LOW LATITUDE IONOSPHERIC ELECTRON CONTENT MEASUREMENTS DURING HALF A SOLAR CYCLE

F. de Mendonça
I.J.Kantor and
B.Clemesha

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Laboratório de Física Espacial

São José dos Campos
São Paulo - Brasil

TABLE OF CONTENTS

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Abstract

This paper presents the results of total electron content measurements made at São José dos Campos (23.22°S, 45.98°W) between 1963 and 1968. The 1963 measurements were made using the differential Doppler shift technique, and from December 1964 onwards the close spaced frequency method was employed, using the 40 e 41 MHz transmission from the BE-B and BE-C satellites. An analysis is made of the variation of electron content with local time, dip angle, season, solar activity and magnetic activity. Special attention is given to the Equatorial Anomaly and the region of the Brazilian Magnetic Anomaly.

1 - INTRODUCTION

The total electron content measurements presented in this paper were obtained, using the Faraday rotation method, from the 40 and 41 MHz signals emitted by the S-66-B and S-66-C beacon satellites. The data used were obtained during the period December 1964 to March 1968. Differential Doppler shift measurements from April and May 1963 have also been used. From this data, annual, seasonal and diurnal variations of total electron content have been derived.

All data processing was done at our laboratory using either an IBM 650 or a Burroughs' B3500 computer. The quasi-transverse point was observable on all the records, enabling the total Faraday rotation to be measured unambiguously. A corrective procedure was used in order to overcome the discontinuity in computed content that appears close to the Q.T. point.

Second order corrections [Ross, 1965] were made in order to counter-balance the errors due to the high frequency approximation and the non--uniformity of the electron distribution in the ionosphere. For this purpose the close spaced frequency method was used.

The coordinates of our station are as follow:

	Geographic	Geomagnetic
Latitude	$23.2^{o}S$	$12.6^{o}S$
Longitude	$45.8^{o}S$	$21.7^{o}S$
Dip angle	-23.7^{o}	

2 - METHOD OF ANALYSIS

The expression given by Ross (1965) was used to derive a correction formula taking into account second order effects. The formula given by Ross is

$$\Omega_2 = \Omega_1(1+\alpha/2) \;\ldots\ldots\ldots\ldots\ldots\ldots \;(1)$$

Ω_1 being the rotation angle associated with the first order assumption, and α the corrective factor. If we substitute the expression given by Ross for α, and differentiate equation 1 it may be shown that

$$d\Omega_2 = -2\Omega_1 \frac{df}{f}(1+\alpha) \ldots\ldots\ldots\ldots (2)$$

Assuming that the differentials can be replaced by differences, eliminating the unknown corrective term and taking the frequencies received as 40 and 41 MHz we obtain

$$\Omega_1 \cong \Omega_2\left(2 + 20\,\frac{\Delta\,\Omega_2}{\Omega_2}\right) \ldots\ldots\ldots\ldots (3)$$

Relating the Faraday rotation with the electron content we obtain

$$I_2 = I_1\left(2 + 20\,\frac{\Delta\,\Omega_2}{\Omega_2}\right) \ldots\ldots\ldots\ldots (4)$$

Where I_1 is the electron content calculated ignoring second order effects. Errors are introduced by the assumption of a horizontally stratified ionosphere, and a fixed value for the mean ionospheric height, the latter causing the value of the field function M to differ from its correct value. It can be shown, however, that a 10 Km variation about the assumed value of 350 Km for the ionospheric point results in only a 1% change in the computed electron content.

In order to correct for errors in the computed path of the satellite the positional data is shifted so as to ensure M = 0 where the Faraday rotation is zero.

3 - EXPERIMENTAL RESULTS

A detailed analysis has so far only been made for the 1966 data; a full analysis of the data for other years will be presented elsewhere. For this reason the diurnal and latitudinal variations are presented for 1966 only.

3.1 - DIURNAL AND LATITUDINAL VARIATIONS

Since the time of each pass of the satellite receedes as the day advances, about three month's data are required to construct a diurnal pattern. For this reason the data are grouped in seasons. Combining the information about local time and the dip angle of the earth's magnetic field at the subionospheric point, average electron contents were calculated and used to construct the contour maps of constant total content I shown in Fig. 1. Contours have not been drawn in these diagrams where the data were few. The contour maps of Fig. 1 were constructed by visually estimating average diurnal curves drawn on mass plots of each season's data for dip angle intervals of 5^{o}. The data used were obtained from a combined total of 482 satellite passes during 1966, using the BE-B and BE-C satellites, and are for quiet days only ($Kp < 5$).

