"EFFECTS OF PRECIPITATING ELECTRONS IN THE IONOSPHERE"

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By

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'My son be admonished - .... making many books.....
.... is a weariness to the flesh.'

Ecclesiastes 12;12

Except where it is clear from the text that I am describing the work of others, the work described in this thesis is my own.

[signature]

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INTRODUCTION

As early as 1896, around the time of the discovery of the electron by J.J. Thompson, Birkeland was led to propose that aurorae were caused by fast moving electrons or similarly charged particles emitted by the sun and 'sucked in towards" the auroral zones by the geomagnetic field. He later supported this idea by firing electrons at a dipole field surrounding a sphere covered with a fluorescent coating.

Extensive ground based observations of auroral features eventually led, in 1950, to the initial direct evidence of the fact that auroral emissions are due to energetic charged particles, consisting partly of protons, entering the earth's atmosphere (Meinel, 1951).

However, it was only in 1952 and 1953 that the first measurements of what was later interpreted as bremsstrahlung X-rays from precipitating electrons were made at auroral latitudes (Meredith et al, 1955). During the IGY, 1957 - 1958, a number of rockets were fired through and near, visible aurorae and large fluxes of low energy electrons were detected (Van Allen, 1957; McIlwain, 1960; Davis et al, 1960).

In addition to visible aurorae, other geophysical features have been discovered to be related to the influx of electrons to the earth's upper atmosphere. Effects such as electromagnetic V.L.F. and E.L.F. emissions generated in the ionosphere or magnetosphere (Stockflet Jørgenson, 1969), radio wave attenuation - particularly of the type observed by riometers in the auroral or polar cap regions (Hultqvist, 1969) - as well as backscatter from ionospheric inhomogeneities have all been associated with electron precipitation.

Energetic electrons penetrating the earth's atmosphere will collide with molecules in the ionosphere, lose energy and in the process ionize the neutral gas constituents. Thus we would expect bombarding electrons to cause an increase in the ionization density of the ionosphere and therefore clearly affect the characteristics of the ionospheric layers.

Much attention has been paid to the effect of precipitating electrons on the auroral and polar cap ionosphere (e.g. Stoffregen, 1958; Bailey, 1968) and comparatively little is known of the possible effects of particles at other latitudes.

Rocket and satellite observations over the past years have indicated that electron precipitation is a frequent and world wide occurrence (e.g. Rose, 1965). Thus we would expect to observe far more widespread particle precipitation effects than just those in the auroral zones. Evidence of this in the D-region has been presented by Belrose (1969) and some F_2 region anomalies at middle and higher latitudes have been attributed to corpuscular effects. (Mariani, 1963; Williams, 1972; Ivanov Kholodny, 1965; Torr and Torr, 1968.)

In particular we would expect particle effects to be most evident in the vicinity of the South Atlantic geomagnetic anomaly. Gledhill and van Rooyen (1963) have shown that in this anomaly region an enhancement of the radiation precipitating from the Van Allen belts should result from the lowering of the particle mirror altitudes in the reduced magnetic field.

The South African National Antarctic Expedition, SANAE, is situated to the south of this anomaly region and as a result we might expect observable particle effects to be present in Sanae's ionosphere. An indication of this is the occurrence of aurorae at Sanae which lies far from the centre of the auroral zones.

The first direct evidence of electron precipitation effects in Sanae's ionosphere was provided by Gledhill and Torr (1965). They showed a correlation between disturbed ionospheric conditions, as reflected in the parameters f_{min} and $h'F_2$, and high fluxes of electrons observed by Alouette I in the conjugate area to Sanae.

The opportunity for a further investigation of possible particle effects near the anomaly region was provided with the acquisition of both good quality ionograms from the Argentine Islands and overhead satellite electron flux measurements by Alouette I for the period for which ionograms were available.

Initially, however, an analysis has been conducted to try and establish whether F-region disturbances at Sanae exhibit a similar correlation with electron flux measurements made in the South Atlantic region by Alouette I between 30 and 80^{o} west of Sanae, as they do with measurements in the conjugate St. Johns area. (Gledhill and Torr, 1965).

Calculations are then made of the ionization density increases which could result from the influx of electrons with reasonable energy spectra and fluxes to the Sanae ionosphere.

Since electrons measured by Alouette I lie in the energy range greater than 40 keV, which by calculations in this thesis and also by Berger et al (1970) and Rees (1963) have been shown to deposit most of their energy in the atmosphere below 120 km, the latter part of this thesis consists of an investigation into the possible effects of these particles on the lower layers of the Argentine Islands and Sanae ionosphere.

The thesis closes with a brief study of changes which might occur in ionograms as a result of the bombardment of the ionosphere by electrons with typical fluxes and energy spectra. The production of an extra E-layer cusp is shown to be a possibility.

CHAPTER 1: Electron Effects in the F-Region

In the quest to discover possible effects which precipitating electrons may have on the earth's upper atmosphere, let us focus our attention initially on the most variable section, the F-region.

1.1 Introduction

As has been mentioned previously, a number of workers have embodied corpuscular effects in the explanation of certain F-region phenomena at middle latitudes.

Mariani (1963) suggested electrons with energies greater than 40 keV as an explanation of correlations, which he discovered, of f_oF_2 at conjugate stations lying between the latitudes, 30^o S and 30^o N.

Antonova and Ivanov Kholodny (1961), Ivanov Kholodny (1965) and Yonezawa (1965) have proposed particles as a possible source for the maintenance of the nocturnal F-layer and more recently, Torr and Torr (1969) and Williams (1972) have mentioned the need to include a corpuscular ionization source in the solution of the ionospheric continuity equation in order to explain observed magnitudes of f_oF_2.

However these researchers have mainly used corpuscular effects to help explain the 'quiet' F-region behaviour. The main inspiration for the study described in this chapter has come from the previously mentioned results of an analysis which was made by Gledhill and Torr (1965) of the relation between high fluxes of electrons and 'disturbances' in the F-region. To recall in more detail, they have shown that whenever the satellite Alouette I recorded fluxes of electrons in the geomagnetically conjugate area to Sanae, above a certain critical value, either f_{min} or $h'F_2$ for Sanae was found to lie outside the limits set for the quiet day variation.

Before attempting a more specific investigation of the effects of electrons on the lower regions of the ionosphere, it was thought of importance to determine whether the energetic electron data, which were available for this purpose, showed a correlation with F-region disturbances at Sanae and the Argentine Islands. The analysis was conducted by dividing each of the parameters $h'F_2$ and f_oF_2 into two classes, either 'disturbed' or 'quiet', according to an objective criterion and comparing them by means of 2 x 2 contingency tables to the level of the electron flux density.

1.2 Pertinent Data

All the electron flux data used in this thesis were obtained from measurements made by the near polar orbiting satellite Alouette I at an altitude of roughly 1 000 km.

The satellite was launched in September 1962 and carried, amongst other instruments, a particle detector package including two energetic electron counters sensitive to electrons with energies greater than 40 and 250 keV respectively. All measurements were telemetered directly to ground based stations scattered around the world.

The Falkland Islands station (302^o 9' E; 51^o 42' S) recorded telemetry in the southern hemisphere for positions of the satellite between the longitudes 275^o E and 330^o E and roughly between the constant L-shell parameters 1,2 and 8. Thus we are provided with directly overhead energetic electron flux measurements for the Argentine Islands (295^o 44' E; 65^o 15' S) L = 2,41, during the period, October 1962 to February 1963, for which hourly, vertical incidence, swept frequency soundings are available.

Quarter hourly ionograms for this period are also available for Sanae (2^{o} 21' W; 70^{o} 18' S) L = 4, as well as telemetry received at the northern hemisphere station, St. Johns (307,2^{o} E; 47,5^{o} N) L = 3,3, for the conjugate area to Sanae. Thus the opportunity arises of investigating possible correlations which may exist between F-region disturbances observed at the Argentine Islands and Sanae, and high fluxes of electrons measured in the Falkland Islands and St. Johns area. (In the latter case especially for Sanae.)

Limiting our attention to a small region of roughly 300 km in extent centered on the position of the ionospheric station, the range of the constant L-shell parameter was found to lie between 3,75 and 4,25 for Sanae, and between 2,26 and 2,63 for the Argentine Islands. (The determination for the Argentine Islands is shown in Appendix A.)

Satellite measurements made within these L-parameter ranges were read from the magnetic tape supplied by Dr. I.B. McDiarmid of the National Research Council's Division of Pure Physics in Ottawa. The electron count rate was converted to directional flux densities (elec cm^{-2} s^{-1} sr^{-1}) correcting for the background radiation (appendix B). A final 'printout' was obtained of the directional electron flux density within the energy range 40 to 250 keV together with the geographic coordinates, altitude, pitch angle, L-shell parameter and the universal time of observation. (Electrons with energies greater than 250 keV were neglected as they were considered to have a negligible effect on the ionization at F-region altitudes (A. Wulff, 1972)).

1.3 $h'F_2$ - f_oF_2 Disturbance Criterion

It now remains to determine the criterion that should be adopted in deciding whether the F-region parameters $h'F_2$ and f_oF_2, at the times when satellite measurements were made, are 'disturbed' or 'quiet'. A slightly modified approach to that used by Gledhill and Torr was followed.

Graphs of f_oF_2 and $h'F_2$ for each of the ten international magnetically quiet days (J. Virginia Lincoln, 1963) as well as the hourly median values were plotted for each month used in the analysis. After discarding values which showed a marked deviation from the median of the quiet day values, these plots were used to define the maximum limits of the 'undisturbed' range for the parameters.

For each of the months December 1962 and January 1963, the plots of $h'F_2$ for Sanae for the first five quiet days showed a distinction from the plots for the last five quiet days. In order to eliminate any effects of this seasonal variation, the disturbance criteria were set up as above using the first five quiet days for the first half of the month and the last five quiet days for the second half.

1.4 The Method of Correlation

For each pass made by Alouette I through the specified L-parameter range, on an average four to seven readings of electron flux density were recorded at ten second intervals. Whenever at least one of these flux measurements exceeded a certain critical value, the determination of which is discussed later, the electron flux density for that pass was considered to be 'high'. If all measurements were below the critical value, the flux for that pass was described as 'low'.

Each of the parameters $h'F_2$ and f_oF_2 were classified separately as 'disturbed', if on at least one occassion within an hour of the time at which the flux reading was taken, their values were found to lie outside the limits described for the quiet day variation. The parameters were designated as 'quiet' if they remained within the limits for the two hour period.

The electron flux densities and the two ionospheric parameters for the three months of November, December 1962 and January 1963, were now compared by means of 2 x 2 contingency tables using the classifications described above. (The month of October 1962 was excluded from this analysis for two reasons. Firstly, nuclear explosions during this month caused spuriously high counts to be recorded within the Argentine Islands L-coordinate range and secondly, the setting up of a reliable disturbance criterion is complicated by the characteristic instability of the F-region at this time (Torr, 1966; Piggott and Shapley, 1962).)

Initially an arbitrary value for the critical flux density was chosen and then varied so as to improve the observed correlation, with a bias to obtaining a minimum number in the 'high' flux - 'quiet' ionospheric parameter block of the contingency tables.

In order to estimate the probability of the observed correlation being purely random, χ^2 was calculated for each of these tables. The degree of association between the variables is represented by the product moment correlation coefficient r, which is defined in appendix D.

1.5 Correlation for SANAE

1.51 Falkland Islands Data

The method described above was now applied to the electron flux data obtained from the Falkland Islands, within the L-parameter range 3,75 to 4,25 and between the longitudes 275^{o} and 330^{o} E, and the quarter hourly scaled values of $h'F_2$ and f_oF_2 for Sanae.

Even although Sanae lies approximately 65^{o} to the east of the centre of the Falkland Islands telemetry receiving area, we have good reason to expect 'trapped' electrons measured in this region to precipitate over Sanae's ionosphere. Electrons drifting along Sanae's L = 4 shell will encounter a steadily decreasing magnetic field as they approach and pass over Sanae. Their mirror altitudes will be lowered by approximately 350 km, assuming a change in the magnetic field at 100 km from 0,50 gauss at the Falkland Islands longitude to 0,42 gauss at Sanae, and thus the probability of their precipitation will be increased.

This seems to be confirmed by the positive correlation of electron flux density with the F-region parameters as shown in Table 1, where N denotes the total number of data points used in the analysis.

The critical value of the electron flux determining the boundary between 'high' and 'low' fluxes of electrons was found to be 1×10^5 elec cm^{-2} s^{-1} sr^{-1} which is slightly less than the mean value for the three months, of $1{,}4 \times 10^5$ elec cm^{-2} s^{-1} sr^{-1}.

TABLE 1

Sanae $h'F_2$ and f_oF_2 correlation -

Falkland Islands flux data L = 3,75 - 4,25

(a) $h'F_2$ versus ELECTRON FLUX

$h'F_2$	High	Low
Dist.	34	19
Quiet	3	29

N = 85

$\chi^2 = 24,4$; $P < 10^{-6}$

r = 0,54

(a)

(b) f_oF_2 versus ELECTRON FLUX

f_oF_2	High	Low
Dist.	33	15
Quiet	3	33

N = 84

$\chi^2 = 31$; $P < 10^{-7}$

r = 0,60

(b)

These contingency tables reveal a high degree of association between $h'F_2$, f_oF_2 at Sanae and the electron flux density measured in the Falkland Islands area. Table 1 (b) shows a slightly better correlation for f_oF_2 (r = 0,60) than table 1 (a) shows for $h'F_2$ (r = 0,54).

The probability of obtaining a value of χ^2 from a purely random table greater than or equal to the observed values in table 1, is found from plots of χ^2 (Kendall, 1952) to be less than one chance in 10^6 (or $P < 10^{-6}$). Therefore we may conclude that the correlations of both $h'F_2$ and f_oF_2 with electron flux are highly significant.

However it does not necessarily follow that disturbances in $h'F_2$ and f_oF_2 are directly related to the level of the electron flux density. Both F-region disturbances as well as energetic electron flux values have been directly associated with geomagnetic variations. (Somayajulu, 1971;

O'Brien, 1962; Rose, 1965; Parsignault et al, 1971; King, 1961). Thus the correlations, observed in Table 1, may arise purely from this relationship between the electron flux, ionospheric parameters and magnetic disturbances.

In order to test this hypothesis, 2 x 2 contingency tables were again constructed in order to compare the electron flux, $h'F_2$ and f_oF_2 with the international geomagnetic planetary 3-hour range indices, K_p (J. Virginia Lincoln, 1963), at the times of the flux measurements. The classifications of the electron flux, $h'F_2$ and f_oF_2 were maintained as above. All K_p indices above 2o were classified as 'high' and all values less than or equal to 2o were classed as 'low'. This critical value was found to give approximately the best overall correlation of the three variables with K_p indices. H and L in table 2 refer to 'high' and 'low' respectively and D and Q to 'disturbed' and 'quiet'.

TABLE 2

Sanae and Falkland Islands Data

L = 3,75 - 4,25 correlation - K_p indices

(a)

Flux	$K_p \geqslant$ 2+	$K_p \leqslant$ 2o
H	27	11
L	15	34

N = 87

$\chi^2 = 14$; $P < 10^{-3}$

r = 0,40

(b)

$h'F_2$	$K_p \geqslant$ 2+	$K_p \leqslant$ 2o
D	32	21
Q	10	22

N = 85

$\chi^2 = 6{,}7$; $P < 0{,}01$

r = 0,28

(c)

f_oF_2	$K_p \geqslant$ 2+	$K_p \leqslant$ 2o
D	34	14
Q	8	28

N = 84

$\chi^2 = 19{,}4$; $P < 10^{-5}$

r = 0,48

Table 2 (a) exhibits a moderately significant correlation of electron flux density with K_p indices ($r = 0,40$; $P < 10^{-3}$). The parameters f_oF_2, $h'F_2$, Table 2 (b), ($r = 0,28$; $P < 0,01$) also show a positive degree of association with the magnetic indices. This might be expected, as K_p indices are involved in setting up the disturbance criterion.

Making use of these correlation coefficients, we may now calculate the partial coefficient of association, R, between the electron flux and the two parameters $h'F_2$ and f_oF_2, making allowance for the effect of magnetic variations. R is defined by Yule and Kendall (1953).

The partial coefficient of association for $h'F_2$ with electron flux is $R = 0,49$ and for f_oF_2 $R = 0,51$, which both still show a high degree of positive association.

Thus we may conclude that electron flux density measurements, made within the L-coordinate range 3,75 - 4,25 and between the longitudes 270° and 330° E, exhibit a significant correlation with disturbances in the $h'F_2$ and f_oF_2 ionospheric parameters for Sanae even when possible effects of geomagnetic disturbances are taken into account.

1.52 St. Johns Data

In order to determine whether similar correlations exist for electron fluxes measured in the geomagnetically conjugate St. Johns area, contingency tables were again constructed as above for $h'F_2$ and f_oF_2 at Sanae, using northern hemisphere satellite data between the longitudes 290° and 335° E and L-parameters 3,75 and 4,25. The coordinates of the conjugate point to Sanae are 325° E, L = 4.

The critical electron flux used in the analysis was determined to be $4,8 \times 10^4$ elec cm^{-2} s^{-1} sr^{-1} for the month of November 1962 and 1×10^4 elec cm^{-2} s^{-1} sr^{-1} for December 1962 and January 1963. The corresponding mean flux for these two periods was $6,6 \times 10^4$ elec cm^{-2} s^{-1} sr^{-1} and $1,4 \times 10^4$ elec cm^{-2} s^{-1} sr^{-1} respectively.

Once again we find, as shown in Table 3, a positive degree of association to exist between $h'F_2$, f_oF_2 and electron flux measurements.

