomaly

No seasonal anomaly is noticeable near the equator, e.g. at Huancayo and Ibadan. At low to midlatitude stations (15-40°), e.g. Ahmedabad and Delhi, the anomaly is absent during solar minimum, but shows up when the $S_{10\cdot7}$ value increases. At Bangkok and Hyderabad, in the lower latitudes zone, the winter and summer values are nearly the same during the solar minimum. The anomaly is clearly exhibited at Hyderabad during moderate solar activity. It is interesting to note that in the southern hemisphere, during 1966-67, a period of moderate solar activity, the winter anomaly is absent up to latitudes of 34° south, as may be seen from the latitudinal plots of Titheridge and Smith[22]. Titheridge (private communication) confirmed this observation.

It would thus seem that there is asymmetry in regard to the presence of the winter anomaly between the northern and southern hemispheres. Olatunji[14] suggests that the latitude at which the winter anomaly appears is determined by the proximity of the station to the magnetic equator rather than the geographic equator. Thus, a narrow belt close to the equator exists where winter anomaly is absent. This belt may be within a few degrees of the magnetic equator. Beyond this belt, the winter anomaly is present. Titheridge (private communication) suggests that the asymmetry between the hemispheres, i.e. the absence of the winter anomaly in the southern latitudes up to 34°, may be due to the augmentation of the annual and semiannual components in the northern hemisphere, while they completely cancel each other in the southern hemisphere.

### Electron Content Contours in Subtropical Regions

Attempts have been made to specify inputs of ionospheric parameters in the subtropical regions, especially over the Indian subcontinent in order to evaluate the errors in satellite ranging and position fixing, due to refraction effects[27]. Electron content contours are of direct use in such applications. Electron content measurements are available for Delhi from 1963 onward through cosmos V, BE-B and BE-C satellites. In addition, observations have been made—for several years at Ahmedabad and Calcutta and over a restricted period of time at Hyderabad, Kodaikanal and Kurukshetra. Electron content contours for the Indian zone covering 0-20°N geomagnetic latitude are given in Fig. 12, (a) and (b), for winter and summer of low solar activity period of 1964-65. The contours for moderate and high solar activity periods are under preparation.

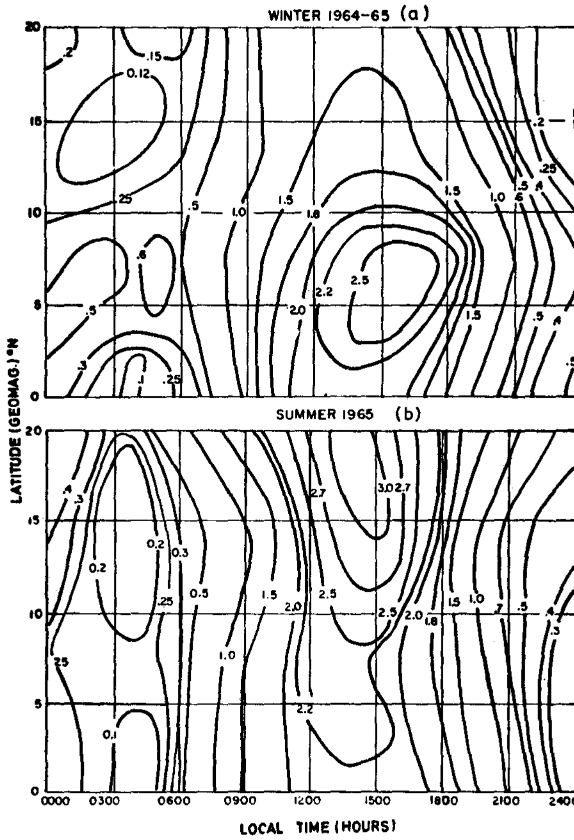


Fig. 12 — Electron content contours over the Indian subcontinent from 0°N to 20°N (geomagnetic) for low solar activity

### Summary

The trend of variation in electron content in the subtropical regions shows the existence of equatorial anomaly similar to that in the topside and bottomside electron density distribution. The anomaly belt extends, at its maximum development, to ±35° in dip, the anomaly crests being located at about ±30° dip. There are significant longitudinal asymmetries in the Asian, African and American sectors.

Beyond the anomaly belt, there is a transition region in which the electron content decreases rapidly with latitude. In the midlatitude ionosphere, the electron content remains relatively constant with change in latitude.

The electron content shows the winter anomaly, annual and semiannual variations as well as both northern and southern hemisphere asymmetries. Based on the available knowledge of electron content, contours have been generated for use as ionospheric inputs for estimating errors in satellite navigation systems.

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