Data from BE-B and BE-C agree very well for the same dip angle and local time, not showing any systematic errors. The results for BE-C show a rather greater dispersion than those for BE-B because of the low inclination of the orbit of the former satellite, leading to slow Faraday rotation rates at our geographic position. The day to day variations observed in total content at a given local time and subionospheric point are of the order of $\pm$ 25%. In Table 2 we show the r.m.s deviations from the mean of the -20^{o} dip angle results for the four seasons of 1966 and summer of 1967.

Table 1 - Day to day variations with respect to the average in total electron content.

	r.m.s. deviation	
Season	BE-B	BE-C
Summer, 1966	15.6 %	18.5 %
Autumn, 1966	20.7 %	24.9 %
Winter, 1966	33.1 %	35.6 %
Spring, 1966	24.5 %	32.8 %
Summer, 1967	9.6 %	15.1 %

The diurnal ratio of maximum to minimum electron content has an average value of 4.6 taking all the 1966 data together. Because of the difficulty in making accurate nightime measurements no seasonal variation in this ratio has been derived.

Our data for nighttime ionization levels are relatively few, but the values that we obtain are unusually high. The mean ratio of maximum to minimum total content of 4.6 is much smaller than that reported by other workers. The Delhi workers for example, obtain values of 8, 13 and 21 for winter, summer and equinox respectively. It is possible that our nighttime values are too high due to errors occuring in the analysis of the Faraday rotation records, and we intend to further investigate this possibility.

The sunrise and sunset gradients of electron content,normalised by dividing by the diurnal maximum, are nearly constant for all seasons and dip angles. The average sunrise gradient is 1.25 times the average sunset gradient. The nighttime content shows a slow decrease after midnight for all seasons.

In general the post-noon maximum in total content occurs approximately 1 hour later in spring and summer than in autumn and winter. For the latitude of São José dos Campos these maxima occur at 1400 L.T. and 1500 L.T. respectively.

Tyagi and Somayajulu (1966) have reported measurements made at Delhi, and state that maximum ionization is observed between 1300 and 1500 at all seasons. Skinner (1966), at Zaria, reports a midday 'bite out' following the f_oF2 results, leading to a second maximum as late as 1600 L.T. The only other results showing a seasonal effect in the time of maximum ionization appears to be those of Hibberd (1964) who observed a diurnal maximum around 1300 L.T. in winter and 1500 L.T. in summer.Our result tends to agree with that of Hibberd, working at Pennsylvania State University (40.8^{o}N), in that diurnal maximum occurs later in summer than in winter.

Latitudinal variations of total content at our station are principally associated with the equatorial anomaly, discussed below. During the post-midnight hours when the anomaly is not observed there is little variation with latitude.

3.2 - THE EQUATORIAL ANOMALY

The equatorial anomaly is clearly visible in the contour maps of Fig. 1. The mean position of the maximum of the anomaly is around -20^{o} dip angle, moving south in summer and north in winter. The extent of this movement of the crest is about $\pm 5^{o}$ of dip angle. In order to show the behaviour of the crest in more detail we have plotted in Fig. 2 the position of the maximum,in terms of dip angle, as a function of time of day, for the four seasons of 1966.

The crest first appears at about 1000 L.T. at a dip angle of -10^{o} and subsequently moves south, reaching its maximum southward point at around 1400 to 1500 L.T., when the total content is also a maximum.During the afternoon and evening hours the crest returns towards the equator, dissappearing at about midnight. The most southerly point reached is approximately -24^{o} dip angle in summer and -18^{o} dip angle in winter. The mean positions and their maximum deviations from the mean are shown in Table 2.