TABLE 3

Sanae $h'F_2$ and f_oF_2 Correlation -

St. Johns Data L = 3,75 - 4,25 ; 290° E - 335° E

(a)

$h'F_2$	FLUX: High	FLUX: Low
D	14	18
Q	3	30

N = 65

$\chi^2 = 10$; $P \leq 0,005$

r = 0,39

(b)

f_oF_2	FLUX: High	FLUX: Low
D	16	24
Q	3	24

N = 67

$\chi^2 = 6,6$; $P \leq 10^{-2}$

r = 0,31

However in this case the levels of significance are comparatively low, $P \leq 10^{-2}$ for Table 3 (b) and $P \leq 0,005$ for Table 3 (a). The coefficients of association, r = 0,39 for $h'F_2$ and r = 0,31 for f_oF_2 are very much less than those observed correspondingly in Table 1 for the Falkland Islands data.

Testing for the possibility that the correlations observed in Table 3 are due to the relation of flux and the ionospheric parameters with K_p indices, contingency tables were drawn up as for the Falkland Islands data and are presented in Table 4.

TABLE 4

Sanae and St. Johns data Correlation - K_p indices

(a) Flux vs K_p

Flux	$K_p \geq 2+$	$K_p \leq 2o$
H	15	24
L	10	24

N = 73

$\chi^2 = 0,66$; $P = 0,42$

r = 0,1

(b) $h'F_2$ vs K_p

$h'F_2$	$K_p \geq 2+$	$K_p \leq 2o$
D	21	11
Q	8	25

N = 65

$\chi^2 = 11,3$; $P \leq 0,001$

r = 0,42

(c) f_oF_2 vs K_p

f_oF_2	$K_p \geq 2+$	$K_p \leq 2o$
D	22	18
Q	8	19

N = 67

$\chi^2 = 4,2$; $P = 0,04$

r = 0,25

The partial correlation coefficients for the relation between the electron flux and the F-region parameters are

$$R = 0,38 \text{ for } h'F_2$$

$$R = 0,30 \text{ for } f_oF_2$$

and thus the pertinent result of this analysis is that flux densities, measured in the geomagnetic conjugate area to Sanae, exhibit a correlation with disturbances in the parameters $h'F_2$ and f_oF_2 at Sanae, but to a smaller degree than that observed for measurements made in the Falkland Islands telemetry area.

A possible reason for this could be that over 60% of the electron flux readings used in the St. Johns correlation lie below the value of $1,4 \times 10^4$ elec cm^{-2} s^{-1} sr^{-1} which has been stated by Dr. I. McDiarmid (Torr 1966) to be the lowest flux which could be reliably detected by Alouette I.

1.6 Correlation for the Argentine Islands

A similar analysis of the ionospheric and satellite data was conducted for the Argentine Islands ($295,7^\circ$ E; $65,3^\circ$ S) L = 2,4. Use was made of electron flux measurements within the longitude range 275° to 330° E and within the L-parameters 2,26 to 2,63 for the southern hemisphere, together with hourly values of the ionospheric parameters h'F and f_oF_2 obtained from monthly bulletins, supplied by the Science Research Council at Slough. All suspect values were checked by scaling the appropriate ionograms.

The critical electron flux value adopted for November 1962, was 5×10^5 elec cm^{-2} s^{-1} sr^{-1} and 5×10^4 elec cm^{-2} s^{-1} sr^{-1} for December 1962 and January 1963. The corresponding mean flux for the two periods is 5×10^5 and $1,4 \times 10^5$ elec cm^{-2} s^{-1} sr^{-1} respectively.

TABLE 5

Argentine Islands h'F and f_oF_2 Correlation -

Falkland Islands flux data $275^o - 330^o$ E, L = 2,26 - 2,63

(a) h'F

h'F	FLUX High	FLUX Low
D	40	28
Q	11	50

N = 129

$\chi^2 = 22,4$; $P < 10^{-5}$

r = 0,42

(b) f_oF_2

f_oF_2	FLUX High	FLUX Low
D	44	27
Q	10	55

N = 136

$\chi^2 = 30,7$; $P < 10^{-7}$

r = 0,48

Here again Table 5 reveals a highly significant ($P < 10^{-5}$) positive correlation of the electron flux with the two ionospheric parameters. The degree of association is less for both h'F (r = 0,42) and f_oF_2 (r = 0,48) than that obtained for Sanae ionospheric data (r = 0,54 for $h'F_2$ and 0,60 for f_oF_2). This seems surprising as overhead electron flux measurements were included in the analysis for the Argentine Islands.

However if the longitude range of the electron flux data is narrowed down to a 10^o interval centered on the longitude for the Argentine Islands, the correlation observed is found to improve notably, as shown in Table 6, together with a slight drop in the level of significance due to the reduction in the amount of data.

TABLE 6

Argentine Islands h'F and f_oF_2 Correlation -

Falkland Islands flux data 290° - 300° E ; L = 2,26 - 2,63

(a)

		FLUX High	FLUX Low
h'F	D	15	10
	Q	2	16

N = 43

$\chi^2 = 10,5$; $P \leq 5 \times 10^{-4}$

r = 0,49

(a)

(b)

		FLUX High	FLUX Low
f_oF_2	D	19	7
	Q	2	18

N = 46

$\chi^2 = 18,1$; $P \leq 5 \times 10^{-5}$

r = 0,63

(b)

The comparison between the electron flux, $h'F_2$ and f_oF_2 and K_p indices at the time of the flux measurements, is shown in Table 7 for the full longitude range 275° - 330° E.

TABLE 7

Argentine Islands and Falkland Islands Data

L = 2,26 - 2,63 ; 275° - 330° E Correlation - K_p Indices

(a) Flux vs K_p

Flux	$\geqslant$ 2+	$\leqslant$ 2o
H	26	41
L	45	58

N = 170

$\chi^2 = 0{,}4$; $P = 0{,}53$

$r = -\ 0{,}05$

(b) h'F vs K_p

h'F	$\geqslant$ 2+	$\leqslant$ 2o
D	34	32
Q	27	39

N = 132

$\chi^2 = 1{,}5$; $P = 0{,}22$

$r = 0{,}16$

(c) f_oF_2 vs K_p

f_oF_2	$\geqslant$ 2+	$\leqslant$ 2o
D	37	33
Q	21	43

N = 134

$\chi^2 = 5{,}5$; $P = 0{,}02$

$r = 0{,}20$

Table 7 (a) seems to suggest that no significant correlation exists between the electron flux data and the geomagnetic K_p indices for the L-parameter range 2,26 to 2,63 ($r = -\ 0{,}05$).

A small degree of positive association is evident for the h'F ($r = 0{,}16$) and f_oF_2 ($r = 0{,}20$) parameters with the K_p indices but may hardly be regarded as significant. Thus geomagnetic variations would be expected to have no effect on the correlations observed in Table 5.

1.7 Discussion and Conclusions

Three main points arising from the above analysis are discussed briefly in this section.

1.71 In the results reported above we have shown that high fluxes of electrons in the energy range 40 to 250 keV show a significant correlation with disturbances in the F-region parameters $h'F_2$, $h'F$ and f_oF_2, even when account is taken of the correlations with geomagnetic variations.

Two of the ways in which energetic electrons precipitating into the earth's upper atmosphere could be expected to lose their energy are in ionizing and in heating the neutral gas in the F-region. These effects may give rise to different kinds of disturbances. An increase in the ionization density of the F-layer would be evidenced by an increase in the value of f_oF_2. However if heating effects become significant, the resultant expansion of the gas and the enhancement of the loss coefficient may result in a net decrease in f_oF_2. Torr and Torr (1967) have shown by solution of the continuity equation that we can also expect an increase in the height of maximum solar production to occur with an increase in temperature. This would be accompanied by an increase in the value of the parameter $h'F_2$. The ionizing effects on the other hand could result in either an increase or a decrease in the height of maximum ionization density of the F-layer depending on the energy spectrum and flux of the electrons. Since $h'F_2$ is a sensitive indicator of the lower lying ionization, we may for the most part expect an increase in $h'F_2$ to accompany ionizing effects due to the group retardation by this ionization which is produced by the higher energy tail of the electron spectrum.

Hence the type of disturbance produced will depend on the predominance of either ionization or heating effects, which in turn is determined by the energy spectrum and flux of the incoming electrons.

For Sanae 78% of disturbances in f_oF_2, corresponding to high fluxes of electrons in the Falkland Islands area, were characterised by decreases in f_oF_2. Only 40% showed decreases for the Argentine Islands. A small percentage, 6%, of the high flux correlated disturbances of $h'F_2$ data for Sanae showed decreases while 12% of the h'F values for the Argentine Islands lay below the lower limits for the 'quiet' day variation.

The high percentage of decreases in f_oF_2 at Sanae would seem to suggest that heating effects are mainly predominant in disturbances there. For the Argentine Islands ionization effects seem to be dominant in the larger number of cases.

This discrepancy would tend to indicate that different fluxes and/or spectra of electrons are experienced at the two stations. The probability of heating being the main effect is increased by the influx of larger fluxes of electrons as the energy input to the ionosphere will be greater. Thus we may expect the precipitated electron flux to be greater at Sanae than at the Argentine Islands. Unfortunately no direct flux measurements are available for Sanae in order to test this prediction. However some evidence is provided by Torr (1966), who has shown by means of an analysis of conjugate flux data for Alouette I, that a peak in the precipitated flux values occurs close to Sanae along the L = 4 shell, whereas the Argentine Islands lie to the west of a corresponding peak along L = 2. Further indication of a higher flux existing for Sanae has been provided by an analysis of Alouette I data by J.G. Greener (private communication). He reports a median flux value at the conjugate point to Sanae of roughly four times the magnitude of the median flux at the conjugate point to the Argentine Islands.

The problem now arises as to the energy range of the electrons which are responsible for the observable effects.

In order for electron bombardment of the upper atmosphere to cause significant heating effects, the energy input to the ionosphere must be comparable to that supplied by solar radiation, which is of the order of 3 ergs cm^{-2} s^{-1} at sunspot minimum (Allen 1965). Assuming a typically high incoming electron flux of 1×10^{6} elec cm^{-2} s^{-1} with an average energy of 40 keV, which is also typical of the Falkland Islands measurements if an exponential energy spectrum is assumed, the total energy deposited would be 0,06 erg cm^{-2} s^{-1}. This is almost two orders of magnitude less than the solar source. Much higher fluxes of the order of 5×10^{7} elec cm^{-2} s^{-1} are needed if the observed heating effects are to be explained on the basis of electrons with average energies of 40 keV.

Savenko et al (1963) have detected directional fluxes of 10 keV electrons at an altitude of 320 km of the order of 5×10^{9} elec cm^{-2} s^{-1} sr^{-1} at equatorial latitudes. Assuming an isotropic pitch angle distribution, this corresponds to an overall energy flux of 230 ergs cm^{-2} s^{-1} which exceeds the solar input by almost two orders of magnitude. Willmore (1964) has accounted for heating effects between 400 - 1 200 km by means of fluxes of 2 - 3 keV electrons of 8×10^{9} elec cm^{-2} s^{-1} having an energy input of 3 ergs cm^{-2} s^{-1} and Knudsen (1968) has detected typical fluxes of 10^{10} to 10^{11} elec cm^{-2} s^{-1} of 0,01 keV electrons with an equivalent energy input of 1,6 ergs cm^{-2} s^{-1}.

The energy fluxes of these low energy electrons are all comparable to the solar flux and thus we can probably account for the temperature effects observed at Sanae and the Argentine Islands by assuming, high fluxes of low energy electrons, 0,01 - 10 keV, to accompany the observed precipitation of electrons in the energy range 40 to 250 keV.

Calculations later in this thesis show that electron fluxes with spectral characteristics estimated from typical > 40 and > 250 keV measurements by Alouette I have a negligible ionizing effect at F-region altitudes. Rees (1963), Berger, Seltzer and Maeda (1970) and others have shown that electrons with energies less than 2 keV will have the greatest effect on the ionosphere above 120 km. This once again would tend to indicate that accompanying high fluxes of low energy electrons are probably responsible for the observed ionization effects in the F-region.

A recent publication by Turunen and Liszka (1972) suggests that the precipitation of soft ($\sim$ 1 keV) electrons is related to the enhancement in f_oF_2 which is observed at invariant latitudes greater than 65°. This seems to confirm the prediction made above.

It thus becomes evident that even although a clear relationship has been established between 40 to 250 keV electrons and F-region disturbances, categorical evidence of the direct relation between electrons and these disturbances can only be supplied once measurements of low energy electrons, 0,1 - 10 keV, become available.

1.72 It has also been shown in the above analysis that the value of the critical flux which was used to delineate 'high' from 'low' fluxes follows approximately the mean value of the maximum flux for each pass for the period under consideration. In other words when this mean value of the flux for the period being considered is relatively high, the critical flux, which may be regarded as an indicator of the level of the flux necessary to produce an observable disturbance, is found to be correspondingly high and similarly for low fluxes. This correspondence between the critical and mean flux values is shown in Table 8. It may be mentioned that unusually high fluxes were disregarded in the calculation of the mean values.

TABLE 8

DATA	PERIOD	CRITICAL FLUX $x\ 10^{-4} cm^{-2} s^{-1} sr^{-1}$	MEAN FLUX $x\ 10^{-4} cm^{-2} s^{-1} sr^{-1}$
Sanae / Falkland Islands	Nov.62 - Jan.63	10	14
Sanae / St. Johns	Nov.62	4,8	6,6
	Dec.62 - Jan.63	1	1,4
Argentine Islands / Falkland Islands	Nov.62	50	50
	Dec.62 - Jan.63	5	14

This result at first seems a little surprising as we might expect that if a certain flux was found to produce a noticeable disturbance at a certain time, it would still produce a similar disturbance at a later date independent of the mean flux during this period. However, considering the mean flux as an indicator of the level of the radiation which is present even on the magnetically quiet days and assuming that the magnitudes of the F-region disturbances are qualitatively proportional to the level of the electron flux producing them, we may expect disturbances to be present on these days in proportion to the mean flux. Thus if the mean flux for a period is relatively high, the disturbances on the quiet days will be greater and a larger flux is required to produce a recognizable disturbance. Alternatively, if the mean flux is relatively low, it will be easier to distinguish disturbances from the lower disturbance 'noise' level on the quiet days and thus the critical flux will be correspondingly lower.

Hence we may suggest that our assumption, that the magnitude of F-region disturbances is qualitatively related to the level of the electron flux data, could be valid. This aspect could be investigated further with the acquisition of more flux data in the right energy range. By adopting a suitable method of estimating the severity of F-region disturbances, a quantitative comparison could be made with the level of the average electron flux for short or long periods.

1.73 The third and final point which is pertinent to this analysis is the significant positive correlation which was found between the electron flux densities and the international geomagnetic K_p indices ($r = 0,40$) for the L-parameter range 3,75 to 4,25 (Table 2 (a)). A number of workers such as O'Brien (1962), Rose (1965), Parsignault et al (1970) have reported similar findings.

In contrast to the above we have found that no significant correlation exists between flux and K_p indices for the L-parameter range 2,26 to 2,63 ($r = - 0,05$). This seems to be a surprising result. A recent publication by Parsignault et al (1971) has reported a similar effect for electrons, in the energy range 12 to 48 keV, measured using electrostatic analysers which were flown aboard the Air Force Satellite OV-13 (1968-26A). No discernible correlation between the electron intensity and K_p was found for the $2,5 \leq L \leq 3,0$ range. For $L > 3$ a direct correlation between flux densities and K_p indices was observed. They suggest an inward radial diffusion of particles to lower L-values and concurrent acceleration as an explanation of the observed phenomena.

Thus we have provided independent evidence of these effects occurring at an earlier date, 1962 - 1963, to the observations by Parsignault et al in 1968. This seems to indicate a temporal stability of the phenomena. We have also established that these phenomena exist for electrons in a different energy range to those observed by Parsignault et al.

It may be of interest to future researchers to determine more clearly the boundary between K_p correlated and non-correlated flux values and relate this boundary to the magnetospheric structure.

1.8 Summary

We have shown that fluxes of electrons in the energy range 40 to 250 keV exhibit a significant correlation with disturbances in F-region parameters. Temperature effects due to electron fluxes are suggested as being predominant in disturbances at Sanae. Ionization may be the main effect at the Argentine Islands. The disturbances are probably caused by accompanying high fluxes of lower energy electrons.

The level of the flux shows a correlation with K_p indices for $3,75 \leq L \leq 4,25$ but exhibits no observable relation with K_p for $2,26 \leq L \leq 2,63$.

The magnitude of the F-region disturbances are suggested as being qualitatively proportional to the level of the electron flux.

CHAPTER 2: Electron Ionizing Effects

In the previous chapter we have presented some evidence for the ionizing effect of electrons precipitating into the upper atmosphere. The question now arises as to the altitude and magnitude of the increases in the ionization density of the ionosphere which we may expect typical fluxes of these electrons to produce.

2.1 Introduction

Calculations of the altitude profiles of the ion pair production rate due to monoenergetic electrons precipitating into model atmospheres have been made by several workers.

Chamberlain (1961) has based his computations of the ionization production rate on theoretical results of Spencer (1955, 1959) for the range of high energy electrons in air and the normalised energy deposition function λ. Rees (1963) used laboratory measurements by Grün (1957) for the range energy relation and λ function, and Maeda (1965) incorporated the use of Monte Carlo type calculations to estimate the ionization rate profiles for isotropic or monodirectional fluxes of monoenergetic electrons in the energy range 2 to 20 keV. This work has recently been extended with account being taken of the effect of a magnetic field (Berger, Seltzer and Maeda, 1970). A more detailed summary of their calculations is given by A. Wulff (1972).

These production rate profiles may be used to determine the ionization produced in the ionosphere by flux densities of precipitating electrons observed by satellite and rocket particle detectors. Bailey (1968) has computed the ionization density profiles which would be produced by fluxes of electrons distributed according to an assumed exponential energy spectrum. Exponential spectra have often been used to fit satellite and rocket observations.

In this chapter computations are made of the changes which may occur in characteristic ionization - height profiles for Sanae upon the introduction of an extra ion pair production source due to electrons with typical fluxes and exponential energy spectra. For this computation use is made of altitude profiles of the ionization production rate calculated using results of Berger, Seltzer and Maeda (1970). Reasonable values for the ionospheric loss coefficients are assumed in order to effect the conversion from production rates to ionization density profiles. It is of particular interest to know whether the electron fluxes measured by Alouette I could be expected to have an observable ionization effect on the ionosphere at Sanae.