Table 2 - Maximum southward excursion of the crest of the equatorial anomaly

	Dip Angle	Maximum deviation
Summer, 1966	-24^{o}	$\pm 4^{o}$
Autumn, 1966	-20^{o}	$\pm 7^{o}$
Winter, 1966	-18^{o}	$\pm 9^{o}$
Spring, 1966	-24^{o}	$\pm 5^{o}$

In general the behavior of the equatorial anomaly under quiet magnetic conditions is as expected. The motion of the crest away from the equator in the morning hours, returning towards the equator in the afternoon and evening hours closely follows the behavior of the f_oF2 anomaly. The most southerly excursion of the maximum is -20 to -25^o dip angle, which may be compared with the $+30^o$ dip angle reported by the Delhi workers. King et al (1967) also report the maximum to occur at 30^o dip angle, using topside data for their analysis.

Basu and Das Gupta (1968) have reported that under disturbed magnetic conditions the magnitude of the equatorial anomaly decreases and the position of the crest moves towards the equator. We have examined our data for 1965 and 1966 in an attempt to determine the effect of sudden commencements on the equatorial anomaly. With regard to changes in the actual total content we see no consistent effect, other than perhaps a slight increase in the day to day variations observed. The position of the crest appears to move away from the equator immediately after a sudden commencement. Out of 10 cases where a clear maximum was observable both on the day before and the day of a sudden commencement we observed a southward movement in 8 cases and a northward movement in 2 cases. This result appears to contradict that of Basu and Das Gupta as mentioned above. In Fig. 5 we show the displacement of the crest from its position on the day proceeding a sudden commencement as a function of storm time.

3.3 - THE BRAZILIAN MAGNETIC ANOMALY

Mendonça (1965) has analysed differential Doppler shift measurements taken at São José dos Campos during 1963, and shows enhanced ionization in the region of the Brazilian Magnetic Anomaly at around -35^o dip angle. He attributed this ionization as being caused by the trapped radiation from the Starfish Experiment, which would be able to reach F layer heights in the region of the Brazilian Anomaly due to the low magnetic field values. We have analysed our data for 1965, 1966 and 1967 with a view to determining whether or not enhanced ionization continues to exist. Out of a total of 447 records analysed so far, only 8 have shown a second maximum to the south of that associated with the equatorial anomaly. This tends to support the view that the enhanced ionization observed during 1963 was in fact due to the temporary artificial radiation belt produced by the Starfish detonation.

It is of interest to note that the few occasions when we have observed a secondary maximum on our data all occur during the months of December or January. The infrequent observation of a secondary maximum cannot, however, be taken as definitive evidence against its existence as a normal feature, as its position at -30 to -35 dip angle is at the extreme south of the region which we can examine. The zenith angle subtended to our station by a satellite whose subionospheric point is at -30^{o} dip angle is 60^{o} or greater, making accurate total content measurements using the Faraday rotation method extremely difficult.

3.4 - SOLAR CYCLE VARIATIONS

In order to determine a relationship between total electron content and solar activity we have analysed data for 1963 to 1968. The mean values of total content I between 14 and 15 hr for dip -20^{o} have been calculated for the four seasons and plotted against the 10cm mean solar flux S_A and the mean Zurich sunspot number $\overline{R}$.

If we express I as a first order function of S_A then we obtain

$$I = I_o \left[1 + a \, (S_A - 80)\right] \times 10^{17} \text{ electrons/m}^2$$

for S_A values greater or equal to 80. Where I_o and are given in Table 3.

Table 3 - Values of I_o and a for solar flux

Season	I_o	a
Summer	3.7	0.012
Autumn	4.1	0.022
Winter	2.7	0.011
Spring	3.2	0.023

The plot of electron content against solar flux is shown is Fig. 3

Expressing I in terms of the sunspot number $\overline{R}$ we obtain

$$I = I_o \left[1 + b\ (\overline{R} - 40)\right] \times 10^{17} \text{ electrons/m}^2$$

for $\overline{R}$ values greater or equal to 40. Where I_o and b are given in Table 4.

In Table 4 we also give, for comparison, the values of b obtained by Bhonsle et al (1965) working at Stanford, and Yeh and Flaherty (1966) working in Illinois. It should be noted that the Stanford and Illinois results were obtained during the declining phase of a sunspot cycle, whereas our results are for the increasing phase.