2.2 Altitude Production Profiles

The opportunity to study ionization density changes in the ionosphere due to precipitating electrons was provided with the development of a computer program by Miss A. Wulff (1972) to calculate the altitude distributions of the ionization rate of energetic electrons. In essence this program uses the λ function and range energy relation computed by Berger et al (1970) for electrons with an IDH (isotropic over the downward hemisphere) pitch angle distribution, to calculate the ionization production rate profile per unit flux for monoenergetic electrons. A. Wulff (1972) has substituted Jacchia's model atmospheres (1965) above 120 km for the CIRA (1965) mean model atmosphere used by Berger et al (1970) as it is hoped that this would give more realistic results for higher latitudes.

In order to calculate the ionization rate profiles which would be produced by a more realistic energy spectrum of electrons than for the monoenergetic case, it was decided to assume after Bailey (1968) and Ulwick, Reidy and Baker (1967) that the electrons were distributed according to an integral energy spectrum of the type

$$J(>E) = J_o \, e^{-E/E_o} \quad \text{elec cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1} \qquad 2.1$$

where

$J(>E)$ is the directional flux density of electrons having energy greater than E.

E_o is the characteristic or average energy of the flux in the energy range 0 to ∞.

J_o is the total directional flux density above zero energy.

Satellite measurements of electron fluxes have often been expressed in this exponential form. Power law spectra have also been fitted to observations but appear to overestimate the intensities when extrapolated to higher and lower energies and thus were not used in this case.

Where the flux shows an IDH distribution of pitch angles equation 2.1 becomes (A. Wulff, 1972)

$$j(>E) = \pi J_o \, e^{-E/E_o} \quad \text{elec cm}^{-2}\,\text{s}^{-1} \qquad 2.2$$

where

$j(>E)$ is the IDH flux density of electrons with energy greater than E.

For each height interval for which the ionization rate per unit flux was previously calculated for the monoenergetic case the production rate for an energy spectrum was now computed by integrating the ionization rate over the differential spectrum

$$\frac{d\ j(>E)}{dE} = \pi \frac{J_o}{E_o} e^{-E/E_o} \text{ elec cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1} \qquad 2.3$$

(A. Wulff, 1972)

$$Q_h = \frac{\pi J_o}{E_o} \int_{E_1}^{E_2} q_E\, e^{-E/E_o}\, dE \qquad 2.4$$

where q_E is the ionization production rate per unit IDH flux at the energy E.

Q_h is the total production rate due to the IDH flux density $j(>E) = J_o e^{-E/E_o}$ at height h.

Thus in order to calculate the ionization rate altitude profile for a flux of electrons conforming to an exponential energy spectrum, we are required to estimate values for the constants E_o and J_o and subsequently perform the integration in equation 2.4.

It is a simple matter to obtain the constants E_o and J_o from the Alouette I satellite measurements if an exponential spectrum is fitted to the two readings of flux $J(>40 \text{ keV})$ and $J(>250 \text{ keV})$. From which we obtain the two equations

$$J(>40) = J_o e^{-40/E_o} \qquad 2.5$$

$$J(>250) = J_o e^{-250/E_o} \qquad 2.6$$

Solving for J_o and E_o in 2.5 and 2.6 we obtain

$$J_o = \exp\left(\frac{\log_e J(>250) - 6{,}25 \log_e J(>40)}{- 5{,}25} \right) \qquad 2.7$$

and $$E_o = 210 \log_e\left(\frac{J(>250)}{J(>40)} \right) \qquad 2.8$$

The integral in equation 2.4 was computed using numerical methods as described by A. Wulff (1972). The range of integration was chosen to lie between 0,1 keV and 10 E_o. The flux above 10 E_o has been shown by A. Wulff (1972) to be always relatively insignificant. (For $E = 10\ E_o$ in equation 2.1, $J(>E) = J_o/50\ 000$.) The energy interval of integration ΔE (described by A. Wulff, 1972) was taken for our purposes to be E/50 which varies proportionately to E over the range of integration. Decreasing this interval was not found to improve the values of the production rates significantly.

It now remains to compute the ionization density increases which would result in the ionosphere if this ionization production rate due to electron fluxes is added.

2.3 Conversion of Production to Density Profiles

The balance of ionization in the ionosphere may be represented by the continuity equation

$$\frac{\partial N}{\partial t} = q - L(N) - \mathrm{div}(NV) \qquad 2.9$$

where

N is the electron or ion concentration.

q is the ionization production rate.

L(N) is the loss term due to chemical processes.

div(NV) is the loss term due to diffusion and transport processes.

If we assume steady state conditions to exist, then the rate of change of the electron density, $\frac{\partial N}{\partial t}$, will be zero. Shutte and Knorin (1969) have shown that the transport term due to vertical diffusion, only becomes significant above 250-300 km and thus for our purposes this term has been neglected.

The loss term, L(N), may be reasonably represented by the expression

$$L(N) = \frac{\alpha\beta N^2}{\beta + \alpha N} \qquad \text{(Ratcliffe, 1956)} \qquad 2.10$$

where α and β are the square and linear loss coefficients respectively.

(At greater altitudes $\beta \ll \alpha N$ and L(N) reduces to a linear law $L(N) = \beta N$. At lower altitudes N is smaller $\therefore$ $\alpha N \ll \beta$ and $L(N) = \alpha N^2$.)

Substituting equation 2.10 into the steady state continuity equation we obtain a quadratic equation for the electron concentration N (Hirsch, 1959).

$$\alpha\beta N^2 - \alpha q N - \beta q = 0 \qquad 2.11$$

from which we may obtain the electron density, N, in terms of the production rate and loss coefficients

$$N = (q/2\beta) \left[1 + \left(1 + \frac{4\beta^2}{\alpha q} \right)^{\frac{1}{2}} \right] \qquad 2.12$$

Assuming reasonable values for the two coefficients α and β we may use equation 2.12 to convert the altitude profiles of the ionization production rate due to electrons with a specified flux and energy spectrum into ionization density profiles. However, in order to calculate the increase in ionization which would occur due to these electrons impinging on an 'already existing' ionosphere, it is necessary to add the production rate due to other sources such as photoionization by solar ultraviolet and X-rays to the electron production rate and then compute the resulting N(h) profile. A comparison can then be made with the N(h) profile that would be produced if the ionizing effect of electrons were excluded.

An estimate of the ionization production rate due to solar ultraviolet and X-ray radiation may be calculated directly from the theory of photoionization described by Rishbeth and Garriot (1966). However, for the purposes of this computation we have adopted a far simpler approach which permits a direct comparison of results with actual ionospheric records.

A typical ionogram for the period under consideration was converted to an N(h) profile using Titheridge's method of ionogram reduction. These electron density data points were then used together with equation 2.12 to calculate the solar production rate profile necessary to produce the observed ionization profile. Steady state conditions and reasonable values for α and β were assumed. The ionization rate profile calculated for electrons with a characteristic flux and energy spectrum was added to the estimated solar production profile and the resultant N(h) profile computed using the same values for α and β. A comparison of the initial and final N(h) profiles will reveal the order of magnitude and altitude range of the ionization effects of precipitating electrons.

Reasonable estimates for the linear and square law loss coefficients will now be considered.

The Linear Loss Coefficient β

Shutte and Knorin (1969), for two measurements of electron density profiles and solar ultraviolet radiation above 200 km, have found β to vary roughly exponentially between the values $0,5 \times 10^{-3}$ to $2 \times 10^{-3}\ s^{-1}$. Ratcliffe et al (1956) have deduced a formula for β based on the study of N(h,t) data from various stations

$$\beta\ (h) = 10^{-4} \exp \left[(300 - h)/50 \right] \quad s^{-1} \qquad 2.13$$

where h = altitude in km. At 300 km $\beta = 10^{-4}\ s^{-1}$.

Shimazaki (1964) has deduced $\beta = 10^{-4}\ s^{-1}$ at 300 km for nighttime data and Chun-Ming Huang (1966) has estimated β to lie between 2×10^{-4} and $4 \times 10^{-4}\ s^{-1}$ at sunspot maximum.

Since we are working in a period roughly midway between solar minimum and maximum, the Ratcliffe et al formula was adopted as an estimate for β as it seem to show good agreement at 300 km with other measurements, (Rishbeth and Garriot, 1966).

The Square law Coefficient α

A number of methods have been applied to measure the effective recombination coefficient α . Deductions from eclipse phenomena tend to indicate an α of the order of $10^{-8}\ cm^3\ s^{-1}$ (Ratcliffe, 1956 b) but are not regarded as very reliable. Allen (1965) has estimated an α of $1,6 \times 10^{-7}\ cm^3\ s^{-1}$ from direct rocket measurements of solar ionizing radiation under normal conditions. Laboratory measurements tend to indicate an α of a similar order of magnitude. Biondi (1967) has found the values of the recombination coefficients for the three main reactions in the E-region to lie in the range $0,7 \times 10^{-7}$ to 5×10^{-7} cm^3 s^{-1}. Bailey et al (1970) have estimated α to vary within the range 4 to $1,4 \times 10^{-7}$ cm^3 s^{-1} between the altitudes 90 and 150 km respectively. For our purposes we have adopted the constant value of 2×10^{-7} cm^3 s^{-1} as a reasonable estimate for α. The estimate for α was not found to be critical as varying the coefficient by an order of magnitude had only minimal effects on the final result.

2.4 Ionization Density Increases

The ionogram selected for the investigation was one occurring at 14.30 hrs. U.T. on the 11 January 1963 at Sanae. This particular ionogram was chosen because the critical frequency of the E-layer was not affected by absorption, which is very seldom the case for Sanae records, and thus allowed the complete trace to be scaled in detail. The 'undisturbed' nature of this ionogram also gave preference to its selection. By 'undisturbed' is implied the absence of occurrences such as spread-F, travelling disturbances, sporadic-E layers and unusual values for the critical frequencies or virtual heights of the three layers E, F_1 and F_2. The N(h) profile was computed for this ionogram using a program developed by Mr. A.W.V. Poole, the Antarctic Research Officer at Rhodes University. The corresponding altitude distribution of the solar production rate was then calculated as mentioned above using equation 2.12 and the assumed values for α and β.

In order to compute the extra ionization rate which would be caused by typical fluxes of electrons measured by Alouette I, it is necessary to know the IDH flux and spectrum of these electrons at 300 km. All measurements made by Alouette I were of directional intensities at roughly 1 000 km. However, from considerations of the magnetic field intensities, trapped electrons mirroring below 1 000 km in the conjugate St. Johns area to Sanae, will mirror below 450 km over Sanae (appendix E). Thus we may use the St. Johns data to estimate the order of magnitude of spectra and fluxes of electrons which may occur at Sanae.

Typical values of the characteristic energy E_o for St. Johns data for the L = 4 shell were found to lie roughly in the range 30 to 120 keV with most fluxes having characteristic energies between 50 and 70 keV. The three values 30, 50 and 100 keV were chosen for the computation to represent characteristic E_o values.

Although the intensity measurements, J(>40), occasionally reached values as high as 1×10^6 cm^{-2} s^{-1} sr^{-1}, a value of J(>40) = 5×10^5 cm^{-2} s^{-1} sr^{-1} was found to be representative of what may be regarded as a typically high flux for the data. This corresponds to a J_o value of roughly 1×10^6 cm^{-2} s^{-1} sr^{-1} for E_o = 50 keV. (The mean intensity, J(>40), of the St. Johns data over the period being considered is approximately 4×10^4 cm^{-2} s^{-1} sr^{-1}.) An isotropic pitch angle distribution was assumed for the particles, which is not an unreasonable assumption, as evidence has been given which shows that when the electron intensity increases, the angular distribution tends to become more isotropic (e.g. O'Brien, 1964; Mozer and Bruston, 1966; and McDiarmid et al, 1967).

Thus the production rate profiles due to electrons with $J_o = 1 \times 10^6$ cm^{-2} s^{-1} sr^{-1} and E_o = 30, 50 and 100 keV were calculated and added to the solar production rate altitude distribution computed above. T_{exo} for the model atmosphere used was 1270 K. The final N(h) profiles due to these increased production rates were estimated using equation 2.12 and the assumed values for α and β and are represented in fig. 2.1 together with the original ionization density profile.

An inspection of these curves indicates that electrons with the typical flux and energy spectra assumed at 300 km for Sanae may cause observable changes in the ionization density below 125 km with negligible effects above this altitude. We may expect an increase in f_oE of roughly 0,8 MHz to occur which is well above the level of accuracy to which an ionogram can be scaled. However, the magnitude of this increase is very dependent on the height of the E-layer and may not necessarily be used as a quantitative prediction of the increases in f_oE which we may generally expect at Sanae, but rather as an indication that observable electron effects could occur. It may be noted that the increase in ionization at 100 km does not vary significantly for the three values of E_o used in the calculation. However the ionization density below the E-layer is found to increase markedly as E_o is increased.

If we now successively reduce the J_o value maintaining E_o at 50 keV, we could determine roughly the flux below which we may regard the electrons as causing 'unobservable' increments in the ionization density. (In all these calculations we have assumed an initial zero flux level which in practice is not necessarily the case since we may always expect some flux to be present. This would imply that we may be overestimating the ionization increases in each case. However if the initial flux level is less than an order of magnitude below the value used to estimate the ionization increase, this effect may be regarded as negligible.) Assuming an accuracy in scaling ionograms at E-region altitudes of $\pm$ 5 km in vertical height and $\pm$ 0,05 MHz

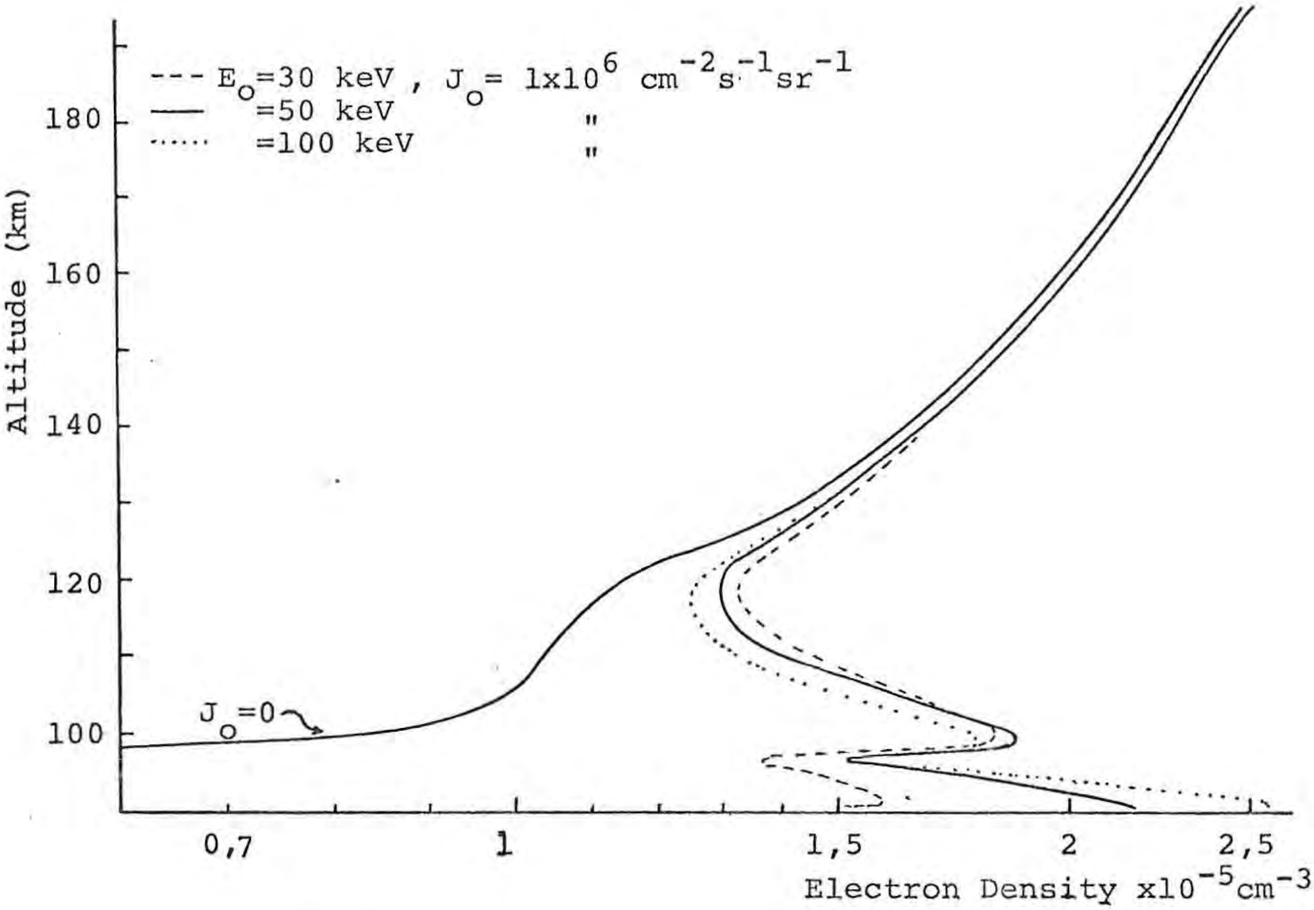


Fig 2.1 N(h) profiles showing the increase in electron density due to an eletron flux with E_o=30 ,50 ,100 keV,J_o=1x10^6 .