Table 4 - Values of I_o and b for São José, Stanford and Illinois

	S.José		Stanford	Illinois
	I_o	b	b	b
Summer	3.3	0.011	0.011	0.028
Winter	1.65	0.032	0.022	0.032
Equinox	2.7	0.037	0.025	0.024

The plot of electron content against sunspot number is shown in Fig. 4.

Comparing Fig. 3 with Fig. 4 the electron content seems to be better correlated with solar flux than with sunspot number.

3.5 - SEASONAL VARIATION

From Fig. 3 and Fig. 4 we can see that the total content peaks at the equinoxes and reaches minimum values at the solstices. This agrees with the results of other workers; see for example the observations of Tyagi(1966) for 1964, 1965 and 1966.

Our summer values of total content are consistently higher than the winter values, showing an absence of any winter anomaly for solar fluxes less than 150.

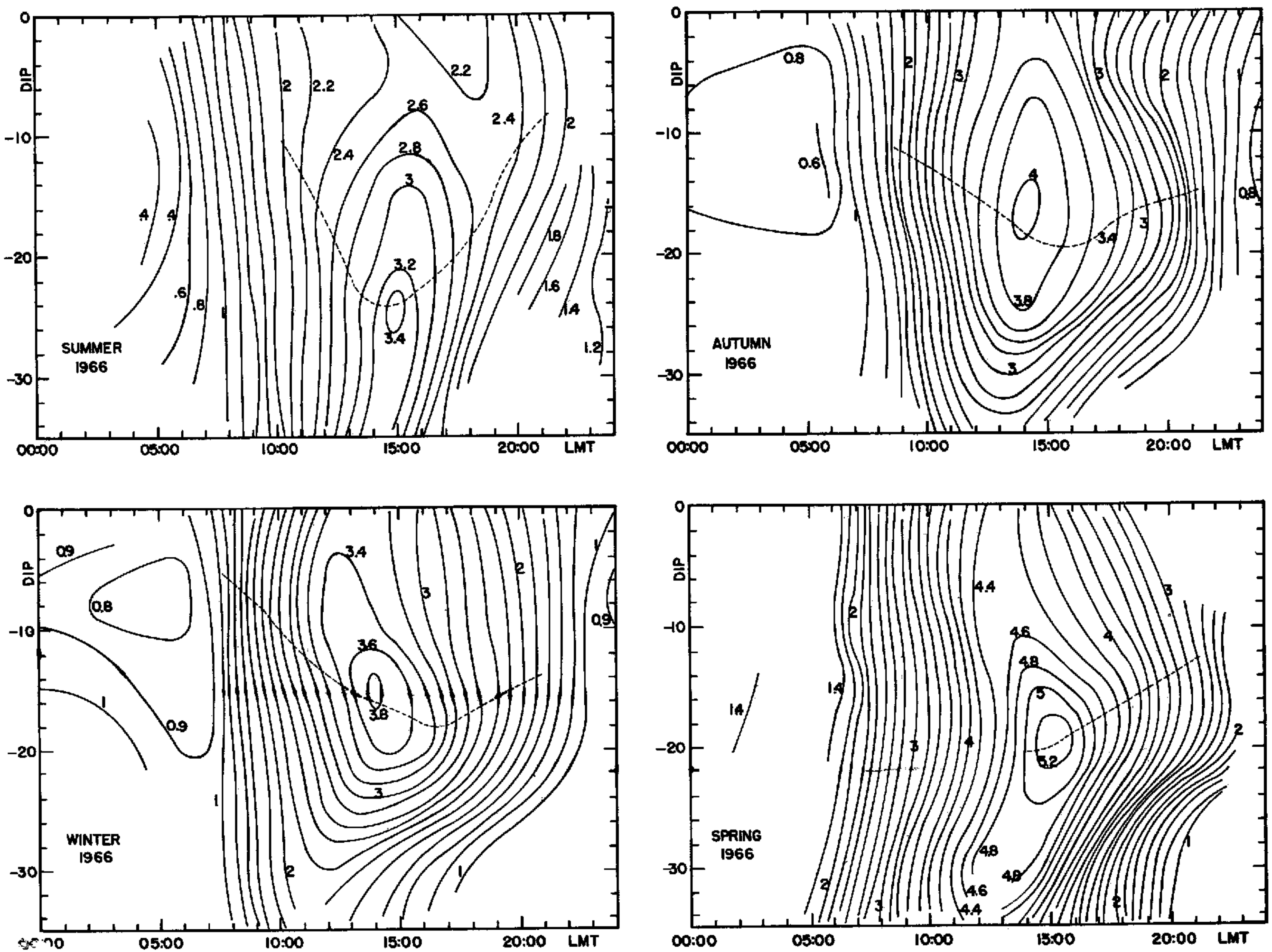

FIG (1) CONTOUR MAPS OF TOTAL ELECTRON CONTENT FOR THE FOUR SEASONS OF 1966 (BE-B AND B-C)