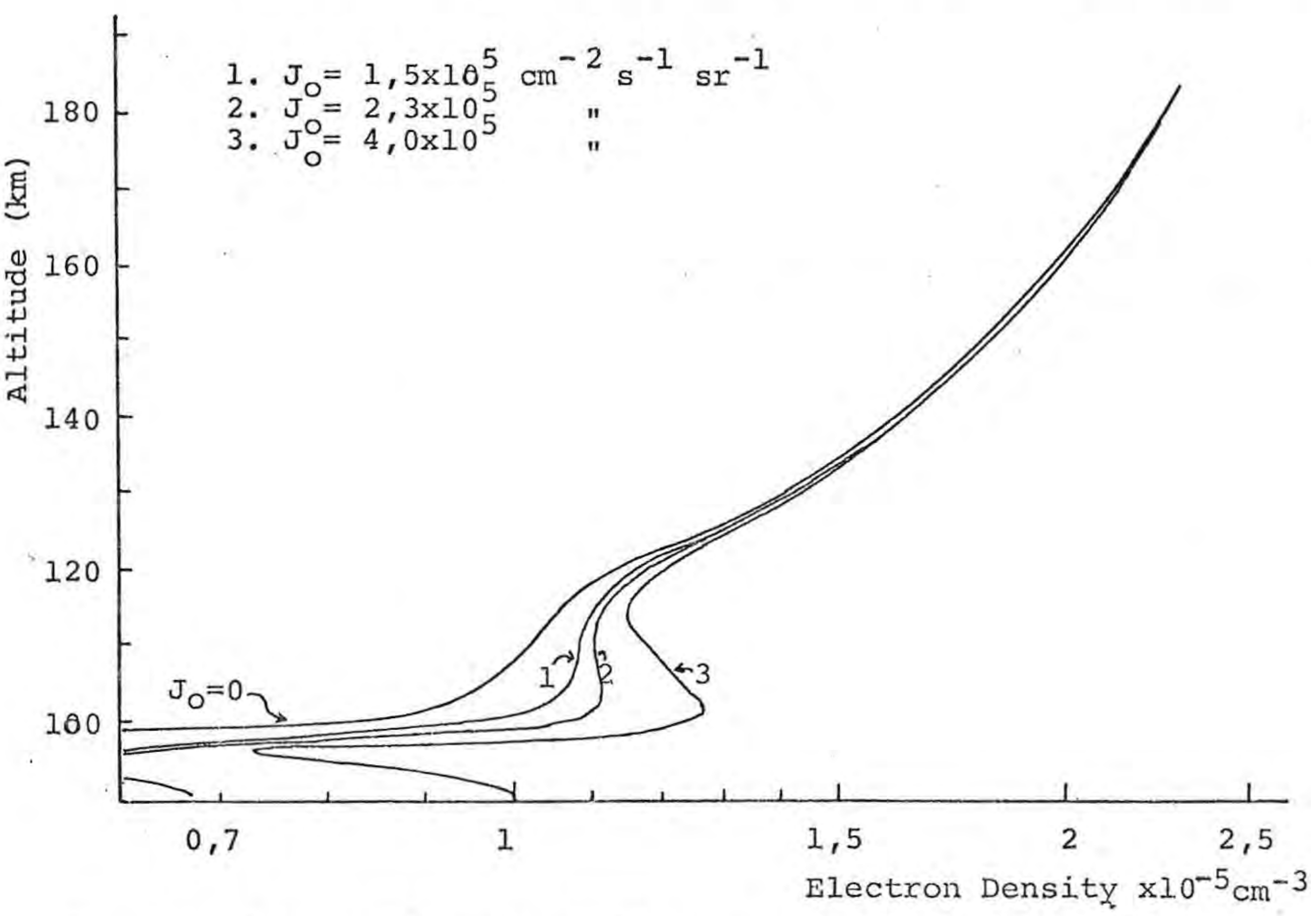


Fig 2.2 N(h) profiles for different values of J_o , E_o= 50 keV .

in frequency values, we may regard changes in the corresponding N(h) profile greater than these levels of accuracy as being 'observable' and changes within these limits as 'unobservable'.

Reducing J_o in even multiples to a value of 1,5 x 10^5 cm^{-2} s^{-1} sr^{-1}, which corresponds to a $J(>40) \sim 6,6 \times 10^4$ cm^{-2} s^{-1} sr^{-1}, reduces the increment in the ionization density to a level which may still be observable from the N(h) profile but corresponds to an increase in the critical frequency of the E-layer of $\leqslant$ 0,05 MHz at 117 km. Thus this effect may be regarded as negligible (fig. 2.2). The density of the low lying ionization is found to drop off sharply as J_o is decreased.

In order to determine what flux and spectrum of electrons may be responsible for the F-region effects discussed in the previous chapter, the value of E_o was reduced to 10, 5 and 2 keV computing the ionization profile on each occasion for J_o = 1 x 10^6 cm^{-2} s^{-1} sr^{-1} (fig. 2.3). As may be expected, since by reducing E_o we are decreasing the energy input to the ionosphere, the nett result is a decrease in the ionization density below 130 km with no apparent F-region effects. Thus it would seem that much higher fluxes of these lower energy electrons are required. Increasing J_o to 1 x 10^7 cm^{-2} s^{-1} sr^{-1} and computing the profiles for the E_o values 0,5, 1 and 2 keV, the results, as shown in fig. 2.4, clearly indicate significant ionization effects at F-region altitudes. Plasma frequency increases of roughly 0,5 MHz should be produced. In practice much higher fluxes of these low energy electrons are observed of the order of 10^9 - 10^{10} cm^{-2} s^{-1} sr^{-1} as mentioned in the previous chapter. Thus we may expect that if electrons with these fluxes and energies occur at Sanae, they will very likely result in quite large disturbances in the F-region. Since the observations by Alouette I for energies greater than 40 keV and 250 keV do not predict such high fluxes

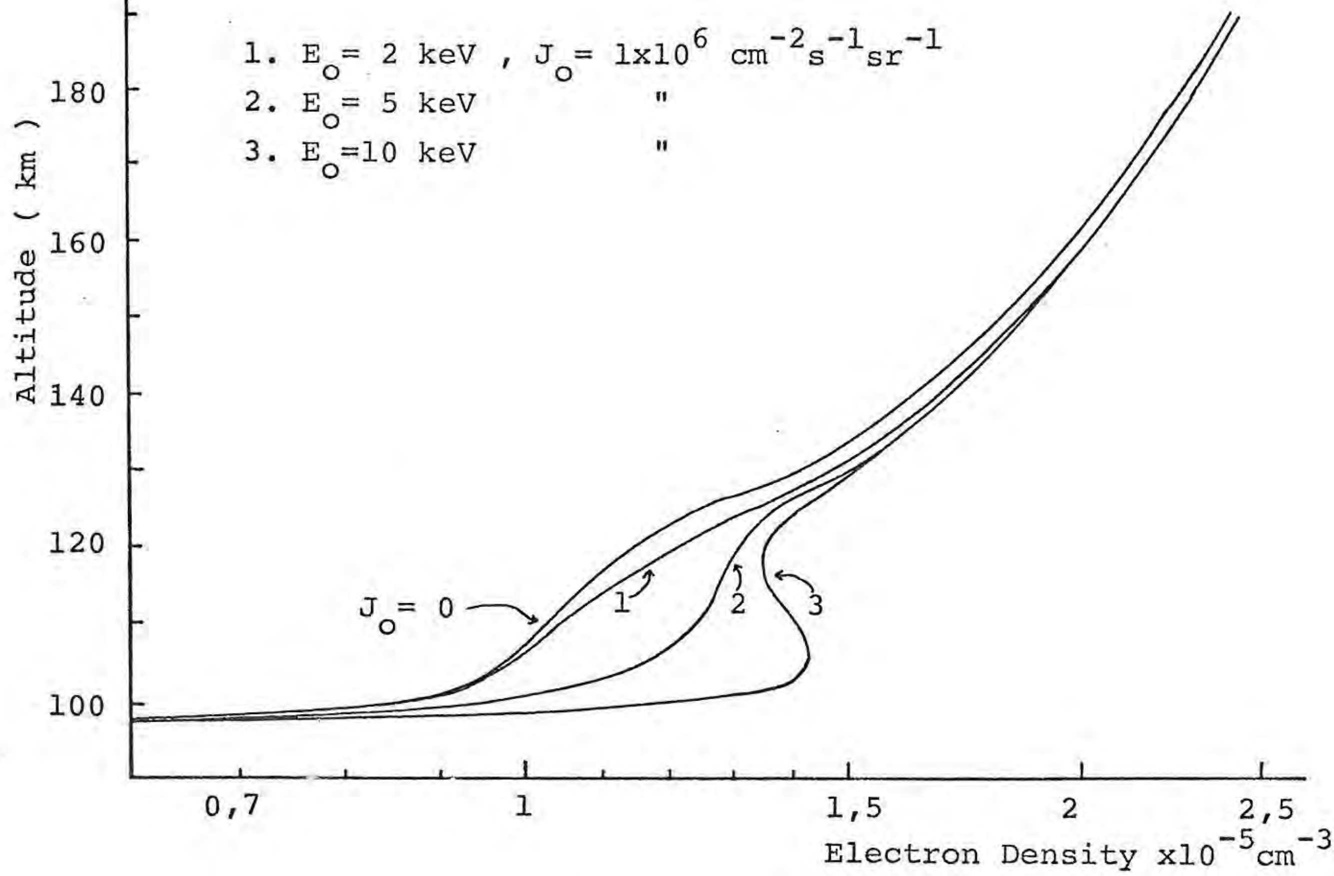


Fig. 2.3 Ionization density increases due to electron fluxes with E_o values 10 , 5 , 2 keV , $J_o = 1 \times 10^6\ cm^{-2}\ s^{-1}\ sr^{-1}$.

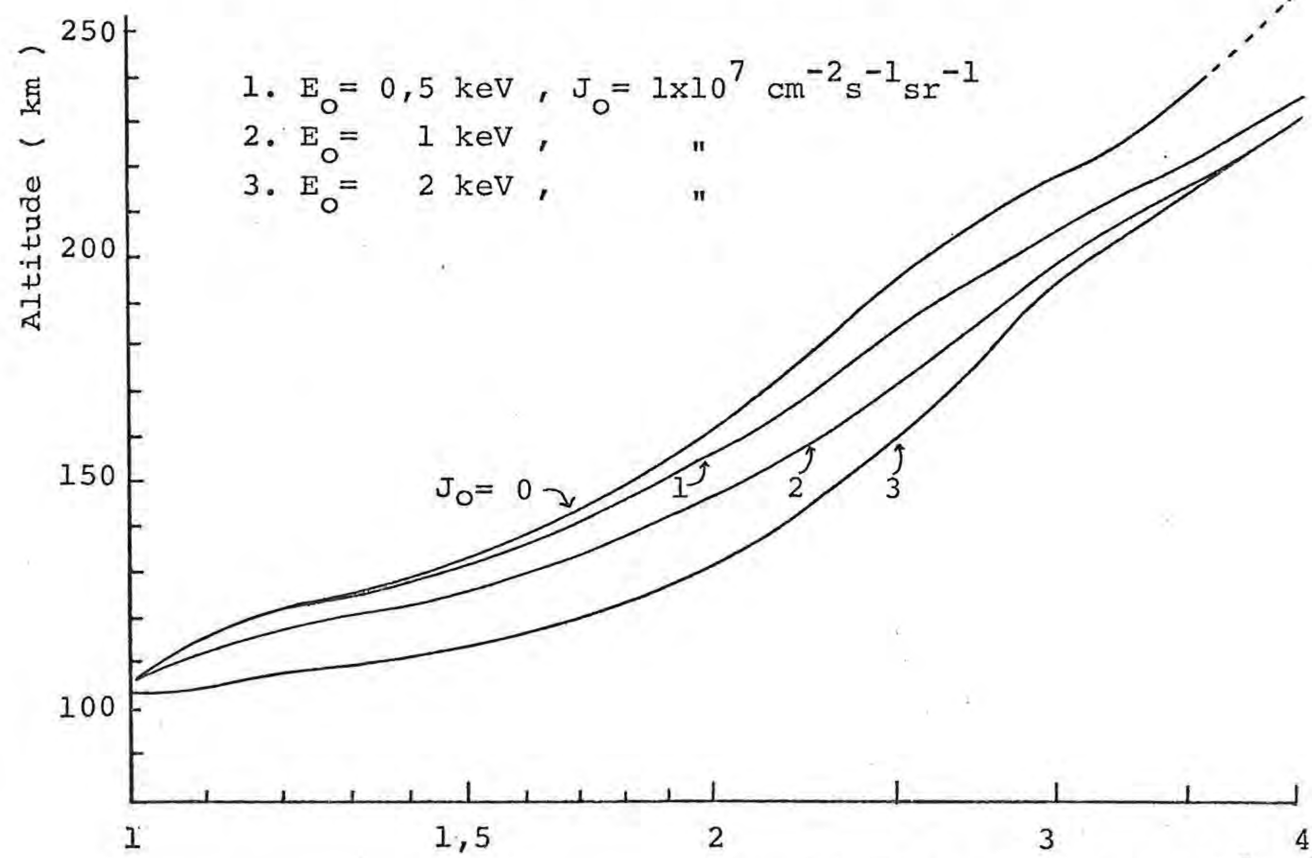


Fig. 2.4 Ionization density increases due to electron fluxes with E_o values 0,5 , 1 and 2keV , $J_o = 1 \times 10^7\ cm^{-2}\ s^{-1}\ sr^{-1}$.

of low energy electrons when the spectrum is extrapolated back to zero energy, it may be necessary to use double exponential spectra of electrons in order to explain the observed F-region disturbances as related to electron precipitation. Hultqvist (1964) has introduced separate exponential spectra to fit satellite observations in the energy range 1 - 40 keV, $E_o = 5,7$ keV, and for the range greater than 40 keV, $E_o = 41$ keV. Bailey et al (1970) have also deduced a double exponential spectrum to explain observed energy distributions of X-rays.

Thus this tends to confirm the suggestion made in the previous chapter that F-region ionizing effects are probably caused by high fluxes of low energy electrons accompanying the observed fluxes of J(>40·keV) electrons measured by Alouette I.

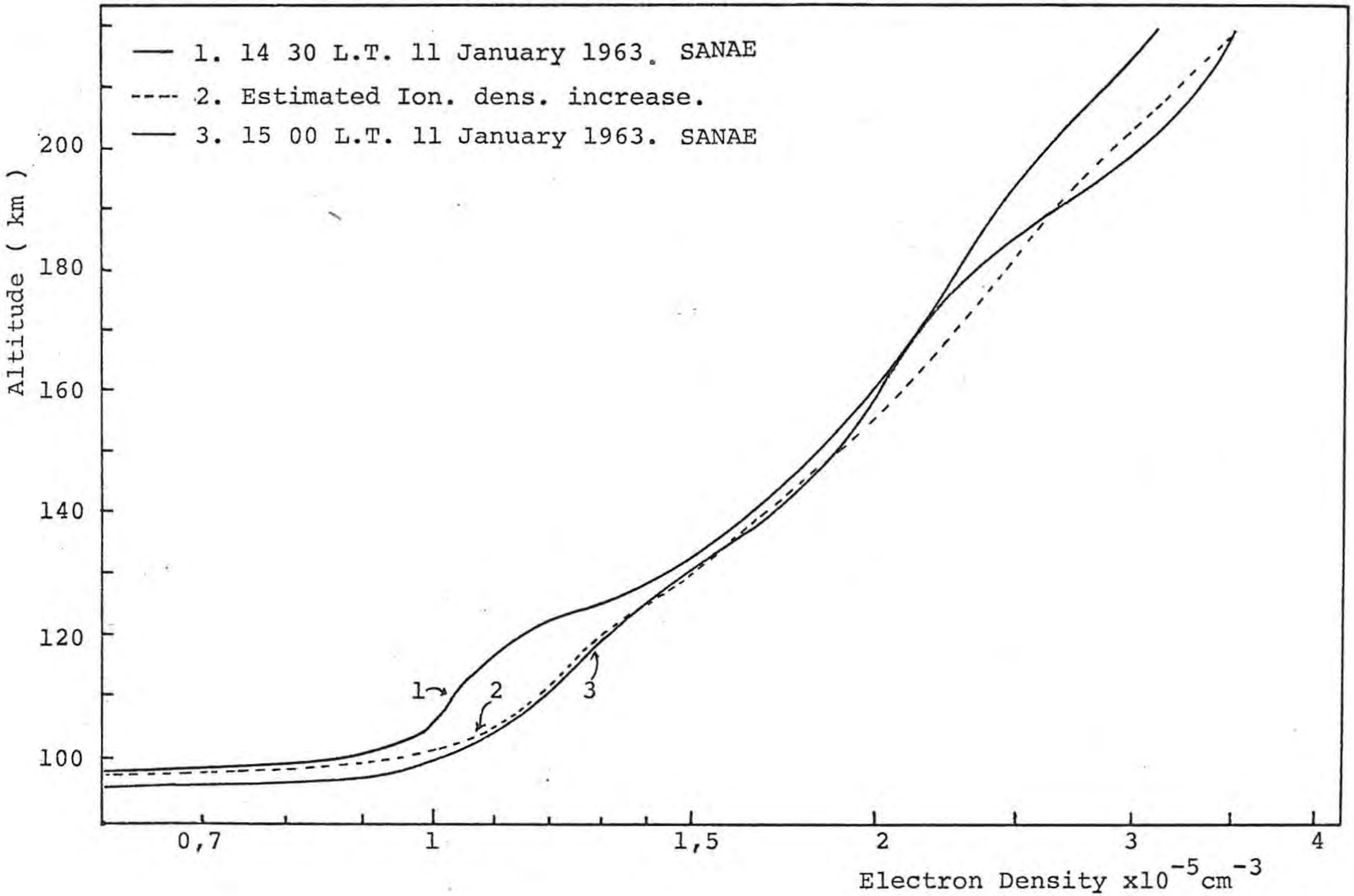
Finally, we will attempt to demonstrate that increases in the ionization density actually observed in the ionosphere could be explained in terms of double exponential spectra.

The N(h) profile at 15.00 hrs. L.T. showed distinct increases in the ionization density both at E- and F-region altitudes when compared to the N(h) profile selected above at 14.30 hrs. L.T. on the same day, 11 January 1963. From considerations of the solar production rate theory we may have expected the ionization density to decrease during this half-hour period due to the increase in the solar zenith angle.