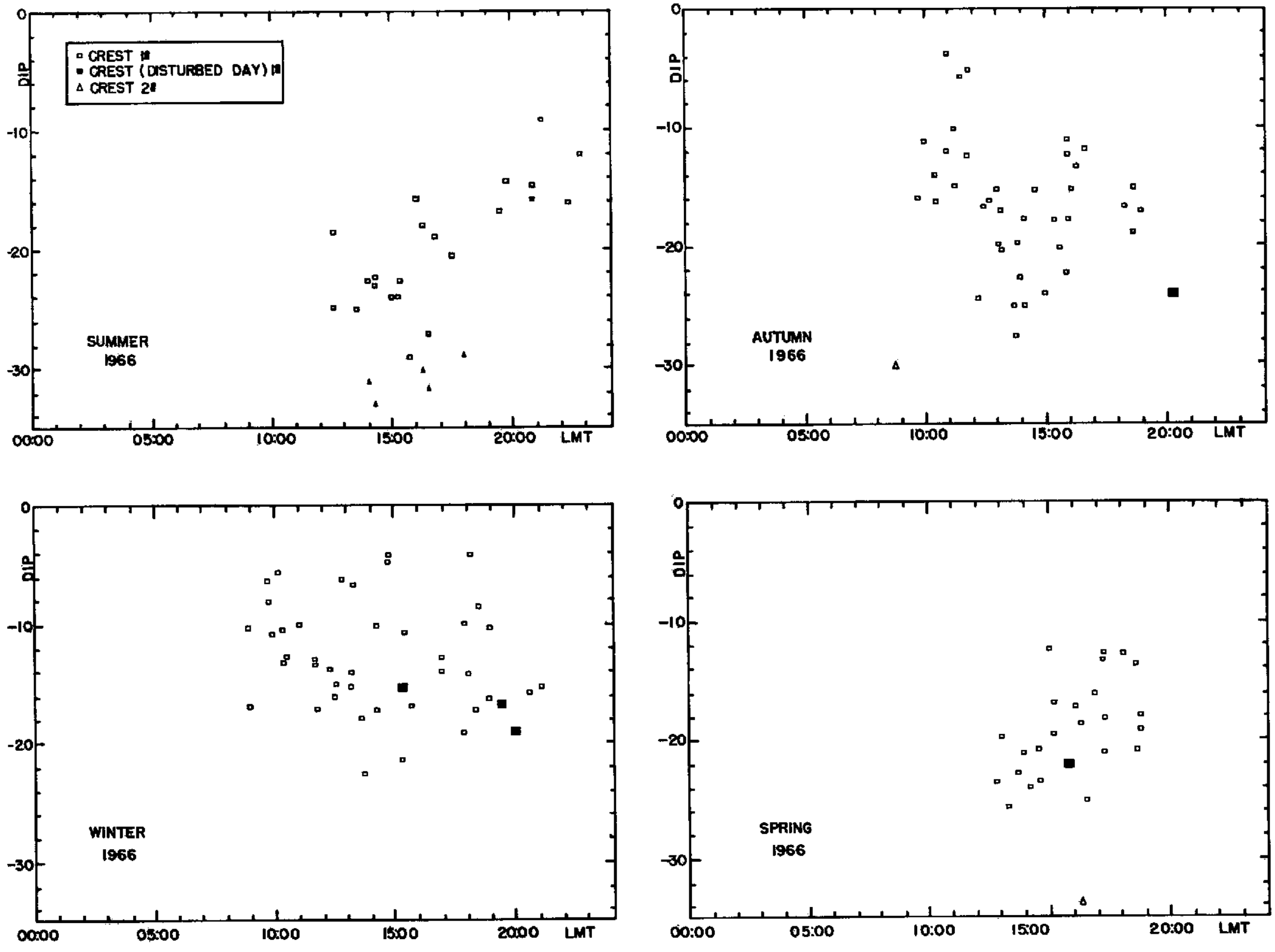

FIG (2) DIURNAL VARIATION IN THE POSITION OF THE CREST OF THE EQUATORIAL ANOMALY (BE-B)