If we now add the production rates which would be produced by the spectra of electrons

$$J(>E) = 1 \times 10^7 e^{-E/0,5} \quad \text{elec cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

$$J(>E) = 1 \times 10^6 e^{-E/4} \quad \text{elec cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$



1. 14 30 L.T. 11 January 1963. SANAE
2. Estimated Ion. dens. increase.
3. 15 00 L.T. 11 January 1963. SANAE
Altitude (km)
200
180
160
140
120
100
1
2
3
0,7
1
1,5
2
3
4
Electron Density x10^{-5}cm^{-3}

Fig. 2.5

to the solar production rate estimated from the 14.30 hrs. N(h) profile we will obtain the ionization distribution curve, as shown in fig. 2.5, which shows close agreement with the N(h) profile observed at 15.00 hrs.

These results may not be regarded as very reliable due to the unknown effect which the diffusion term may introduce above 250 km if included in the continuity equation, but once again they emphasize the fact that measurements of electrons with energies less than 10 keV are required if ionization increases at Sanae are to be explained.

2.5 Discussion and Conclusions

The increases in ionization which we may expect high fluxes of electrons typical of observations made by Alouette I to produce, are confined mainly to altitudes below 130 km and seem to display certain characteristics.

a) For total fluxes of electrons above 1,5 x 10^5 cm^{-2} s^{-1} sr^{-1} (and E_o = 50 keV), a valley in the ionization density profile seems to be formed above the height of maximum ionization production of these electrons. The depth of the valley is dependent on the level of the electron intensity.

An attempt was made to investigate whether valleys were present above the E-layer on occasions where high fluxes of electrons were observed by Alouette I. Use was made of an ionogram to N(h) profile reduction program developed by Dr. M.H. Williams, of the Computer Science Department, Rhodes University, in order to test for the presence of valleys.

Sanae ionograms were found to be unsuitable for this purpose as on most occasions where high fluxes were experienced the disturbed nature of the trace as well as the absence of a clear extraordinary ray reflection made this sort of analysis virtually impossible. Little more success was obtained by using the better quality ionograms for the Argentine Islands due to the limited accuracy to which the trace could be scaled in the close vicinity of the E-critical frequency. It seems that this aspect may only be investigated further once better techniques for detecting valleys from actual ionograms are developed or improved height and frequency resolution obtained in ionospheric soundings. Improved height resolution may be attained by means of the phase ionosonde.

b) A highly significant increase in the peak electron density of the E-layer is also observed to be produced by high intensities of these measured electron fluxes. This increase in the ionization density in the E-region could be accompanied by an increase in the critical frequency of the E-layer and/or the production of a fairly thick (on the average of about 10 km (fig. 2.1)) sporadic E-layer. This sporadic E-layer would probably exhibit retardation and/or blanketing properties and may be particularly observable at night when the ionization density of the normal E-layer is very low in comparison to the daytime level. Bailey (1968) has suggested an association between electron precipitation and retarded E_s (or night E).

An investigation of the occurrence of sporadic E-layers for the months of April and May, 1963 was undertaken for Sanae on all the occasions when relatively high fluxes of electrons were measured by Alouette I during the night hours. Typically for this period, the critical frequency of the F-layer was found to decrease below f_{min} at around 21.00 hrs. L.T. and reappear the next morning at about 6.00 hrs. L.T. For most occasions where high fluxes of electrons were recorded during this blackout period, either sporadic E-layers or the complete reappearance of the F- and E-layers were observed. Unfortunately insufficient data was available for this period to allow a statistical analysis to be undertaken.

The possible increase in f_oE due to the ionization effects of the electrons will be discussed in a later chapter.

c) From Fig. 2.1 we may deduce that the observed fluxes of electrons may be expected to produce a high ionization density below 98 km. The harder the spectrum (i.e. the greater E_o), for a constant flux, the greater the low lying ionization density which would be produced.

This low lying ionization may have two observable effects.

(i) Absorption of the low frequency radio waves reflected from the E-layer which would be evidenced by an increase in f_{min}. This aspect will be investigated later.

(ii) A possible increase in the virtual height of the E-layer due to the retardation of the radio wave in in this low lying ionization. This would probably be indicated by retardation of the lower end of the E-layer reflection. This aspect is also investigated further later.

Thus even although the measurements made by Alouette I are in the wrong energy range to cause observable effects in the upper ionosphere, we now have good reason to expect that the ionizing effects of these electrons should be observable in the altitude range below 130 km. It is intended in the next few chapters to investigate the reality of this statement.

By way of summary, it may be mentioned, that we have shown in this section, that F-region ionization effects are probably due to high fluxes, $> 10^7$ elec $cm^{-2}\ s^{-1}\ sr^{-1}$, of electrons with energies ≤ 2 keV precipitating into the upper atmosphere. High fluxes of electrons with energies greater than 2 keV may also be responsible for F-region effects but would produce accompanying large ionization increases in the E-region.

We have also shown that short term ionization density increases in the ionosphere may be explained in terms of two different energy spectra of electrons with E_o values of 0,5 and 4 keV respectively. Choy et al (1971) have observed a spectrum of electrons in the auroral regions to which we have fitted separate exponential spectra for the energy ranges 0,5 to 2 keV and 2 keV to 10 keV. The corresponding values of E_o for the two spectra are 0,65 and 2,5 keV respectively for the two energy ranges.

A spectrum measured by Hoffman (1969) at about $70\frac{1}{2}^{\circ}$ invariant latitude gives values for E_o of 1,1 and 5 keV for the energy ranges 0,8 to 3 keV and 3 to 10 keV respectively, for what he calls the quiet band of precipitation and values of 0,35 and roughly 5 keV for data where bursts of 0,7 keV electrons were present.

Thus we may propose that the spectra used to explain the observed ionization increases are not unreasonable when compared to high latitude measurements, although there is no reason to believe that energy spectra observed at auroral latitudes bear any resemblance to spectra at lower latitudes.

CHAPTER 3: Electron Effects in the D-region

The computations in the previous chapter have revealed the possibility of relatively high densities of low lying ionization being produced by high fluxes of electrons typical of measurements made by Alouette I. In this section we will investigate whether any evidence for this correlation between low lying ionization and electron fluxes may exist in the data for the Argentine Islands and Sanae.

3.1 Introduction

Variations in the ionization density of the D-region have been studied by means of various techniques such as reflections from low frequency radio waves, absorption measurements at various frequencies and partial reflections from pulsed 2-3 MHz signals.

Anomalous enhancements of the D-region ionization such as the 'winter anomaly' and enhancements roughly 1 000 km in extent found by Thomas (1962), have been associated with 'stratospheric warmings' and magnetic activity. Workers have tended to regard these anomalies as mainly meteorological in origin. However Lauter and Knuth (1967) and Maehlum (1967) have suggested direct bombardment by high energy electrons as a possible explanation of the enhancements and Tulinov (1967), and Tulinov and Yakovlev (1969) have demonstrated the possible importance of corpuscular radiation in the formation of the lower ionosphere even at middle latitudes. Measurements of electron intensities made by satellites have been related to auroral absorption. McDiarmid et al (1963) have used results from Alouette I to show that there is a statistical agreement between the frequency of occurrence of precipitated electrons and the percentage time of auroral radio absorption. Maehlum and O'Brien (1963) using Injun I data have studied the relation between trapped electrons and auroral absorption and Jelly et al (1964) using particle detectors on Alouette I and on rockets, have shown that the average relationship between the intensity of precipitated electrons and the amount of absorption is in approximate agreement with that expected from theory. Parthasarathy et al (1966) have made similar deductions to Jelly et al using Injun 3 data.

The ionospheric parameter, f_{min}, the minimum frequency for which echoes are observed on ionograms, has been shown by Piggott et al (1957) to demonstrate a reasonable correlation with measurements at Slough of absorption on a 2,0 MHz signal. However they point out that the sensitivity of f_{min} to absorption changes is dependent on the receiver gain and noise level at the time of observation. Assuming changes in these two factors to be relatively small over the period of a month, we could use f_{min} as an indicator of relatively large absorption changes which may occur during this period.

The ionosonde at Sanae, a Cossor portable recorder having a peak power output of roughly 1 kW, gives records which seem to exhibit a high variability of f_{min} over short time intervals with complete 'blackouts' occurring on a relatively large number of occasions. This would seem to indicate that f_{min} for Sanae ionograms should be fairly sensitive to absorption changes and thus suitable as an approximate measure of the relative ionization density in this lower region.

On the other hand, f_{min} for the Argentine Islands records does not display such a high degree of variability and rare occurrences of 'blackouts' are recorded. Thus we may expect that here only relatively large increases in the ionization density will be reflected in noticeable changes in f_{min}.

The present study has been undertaken in order to determine whether any association may be observable between the occurrences of high fluxes of electrons measured by Alouette I and absorption in the D-region as shown by increases in f_{min}. The f_{min} values for the three months of November, December 1962 and January 1963 for the two stations were compared to the flux readings by means of 2 x 2 contingency tables.

3.2 The Analysis

The satellite flux data used in this analysis is identical to that described in chapter 1 for the correlation studies of f_oF_2 and $h'F_2$ and will not be discussed here.

In order to effect the comparison between flux and f_{min} data, the electron flux for each pass was categorized as either 'high' or 'low' depending on whether the maximum value for the pass lay above or below a certain critical flux whose value was adjusted arbitrarily to give roughly the best correlation between the two variables.

f_{min} was classified as 'high' for a particular flux measurement, if its value on at least one occasion within an hour before or after the flux observation was found to lie above the hourly median value for the month being considered. f_{min} was regarded as 'low' if its value did not exceed the monthly median during the two hour period. The method described in chapter 1 for deciding on a 'disturbance' criterion for the parameters f_oF_2 and $h'F_2$ was not used here as it was found that plots of f_{min} for the magnetically quiet days of the month showed a high degree of variability which made the setting up of a purely objective criterion difficult.

Contingency tables with estimates of χ^2 and the association coefficient r were constructed for both Sanae and the Argentine Islands f_{min} values.

3.3 The Results

3.31 Sanae

Quarter hourly f_{min} values scaled from the ionograms were available for Sanae. Initially the flux classifications as used for the correlation analysis in chapter 1 were adopted here. However, the correlation of flux with f_{min} was found to improve if the critical flux value was decreased from 4×10^5 cm^{-2} s^{-1} sr^{-1} to 7×10^4 cm^{-2} s^{-1} sr^{-1} for the Falkland Islands data and from $4,8 \times 10^4$ and 1×10^4 cm^{-2} s^{-1} sr^{-1} to 7×10^3 cm^{-2} s^{-1} sr^{-1} for the St. Johns data. The results are presented in table 3.1a and 3.1b where H and L refer to 'High' and 'Low' respectively.

TABLE 3.1

SANAE Correlation of f_{min}

FALKLAND ISLANDS DATA

f_{min}	FLUX H	FLUX L
H	42	15
L	8	20

N = 85

$\chi^2 = 15,8$; $P < 10^{-4}$

r = 0,43

(a)

ST. JOHNS DATA

f_{min}	FLUX H	FLUX L
H	44	17
L	3	19

N = 83

$\chi^2 = 22,5$; $P < 10^{-5}$

r = 0,52

(b)

Both tables 3.1a and 3.1b reveal a significant correlation between f_{min} at Sanae and the electron flux measurements made in the Falkland Islands and St.Johns telemetry receiving areas. Table 3.1b for the St. Johns data seems to show a slightly better correlation (r = 0,52) to that for the Falkland Islands data in table 3.1a (r = 0,43). This small difference in the value of these coefficients is surprising when compared to the F-region correlations described in chapter 1, where the correlations for the Falkland Islands data (r = 0,60 for f_oF_2 and 0,54 for $h'F_2$) far exceeded those for the St. Johns data (r = 0,31 - f_oF_2 and r = 0,39 - $h'F_2$). This would imply that Falkland Islands flux measurements show a better correlation with F-region disturbances than they do with D-region effects whereas the St. Johns data show a higher degree of association with effects in the lower ionosphere. No reasonable explanation for this phenomenon is immediately obvious. However, the answer may be linked in some way to a decrease in the intensity of the high energy component of the electron flux measured in the Falkland Islands area, as the electrons drift along the L = 4 shell, with a possible corresponding increase in the proposed accompanying lower energy flux.

On the other hand this difference may arise purely by chance from the relatively small sample of data used in the analysis. An extension of this analysis for more data would help to ascertain the reality of this effect.

The improved correlation (r = 0,52) of St. Johns data with f_{min} effects as compared with that for F-region disturbances (r = 0,31; 0,39) is in accordance with what may be expected, as the flux measurements made by Alouette I are in the right energy range to cause D-region ionization increases. Lower energy electrons ($E \leq 2$ keV) are required in order to produce observable F-region effects.(see chapter 2).

3.32 The Argentine Islands

Hourly values only for f_{min} were available from bulletins for the Argentine Islands. The values of the critical flux used to delineate 'high' from 'low' fluxes were not altered from those used in the f_oF_2 and $h'F_2$ correlation study. Decreasing these critical values was not found to improve the correlation significantly. For November 1962 the value used is $4,8 \times 10^5$ cm^{-2} s^{-1} sr^{-1} and for December 1962 and January 1963 a critical value of 5×10^4 cm^{-2} s^{-1} sr^{-1} was adopted.

TABLE 3.2

Argentine Islands f_{min} - Falkland Islands

Flux Data Correlation L = 2,26 - 2,63

(a) $275^o - 330^o$ E

f_{min} \ FLUX	H	L
H	46	45
L	18	52

N = 161

$\chi^2 = 10,2$; $P \leq 0,0014$

r = 0,25

(a)

(b) $289^o - 300^o$ E

f_{min} \ FLUX	H	L
H	16	11
L	7	20

N = 54

$\chi^2 = 6,1$; $P \lessgtr 0,014$

r = 0,34

(b)

The results of the analysis are shown in table 3.2a and seem to indicate a rather low degree of association (r = 0,25) between the flux and f_{min} values for this station. Decreasing the longitude range over which flux measurements were made to a roughly 10^o interval centered on the longitude coordinate for the Argentine Islands, was found to improve the correlation slightly as shown in table 3.2b (r = 0,34). This degree of association is still less than the values of the coefficients observed for Sanae f_{min} data (r = 0,43 ; 0,52). Possible reasons for this will be discussed later.

Encouraged by the correlations observed for Sanae, table 3.1a and b, a more detailed investigation of the events characterised by high fluxes and high values of f_{min} and a comparison of the effect of electron fluxes on f_{min} to theoretical predictions was thought worthwhile. The absorption produced by precipitating electrons measured by Alouette I may be estimated theoretically from a knowledge of the flux and spectrum of these electrons. However in order to relate f_{min} values to the absorption in the lower ionosphere, it is necessary to have concurrent riomèter observations which unfortunately were not available for Sanae for this period.

To be able to study the approximate nature of the disturbances in f_{min} which are caused by high fluxes of electrons, a number of graphs of the f_{min} variation for Sanae were plotted for days where both high and low fluxes were experienced. Typical examples of these graphs are shown in figs. 3.1 and 3.2. The electron intensities have been normalised to the average flux value for the three month period (November, December 1962 and January 1963) in order to be able to compare the magnitudes of the flux readings taken in the St. Johns area with those for the Falkland Islands. These plots seem to indicate that where relatively high fluxes are measured, we may generally expect large 'disturbances' in f_{min} to occur with 'blackouts' being present on most occasions. Similarly, low flux values tend to be accompanied by a relatively 'quiet' f_{min} variation. However the flux data is too sparse to show whether a detailed correlation of flux with the f_{min} variation may be present.

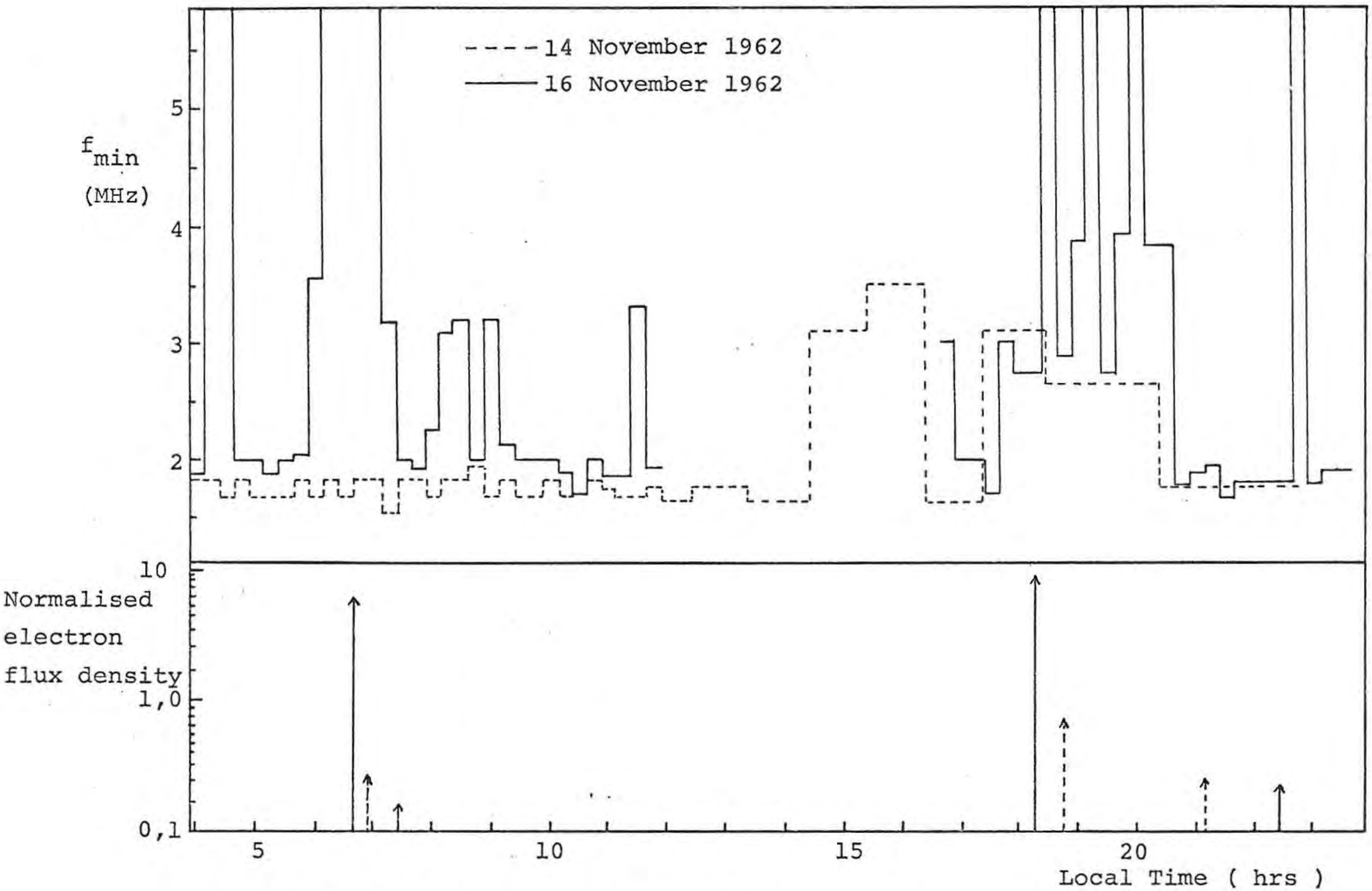


Fig. 3.1 Variation of electron flux density and f_{min} at SANAE with local time .

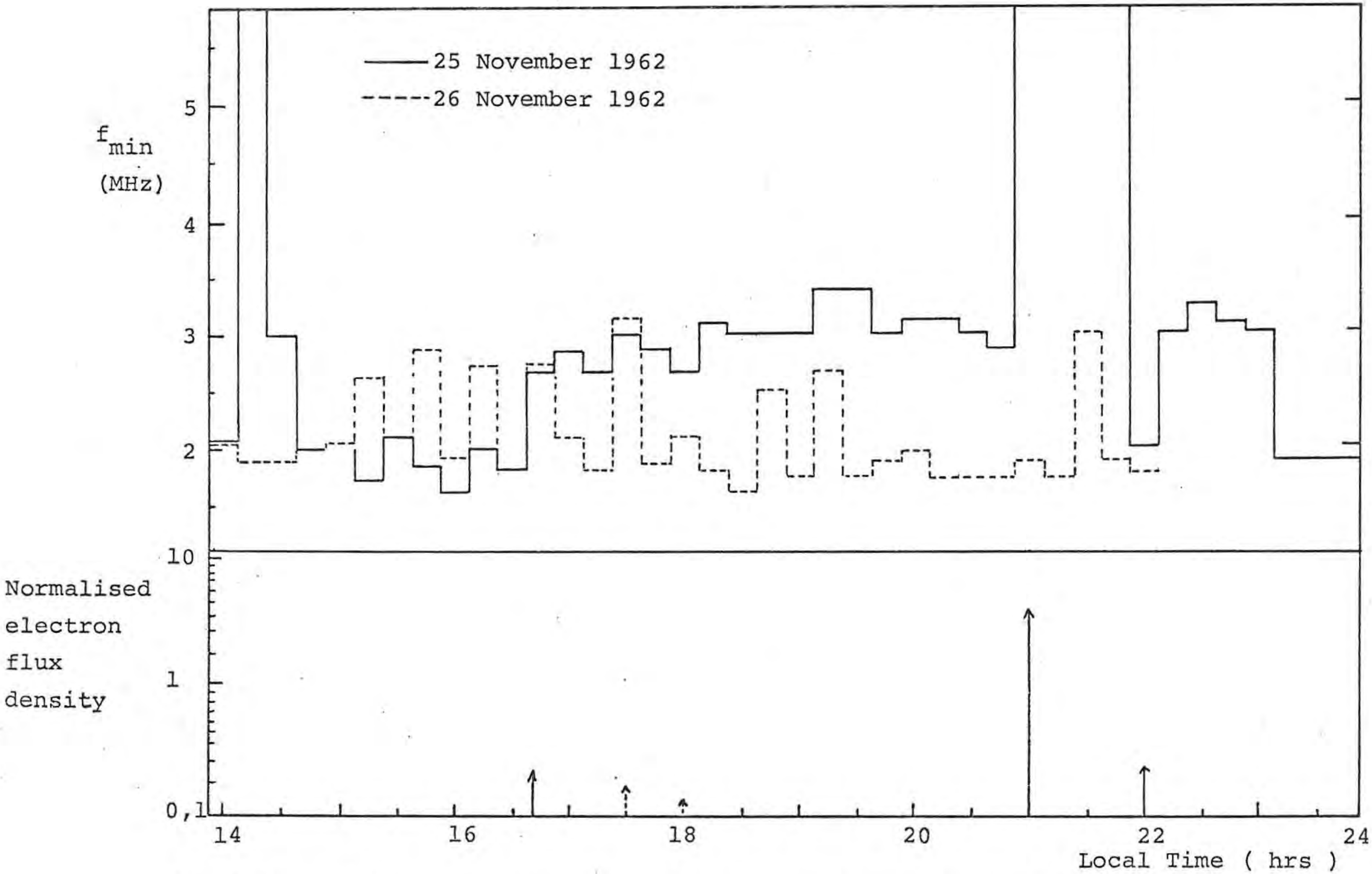


Fig. 3.2 Variation of the electron flux density and f_{min} at SANAE with local time .

3.4 Discussion and Conclusions

The correlation studies in this section have shown that there is a significant positive degree of association between the f_{min} values measured at Sanae and flux readings taken in both the Falkland Islands and St. Johns telemetry receiving areas in the range $3,75 \leq L \leq 4,25$. Thus we may conclude, in agreement with the theoretical prediction made in chapter 2, that high fluxes of electrons measured by Alouette I could be responsible for observable ionization increases in the D-region of the ionosphere at Sanae. This result serves to indicate that the correlations between absorption and precipitating electrons observed at auroral latitudes may also be present at lower latitudes. Gledhill and Torr (1966) have also shown a correspondence between high fluxes measured in the St. Johns area and disturbances in f_{min} at Sanae.

The analysis of the Argentine Islands' records, table 3.2a, displays a comparatively low degree of association for the two variables. Reducing the longitude range of the satellite measurements improves the correlation slightly but leaves the value of the association coefficient well below that observed for the Sanae data.

Two possible reasons for this poor correlation for the Argentine Islands data as compared to that for Sanae are suggested.

a) The relative insensitivity, suggested above, of f_{min} for the Argentine Islands to absorption changes could result in some reduction of the association coefficient. However we may expect that an increase in the critical flux value used should cancel this effect to a certain extent. This was not found to be the case, as altering the value of the critical flux made very little difference to the observed correlation.

b) Absorption effects other than that due to electron fluxes may play a more predominant part in causing increases in f_{min} at the Argentine Islands, whereas at Sanae precipitating electrons may cause the main effect. This could imply, as mentioned in chapter 1, that we may expect overall higher fluxes to occur at Sanae as compared to the Argentine Islands. This occurrence has been observed for the conjugate points to the two stations, where the median flux conjugate to Sanae is found, using Alouette I data, to be roughly four times as high as that observed for the Argentine Islands (J.G. Greener private communication).

Absorption in the D-region has been associated with 'non-corpuscular' phenomena such as the stratospheric temperature and also 'stratospheric-warmings' which are located at roughly 30 km. Williams et al (1972) have shown a correlation between f_{min} values observed over North America and the passage of a deep planetary wave in the stratosphere.

Thus by way of summary we may propose that the predominating effects of ionospheric - stratospheric coupling over that of electron flux densities at the Argentine Islands may have resulted in the poor correlation observed between the flux and f_{min} values for this station. Relatively high fluxes at Sanae have been suggested as an explanation of the probably greater importance of electron effects there.

The use of hourly values of f_{min} for the Argentine Islands as compared to $\frac{1}{4}$ hourly values for Sanae may also contribute an effect to the difference in the correlation observed for the two station.

The greater sensitivity of f_{min} at Sanae to absorption changes, as compared to the Argentine Islands, is indicated in a very crude way by the improved correlation observed for the f_{min} values at Sanae on the reduction of the critical flux value, used for the Falkland Islands and St. Johns data, from those which provided the best correlation of the F-region parameters with flux, whereas little improvement in the correlation for f_{min} values for the Argentine Islands was obtained if the critical flux was reduced from the values adopted for the F-region correlations.

This reduction in the critical flux values used for the Sanae f_{min} correlation would tend to imply that a greater flux is necessary to produce an observable disturbance in either $h'F_2$ or f_oF_2 than will produce an observable disturbance in f_{min}.

The analysis has indicated a better correlation of St. Johns flux data with f_{min} values at Sanae in comparison to the correlations with f_oF_2 and $h'F_2$. On the other hand, the Falkland Islands data display a slight reduction in the level of association with f_{min} in relation to that observed for the F-region parameters. If these differences may be regarded as significant an enhancement of the low energy component of the electron intensity and corresponding reduction of the flux density at higher energies, as the electrons drift towards Sanae from the Falkland Islands area, has been proposed as a hint at a possible explanation.

The graphs of f_{min} for certain days in November 1962 at Sanae have shown the type of disturbance in f_{min} which may accompany high fluxes of electrons. Blackouts are found to occur on most occasions where high fluxes are measured.

Thus the results in this section have revealed some more evidence for the effect of precipitating electrons on the ionosphere at Sanae.

CHAPTER 4: Electron Effects in the E-region

Computations in chapter 2 have shown that we may expect observable ionization increases in the E-region to be caused by high fluxes of electrons typical of those measured by Alouette I. The possibility of a relation between fluxes and the maximum ionization density of the E-layer is investigated in this section.

4.1 Introduction

The behaviour of the normal E-layer has been found to be directly related to the ionizing radiation of solar origin. The diurnal and seasonal variation of the critical frequency of the layer is closely controlled by the zenith angle of the sun and may be represented by the expression (Belrose, 1965)

$$f_oE = k(\cos \chi)^n \qquad 4.1$$

where χ is the solar zenith angle

n is a constant = 0,25 for an ideal Chapman layer

k is a constant = critical frequency when the sun is directly overhead.

f_oE is also related to effects such as the sunspot number and the sun to earth radial distance (Muggleton, 1971). It is well correlated with variations in the intensity of the 10 cm solar flux.

E-layer characteristics have also been associated with magnetic activity. Sato (1957) and Brown and Wynne (1967) have found that f_oE is reduced by a few percent during magnetic storms. The virtual height h'E shows only slight changes of about a $\frac{1}{2}$ km from the usual behaviour. Wakai (1967) has studied the electron density profiles of the nighttime E-region for times of quiet, moderate and severe geomagnetic activity.

An 'intermediate' layer is found to develop above the normal nighttime E-layer during strong disturbances. This 'intermediate' layer is suggested as carrying the electric current in the ionosphere due to the SD field. Particle precipitation is proposed as a source for the nighttime E-layer for geomagnetic latitudes greater than about 52° to 57° N or S.

Both the Argentine Islands and Sanae are situated at geomagnetic latitudes greater than 52° and it is our aim in this chapter to present evidence for precipitating electrons having a noticeable influence on the behaviour of the critical frequency of the normal E-layer at these two stations.

From the calculations performed in chapter 2, we may expect the increase in the ionization density at 100 km produced by a high flux of electrons $J_o = 1 \times 10^6$ cm^{-2} s^{-1} sr^{-1} to result in a rise of approximately 0,8 MHz in the value of f_oE. However the magnitude of the effect of precipitating electrons on f_oE is largely dependent on the altitude of the existing E-layer. At 120 km, we may only expect an increase in f_oE of roughly 0,3 MHz to accompany the same flux mentioned above. Thus without a knowledge of the height distributions of the ionization density, it is not possible to predict the magnitude of the disturbance in f_oE which may be caused by a given flux. However, we may suggest from the computations in chapter 2 that discernible effects on f_oE should be present when high fluxes occur.

4.2 Analysis for Sanae

Initially an attempt was made to try and establish the diurnal variation of f_oE which occurs for conditions corresponding to quiet magnetic activity and low fluxes of electrons. Thereafter it was hoped to compare the behaviour of f_oE at times where high fluxes are experienced to these quiet conditions and relate any differences which may be observed to theoretical calculations of the possible effect of these high fluxes.

Graphs of quarter hourly values of f_oE vs local time were plotted for six magnetically quiet days in January 1963 where low fluxes were measured by Alouette I. The parameters k and n in equation 4.1 were determined for each of these days by means of a regression analysis of plots of log f_oE versus log cos χ where cos χ is given by the expression (Wright et al, 1957).

$$\cos\chi = \sin\lambda\ \sin\alpha + \cos\lambda\ \cos\alpha\ \cos(\pi - \pi C/12) \qquad 4.2$$

where χ = solar zenith angle as above.

λ = geographic latitude.

α = solar declination.

C = local time in hours.

Given cos χ for a particular time and day and estimates of the parameters n and k typical of the quiet day variation, we may determine from equation 4.1 that value of f_oE which would result when the ionizing effects of electrons may be regarded as small. The value of f_oE which accompanies high fluxes of electrons may be compared to the calculated value and the difference related to the magnitude of the flux.

The values of n and k for four of the six days analysed are given in table 4.1

TABLE 4.1

Date	n	k
10 Jan.1963	0,21 ± 0,02	3,01 ± 0,06 MHz
3 Jan.1963	0,34 ± 0,01	3,31 ± 0,03 MHz
8 Jan.1963	0,32 ± 0,01	3,31 ± 0,05 MHz
26 Jan.1963	0,3 ± 0,1	3,23 ± 0,04 MHz

Values for n and k estimated for four magnetically quiet days at Sanae.

Except for January 10th the values of k do not vary significantly. The variation of n for the three days 3rd, 8th and 26th of January would give rise to variation in f_oE of less than 0,05 MHz. This is within the limits of accuracy to which f_oE may be scaled for Sanae ionograms. However at this stage this analysis was thwarted by the difficulty of finding suitable events at Sanae, corresponding to high fluxes, for which the critical frequency could be scaled to sufficient accuracy to allow a comparison with the value calculated using the 'quiet' day parameters. Absorption around the critical frequency rarely allowed f_oE to be estimated to within ± 0,1 MHz.

In view of this our attention was turned to the records which were available for the Argentine Islands. These ionograms allowed an estimate of f_oE to within ± 0,01 MHz and thus we may expect that changes in the ionization density in the E-region, which may be produced by high fluxes, should result in noticeable changes in f_oE for this station. An analysis for the

Argentine Islands has the added advantage that flux readings for this station were recorded on a larger number of passes (roughly 2-4 per day) than were registered within the L-coordinate range for Sanae at the Falkland Islands telemetry station.

4.3 Analysis for the Argentine Islands

A different approach to that used for Sanae was followed in this analysis for the Argentine Islands.

Plots of the variation of f_oE values, scaled from hourly ionograms, were made for the entire period from the 1st to the 18th November, 1962. This particular period was chosen as the flux measurements showed a relatively high level of fluctuation, which it was hoped would result in more easily discernible changes in f_oE. Records for the Argentine Islands were not available from the 19th to 26th November 1962 and nuclear explosions prior to the 1st November caused Alouette I flux measurements to be unreliable because of the high level of background radiation.

The variation of f_oE during this period was now examined carefully at times where fluxes of electrons were recorded in the L-parameter range $2,26 \leq L \leq 2,63$. Encouraging evidence of 'disturbances' in the E-region were noticed on a number of occasions where high fluxes were registered.

These disturbances were distinguished by:

a) A small digression of the critical frequency from its normal diurnal variation.

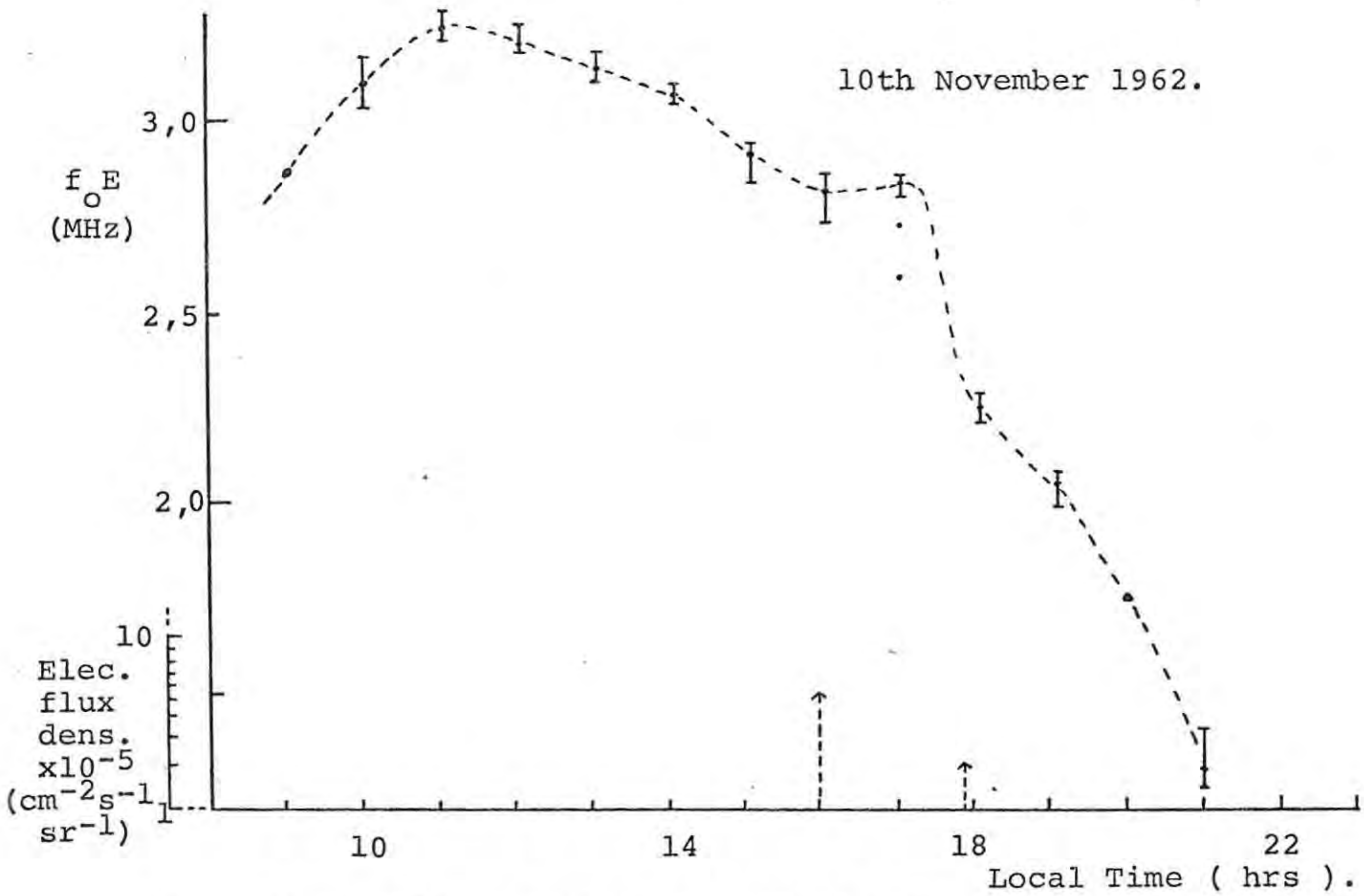


Fig. 4.1 Variation of f_oE with local time at the Argentine Islands showing a correspondence between an increase in f_oE and a high flux reading.