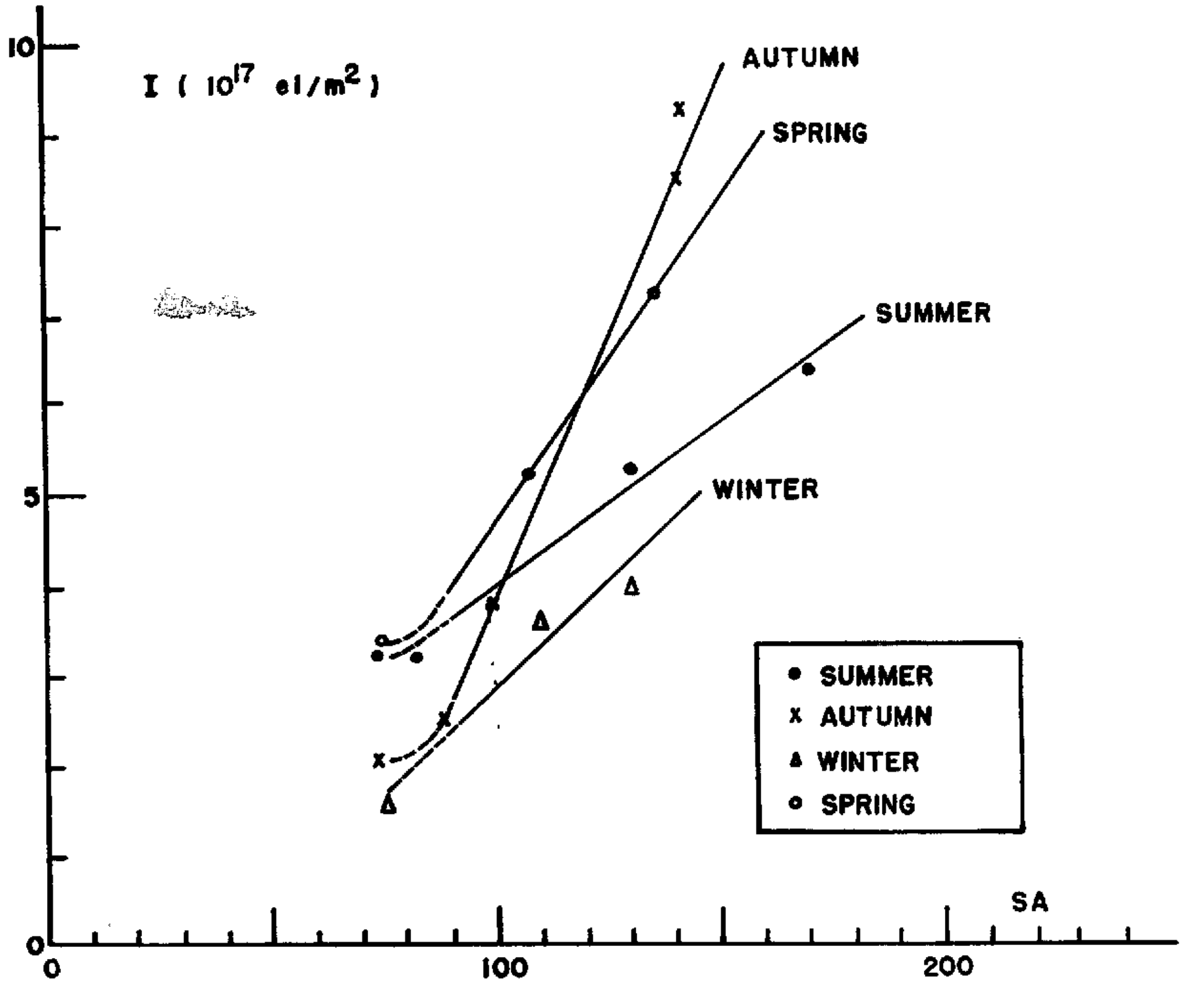

FIG (3) VARIATION OF TOTAL ELECTRON CONTENT WITH SOLAR FLUX. DATA FROM 1965 TO 1967. FOR DIP—20°. BETWEEN 14-15hr LMT