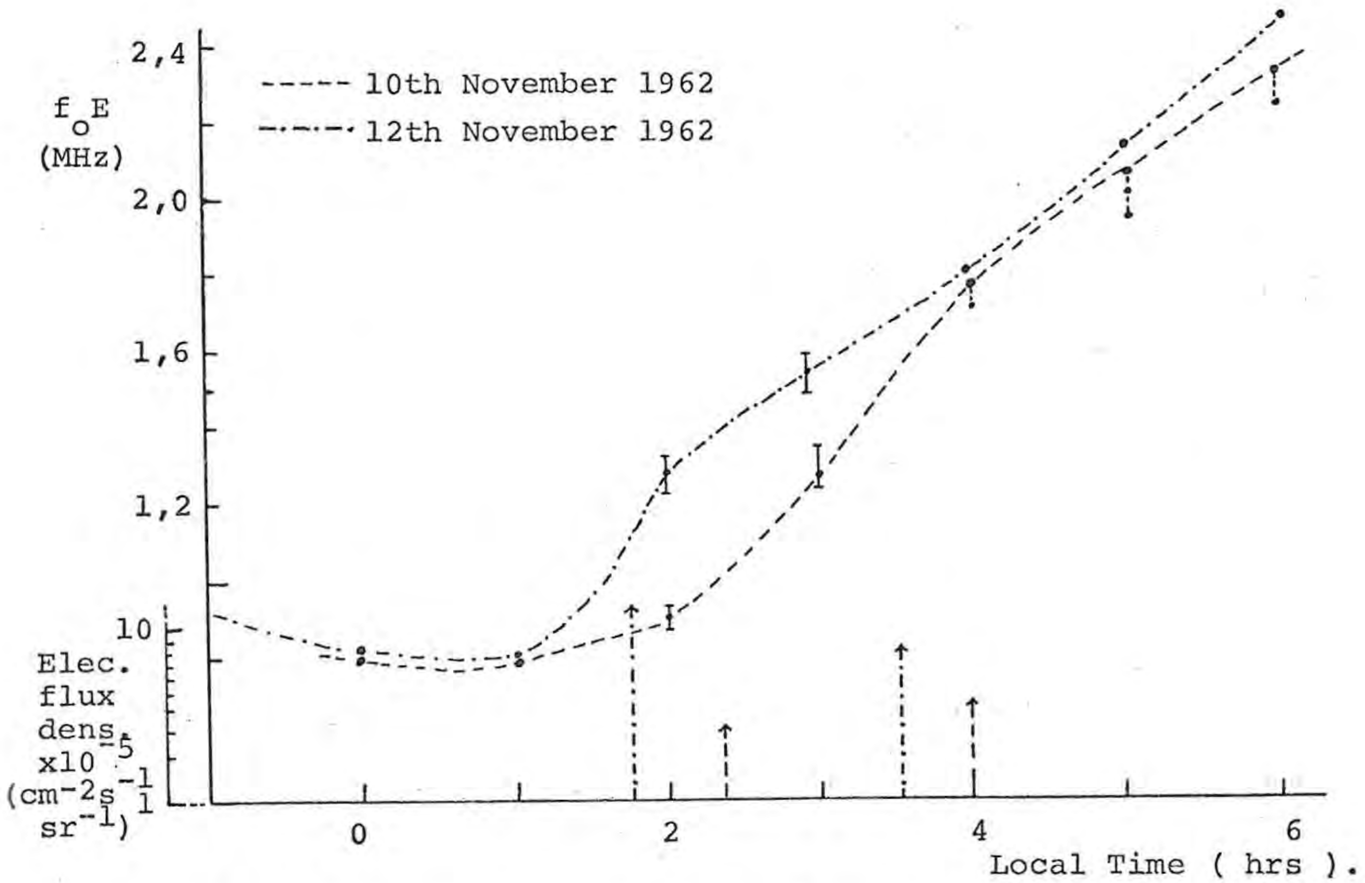


Fig. 4.2 Variation of f_oE at the Argentine Islands with local time for two days corresponding to high and low fluxes.

b) The presence of a blanketing sporadic E-layer usually causing multiple reflections of the sounding pulse.

c) The appearance of extra cusps in the trace close to the critical frequency.

The quantity f_{min} was found to be abnormally high on two occasions while a broadened and sporadic trace accompanied an extremely high flux reading on another occasion.

An example of a sharp increase in f_oE corresponding to a high flux of electrons is shown in fig. 4.1. A comparison of the behaviour of f_oE, at a time where a high flux was measured, to its behaviour at the same local time, but for an occasion where a relatively low flux was recorded, reveals a significantly higher value for f_oE corresponding to the high flux reading. A typical example of this is shown in fig. 4.2 for the two days 10th and 12th November.

If for the moment we may neglect the effect on f_oE which may result from the change in the solar zenith angle at a particular local time between the 1st and 18th November, we may compare the variation of f_oE during this period, at a fixed time, to the variation of the electron flux. A plot of f_oE values at 0300 L.T. for each of the days 1st - 18th November is shown in fig. 4.3 together with the level of the flux recorded between about 0200 and 0400 L.T. Flux values within this time interval were not available for all the days during this period. Nevertheless fig. 4.3 shows an encouraging correspondence between high fluxes and high values of f_oE. This would tend to suggest that a relation may exist between the flux and the critical frequency and a further investigation may prove useful.

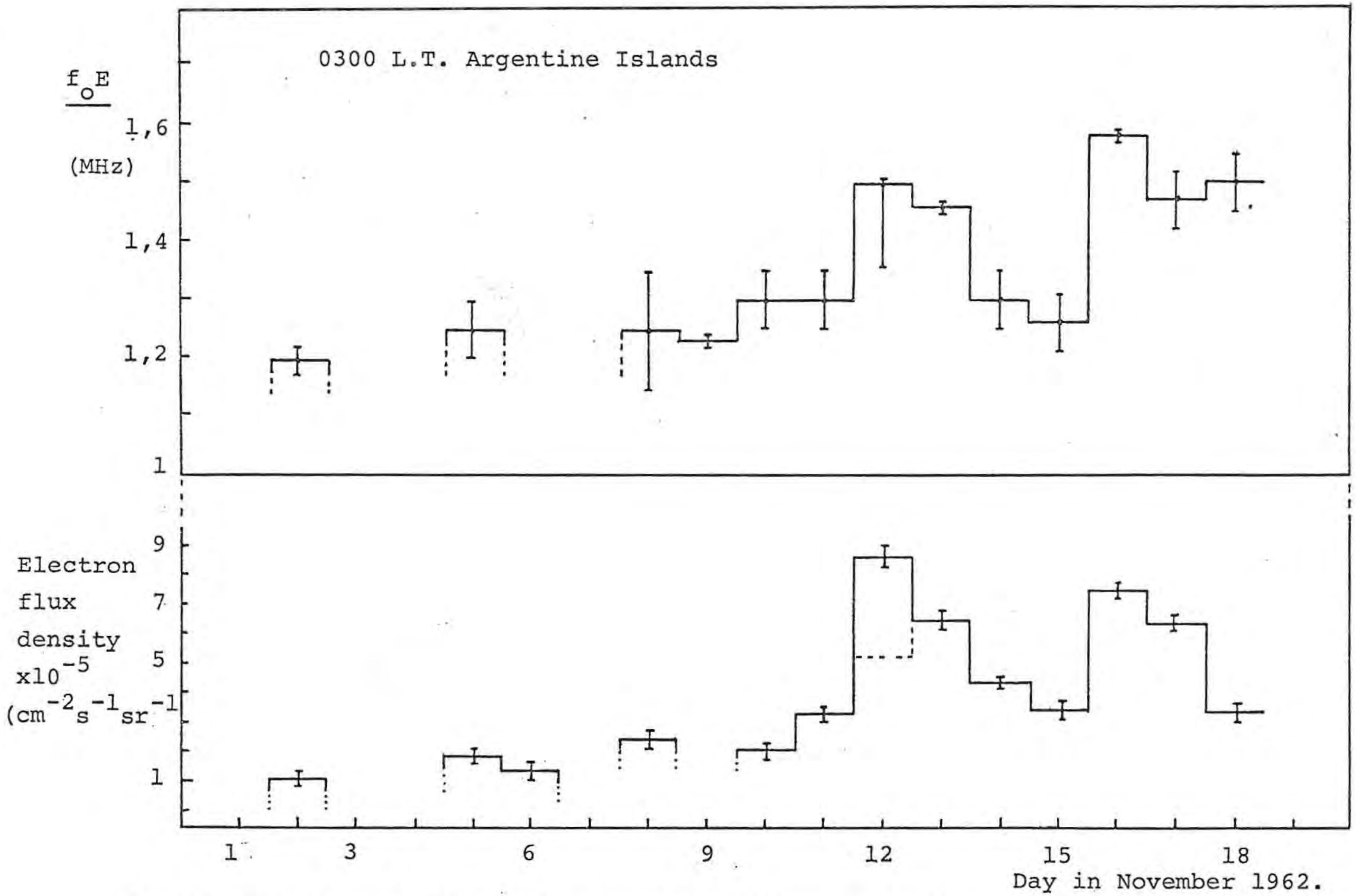


Fig.4.3 Variation of f_oE at the Argentine Islands and electron flux at a fixed local time.

4.31 Correlation of f_oE with flux

In order to investigate more fully the possible relation between f_oE and flux, plots were made of f_oE values at a fixed local time against the values of the average flux per pass which were measured by Alouette I roughly within the period of $1\frac{1}{2}$ hours before or after the time at which the record of f_oE as taken. These 'scatter' diagrams for the local times 0200, 0300, 0400, 0500, 1700, 1800, 1900 and 2000 L.T. are shown in fig. 4.4 for the period 1st to 18th November 1962. For occasions where double or triple cusps were encountered their values were plotted in the graphs shown except when they showed a large disagreement with the value of f_oE at the same time on other days. If the cusp showed no obvious diurnal variation it was disregarded completely. Where double cusps are plotted, their points have been lightly circled. For the sake of convenience the errors in the f_oE values have not been indicated in the diagrams but may generally be taken as approximately 0,05 MHz.

A cursory examination of the diagrams in fig. 4.4 reveals that the plots for the early morning hours, 0200, 0300, 0400 and 0500 L.T. indicate that a relationship may exist between f_oE and the level of the average flux. The plots for the afternoon hours, 1700, 1800, 1900 and 2000 L.T. seem to show no definite trends whatsoever, and for the most part the corresponding points may be considered to be randomly distributed.

However, it now becomes necessary to consider the possible effect on f_oE of the change in solar zenith angle between the 1st and 18th November at a fixed local time. The formulae 4.1 and 4.2 predict an increase in f_oE of the order of 0,5 MHz during this period due to the change in the zenith angle. Thus in order to present a reasonable analysis of the data, a correction must be made for this effect.

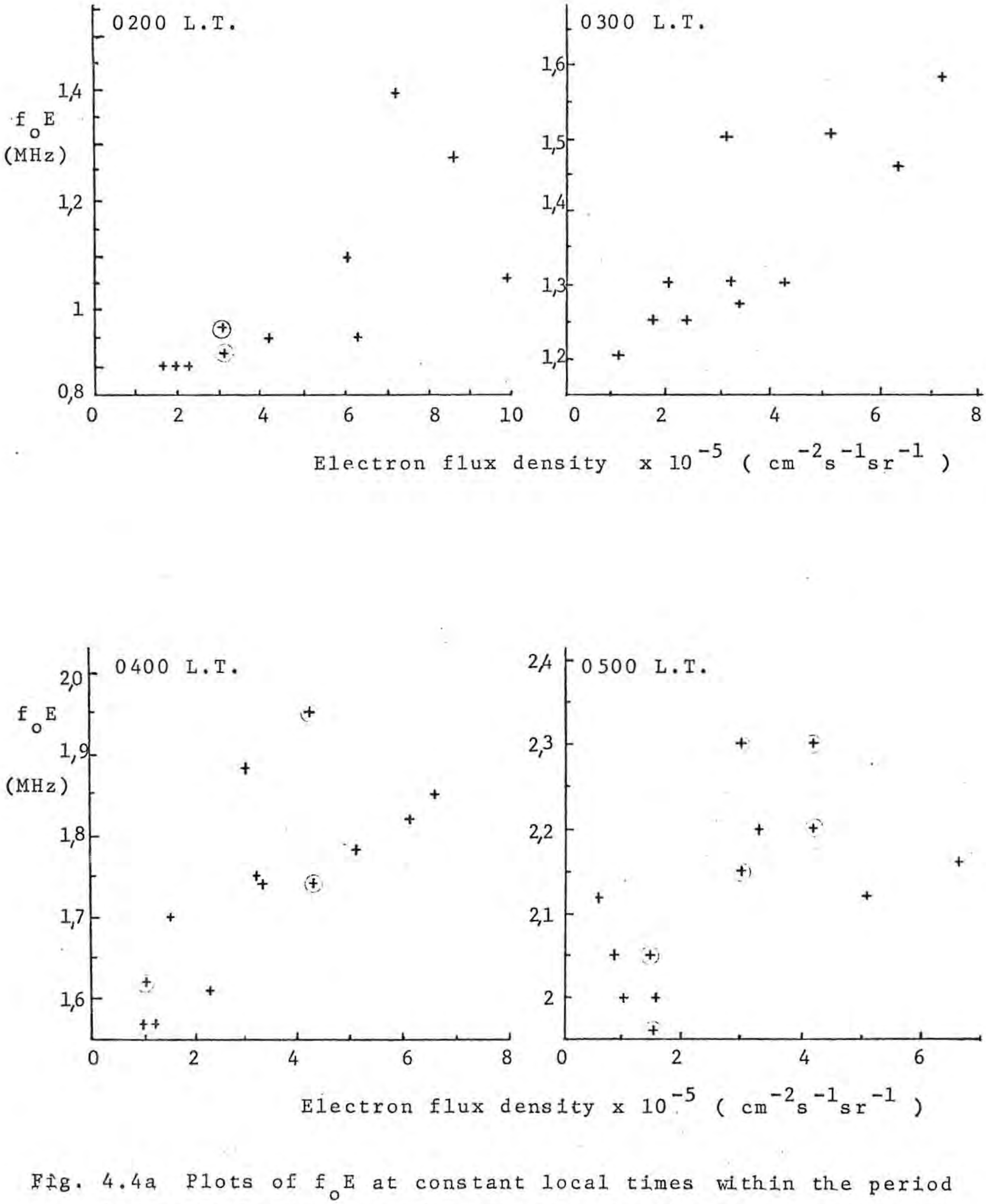


Fig. 4.4a Plots of f_oE at constant local times within the period 1st to 18th November 1963, against the electron flux density recorded within a three hour period centered on the time of measurement of f_oE.