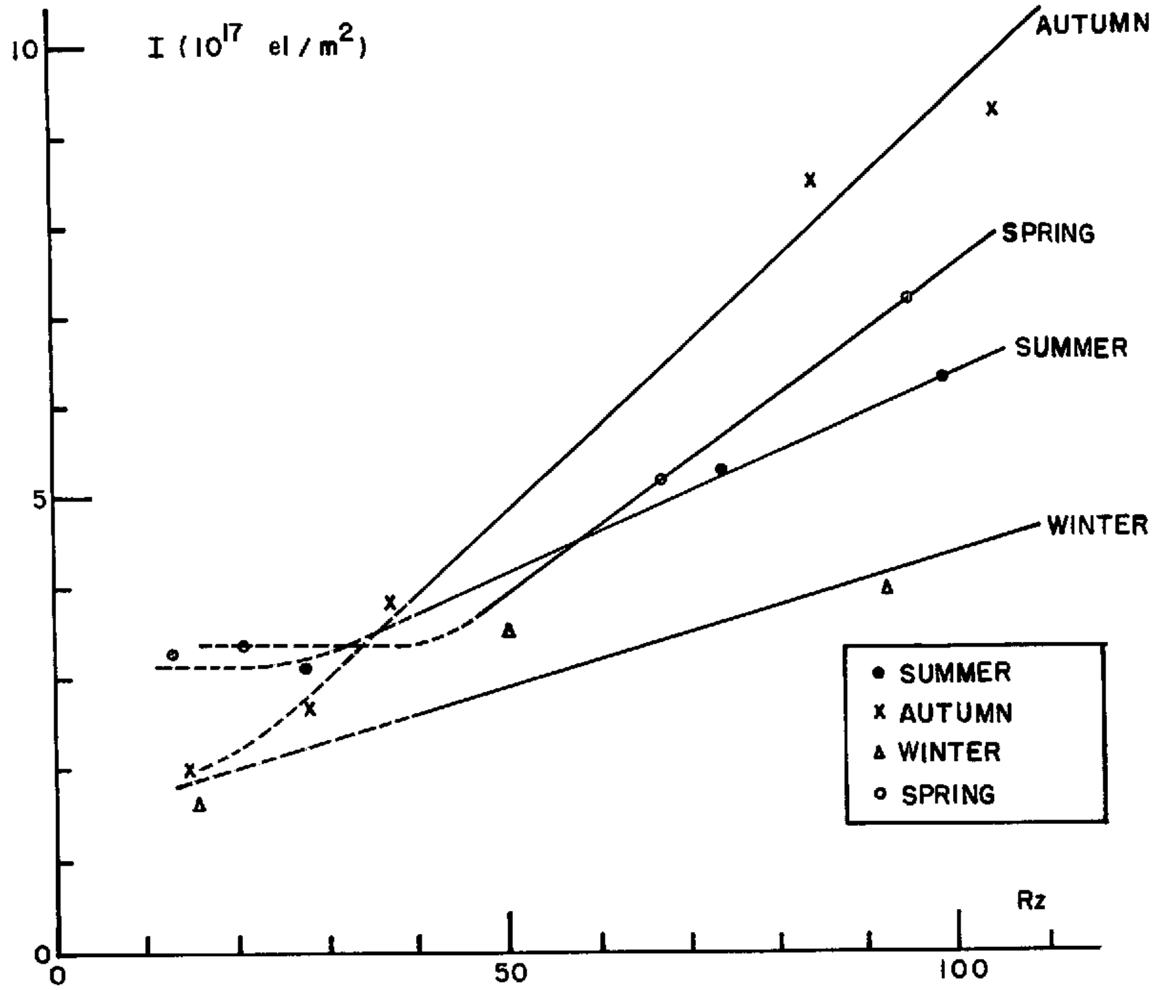

FIG (4) VARIATION OF TOTAL ELECTRON CONTENT WITH SUNSPOT NUMBER. DATA FROM 1965 TO 1967, FOR DIP-20°, BETWEEN 14-15 hr LMT.

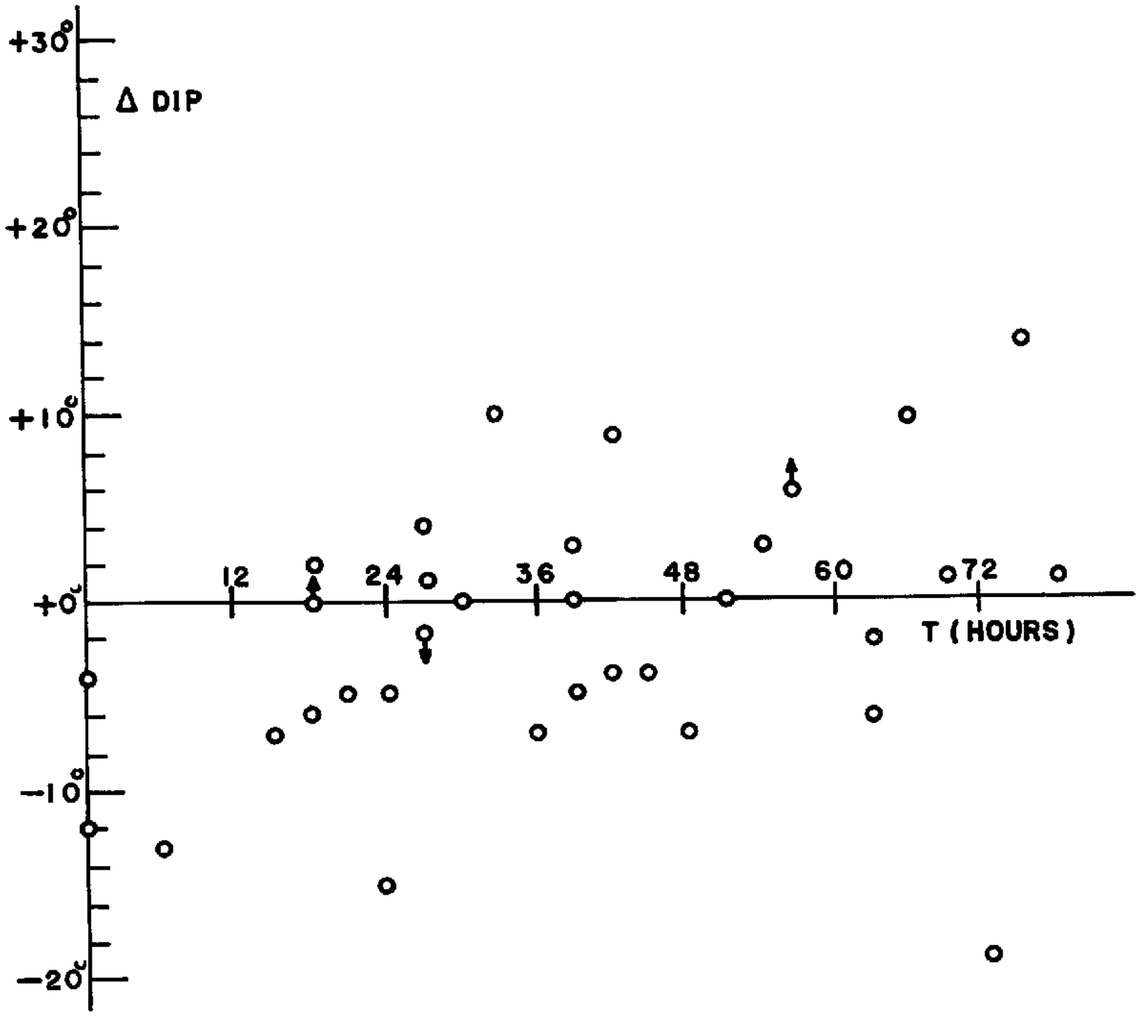

FIG (5) DISTURBANCE VARIATIONS OF THE POSITION OF THE EQUATORIAL ANOMALY CREST DURING MAGNETIC STORMS, AS FUNCTION OF STORM TIME.

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