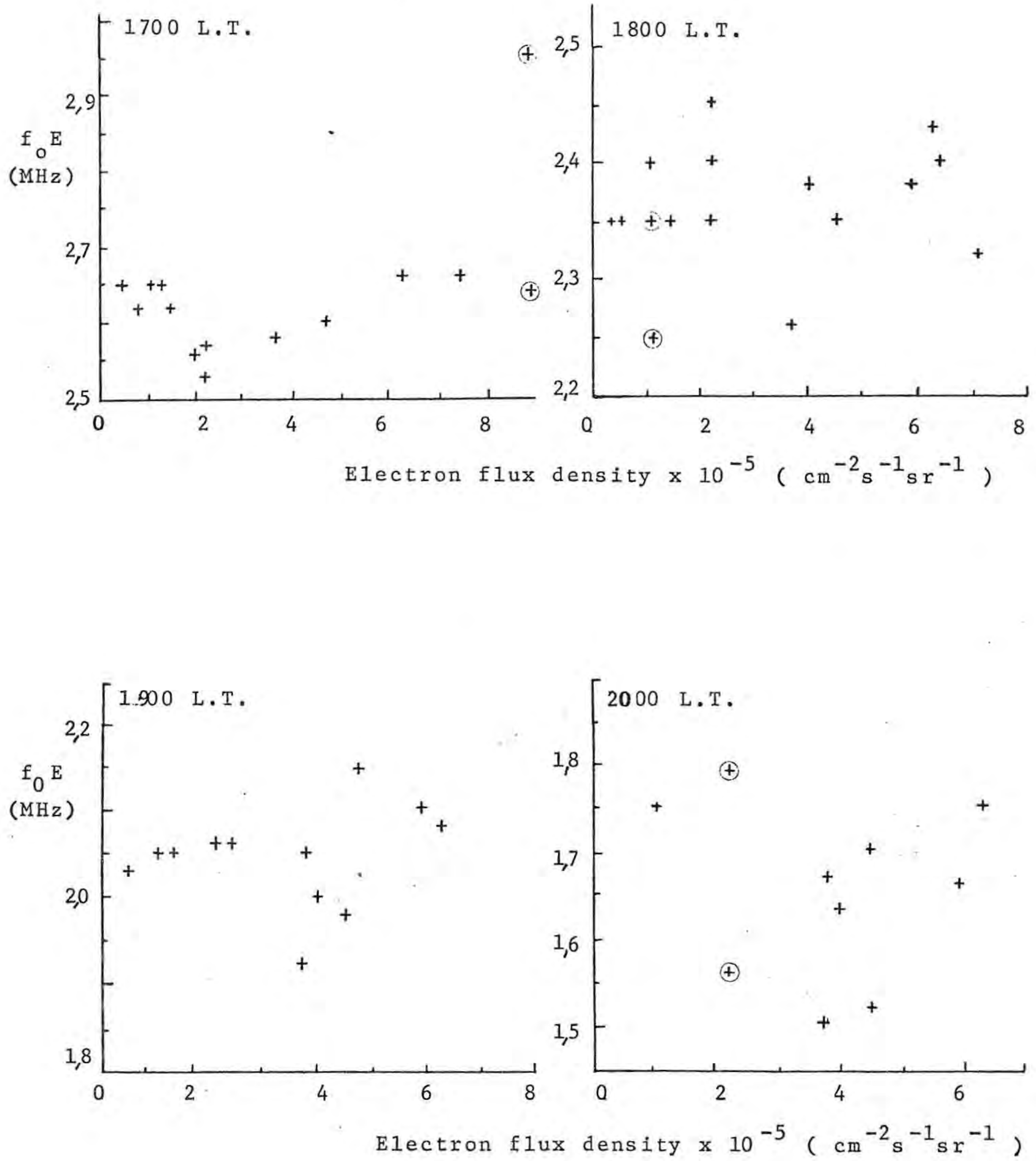


Fig. 4.4b Plots of f_oE at constant local times , within the period 1st to 18th November 1962, against the electron flux density recorded within a three hour period centered on the time of measurement of f_oE .

4.32 Correction for the change in solar Declination

The variation in f_oE at a fixed local time due to the seasonal change in the solar zenith angle χ, may be determined by estimating the parameters n and k, in equation 4.1, for f_oE values covering at least two to three months of data at a constant local time. These parameters may then be used in equations 4.1 and 4.2 to estimate the variation of f_oE for the period being considered.

For the purpose of this analysis for the period under consideration, we have used the diurnal variation of f_oE for particular days on which relatively low fluxes were experienced, to estimate the parameters n and k. This is to eliminate the possible effect which any seasonal anomaly may have on our calculations.

When χ approaches 90^o the relation between f_oE and χ given by equation 4.1 is no longer applicable since it is based on the assumption of a 'plane earth'. Chapman (1931) has defined a 'grazing incidence' function $Ch(x, \chi)$ the inverse of which may be used to replace $\cos\chi$ in equation 4.1 which becomes

$$f_oE = k \; Ch(x, \chi)^{-n} \qquad 4.3$$

$$\text{or} \quad \log_e f_oE = \log_e k - n \log_e Ch(x, \chi) \qquad 4.4$$

where k, n and χ are as defined previously, and

$$x = \frac{r}{H} \qquad 4.5$$

where r = geocentric distance

and H = atmospheric scale height.

The Chapman function $Ch(x, \chi)$ has been tabulated by Wilkes (1954) for values of x ranging in intervals between 50 and 1 000. This function applies accurately only to a spherically symmetric atmosphere and H independent of height.

The scale height for the E-region is found to increase steadily from approximately 7 to approximately 40 km between the altitudes 110 to 150 km (Nicolet, 1960). This would imply that the values of x which we may use in this study would range between 900 and 160, assuming r to be 6 500 km.

For $\chi \sim 90^{\circ}$ the Chapman theory predicts that the height of maximum production will be greater than that for smaller solar zenith àngles. This is found to be true for the Argentine Islands where h'E may rise to as high as 180 km during the sunrise and sunset periods, and fall to a value of roughly 110 km during the daylight hours. Since we are working at times when the solar zenith angle is close to 90°, we have chosen a value for x of 150. This corresponds to an H which occurs at an altitude of approximately 150 km (Nicolet, 1960).

From plots of $\log_e f_oE$ versus $\log_e [Ch(x, \chi)]$ within the period of analysis for particular days on which relatively low fluxes were measured and for the times for which 'scatter' diagrams were plotted, as shown in fig. 4.4, we have estimated values for n and k for the relation between f_oE and χ in equation 4.3. Linear regression techniques were employed. The possible influence of fluxes of electrons on this determination has been minimized by the elimination of all unusually high f_oE values and any values which correspond to high flux measurements.

The estimates for n and k, using f_oE data mainly from the 8th, 9th and 10th November, are 0,36 $\pm$ 0,01 and 3,67 $\pm$ 0,05 respectively. Substituting for n and k in equation 4.3 we may use the relation

$$f_oE = 3,67\,[Ch(x,\chi)]^{-0,36} \qquad 4.6$$

to calculate the variation of f_oE due to the change in solar declination at a fixed local time from the 1st to 18th November with electron effects being minimized.

The observed values of f_oE plotted in fig. 4.4 were now corrected for the effect of this variation. Their values were adjusted to those which would have been observed had the solar zenith angles been fixed at a certain value for a constant local time throughout the period. This fixed χ was chosen to correspond to that which occurs on 9th November, which is the middle of the period of analysis. The method of correction may best be expressed in the form:

$$f_oE_{corr.} = f_oE_{obs.} - (f_oE_{calc.} - f_oE_{9calc.}) \qquad 4.7$$

where $f_oE_{corr.}$ is the critical frequency which would have been observed on the day being considered for the value of χ on the 9th November.

In the above $f_oE_{obs.}$ = the observed critical frequency.

$f_oE_{calc.}$ = the critical frequency calculated for the χ corresponding to the time and day of the observed f_oE, using relation 4.6

$f_oE_{9calc.}$ = the critical frequency calculated using the χ for the 9th November corresponding to the time of the observed f_oE.

The corrected f_oE values, which correspond to a constant χ, are plotted against the average flux per pass in a similar way to that in fig. 4.4. The plots are shown in fig. 4.5 for the values of χ on the 9th November 1962 corresponding to the local times indicated on the diagrams. The error limits for f_oE are indicated on each of the points except where the error in scaling f_oE was greater than, or equal to, $\pm$ 0,1 MHz. Data points for which the record of f_oE and the measurement of the flux are separated by more than an hour are indicated by a light circle. Secondary cusps in the ionogram close to the E-critical were neglected unless their values showed agreement with f_oE at the same time on other days.

No correction has been made to f_oE values corresponding to 0200 L.T. or to those for 0300 L.T. prior to the 9th November. χ for this data is greater than 90^o. For $\chi > 90^o$, $Ch(x, \chi)$ becomes large and varies rapidly with a change in the scale height. Since the scale height H for the E-region changes with altitude, the correction for this data would be unreliable since we have assumed H to be a constant.

The scatter diagrams in fig. 4.5 for the constant values of χ corresponding to 1700, 1800, 1900 and 2000 L.T. on the 9th November, reveal a definite relationship between the average electron flux and the critical frequency and show a notable improvement on the uncorrected plots in fig. 4.4 at the corresponding times.

On correction the association between f_oE and flux for the uncorrected plots 0300, 0400 and 0500 L.T. was found to become less marked. However, the plots for 0300 and 0400 L.T. still show a trend for f_oE values to increase with a rise in flux. The correlation coefficients for these scatter diagrams are shown in table 4.2 but will be discussed later.

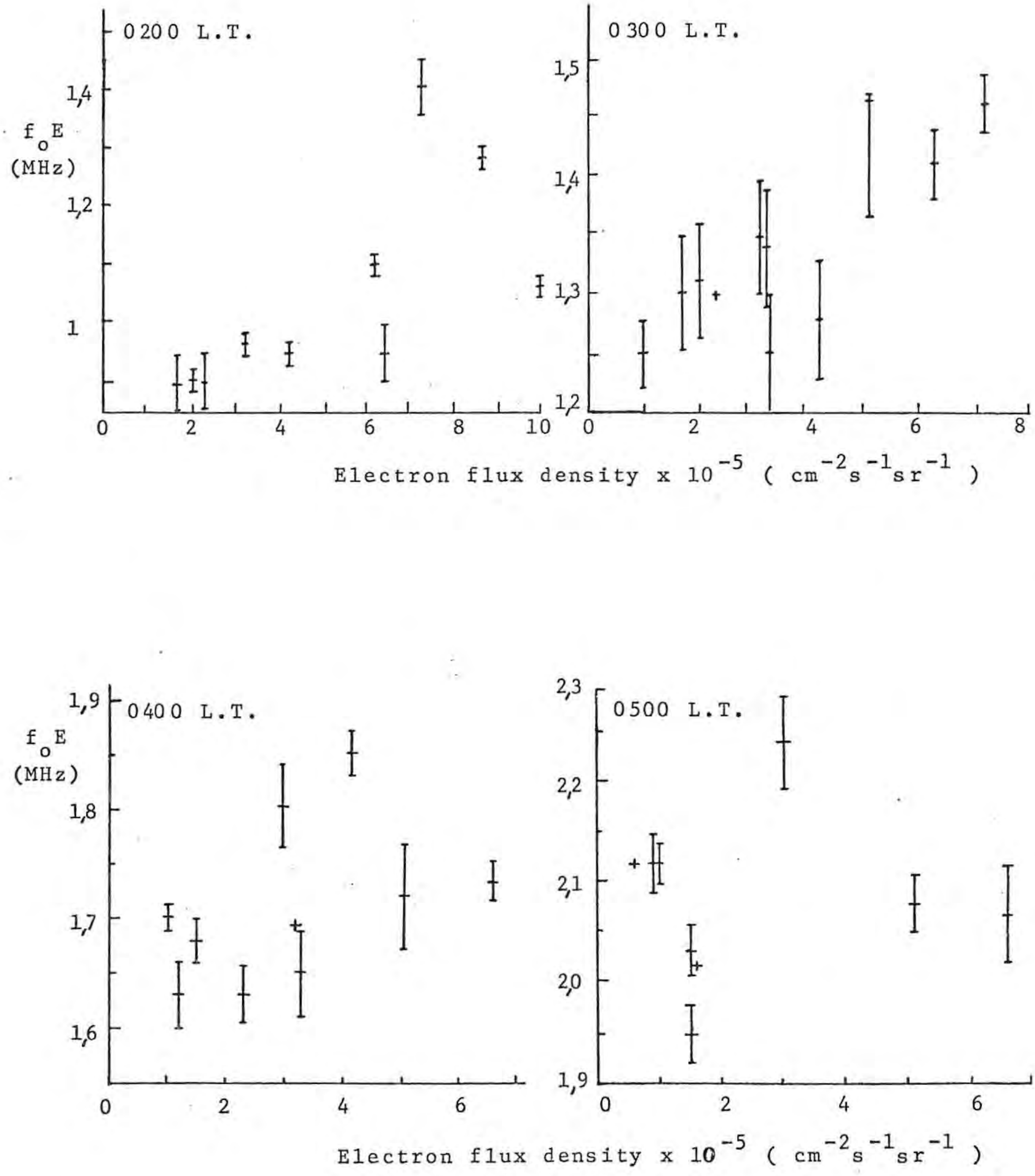


Fig. 4.5a Plots of f_oE vs flux , corrections having been made to f_oE for the change in the solar zenith angle , χ .

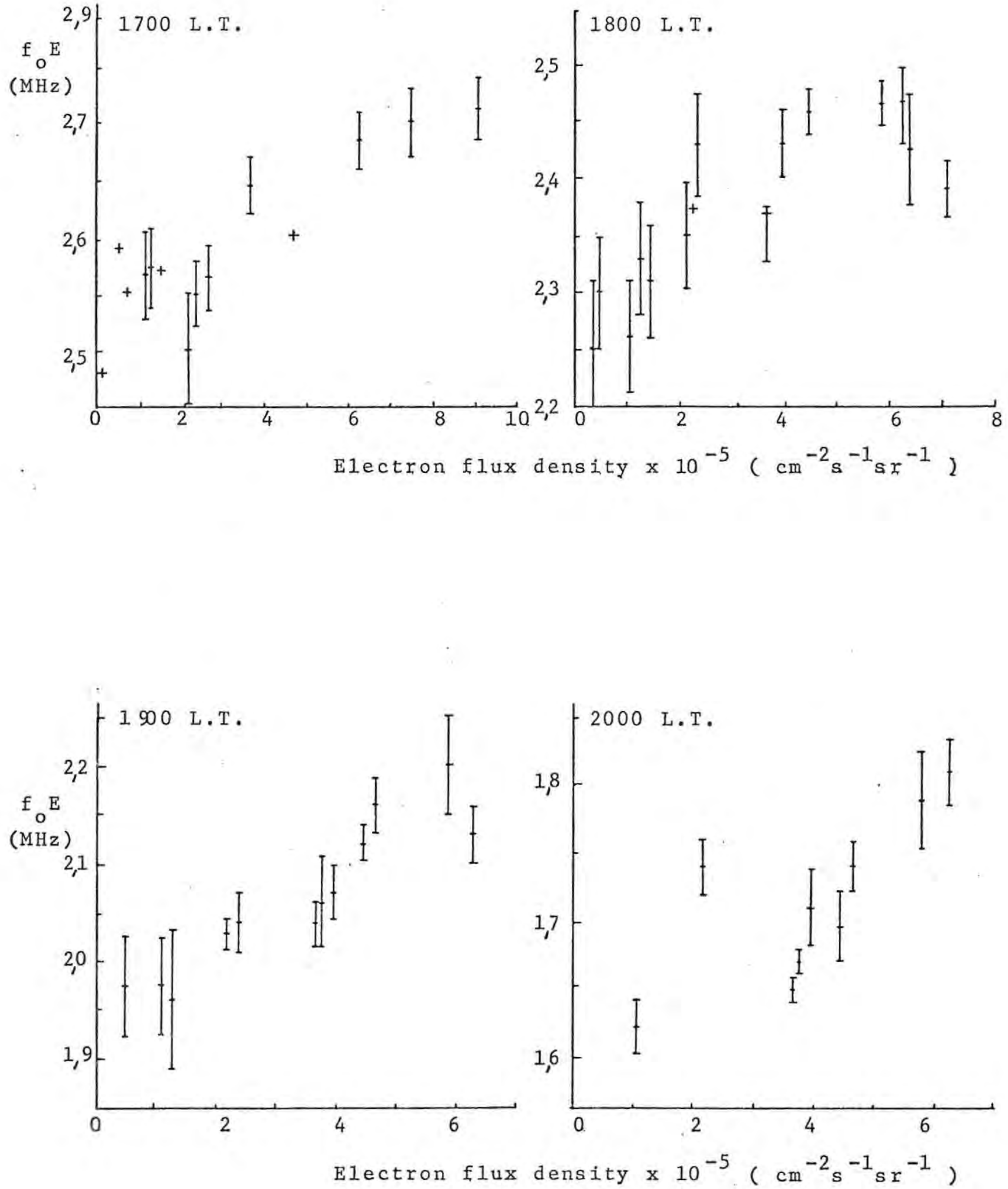


Fig. 4.5b Plots of f_oE vs flux, corrections having been made to f_oE for the change in the solar zenith angle, χ.

Considering the sparseness of the flux data, and the time and longitude interval which may exist between the records of f_oE and the measurements of the flux, the correlations shown in fig. 4.5 reveal a surprisingly clear correspondence between the flux and f_oE values.

4.33 Increase in f_oE due to the Electron Flux

If we may assume a linear relationship to exist between the flux and values of f_oE, for each of the plots in fig. 4.5, regression techniques may be used to determine the value of f_oE which corresponds to a zero flux level. Using these critical frequencies, which will be referred to as f_oE_o, we may now estimate those values of the parameters n and k in equation 4.3 which would correspond to a variation of f_oE with χ for which observable electron effects have been taken into account.

The results for the determination of f_oE_o for each of the plots in fig. 4.5, together with m, the slope of the regression line describing the linear increase in f_oE per unit flux are shown in table 4.2. The product moment correlation coefficients, r', have also been estimated where r' is defined in appendix C.

TABLE 4.2

LT	χ	f_oE_o	m	r'
h	Degrees	MHz	x 10^5 MHz cm^{-2} s sr	—
0200	95.00	0,82	0,043	0,71
0300	91.34	1,17	0,032	0,81
0400	86.57	1,65	0,018	0,44
0500	81.00	2,08	0,002	0,05
2000	86.57	1,60	0,029	0,76
1900	81.00	1,94	0,038	0,92
1800	74.91	2,29	0,026	0,81
1700	68.95	2,52	0,022	0,86

An examination of the correlation coefficients in table 4.2 reveals that f_oE shows a good linear correlation with flux except for the plots corresponding to 0400 and 0500 L.T.

$Log_e f_oE_o$ was now plotted against $\log_e Ch(x,\chi)$ as shown in fig. 4.6, where the values corresponding to 0500 and 0200 L.T. were not considered owing to the poor linear correlation of flux with f_oE for 0500 L.T. and the unreliability of $Ch(x, \chi)$ for 0200 L.T. as suggested previously. The parameters n and k corresponding to a variation of f_oE with χ , for which flux effects have been taken into account, were estimated by means of a regression analysis. They are

$$n = 0,375 \quad ; \quad k = 3,68 \text{ MHz}$$

Since the points plotted for 0300 and 0400 L.T., indicated by a 3 and 4 in fig. 4.6, lie slightly off the regression line the parameters were recalculated with this data excluded.

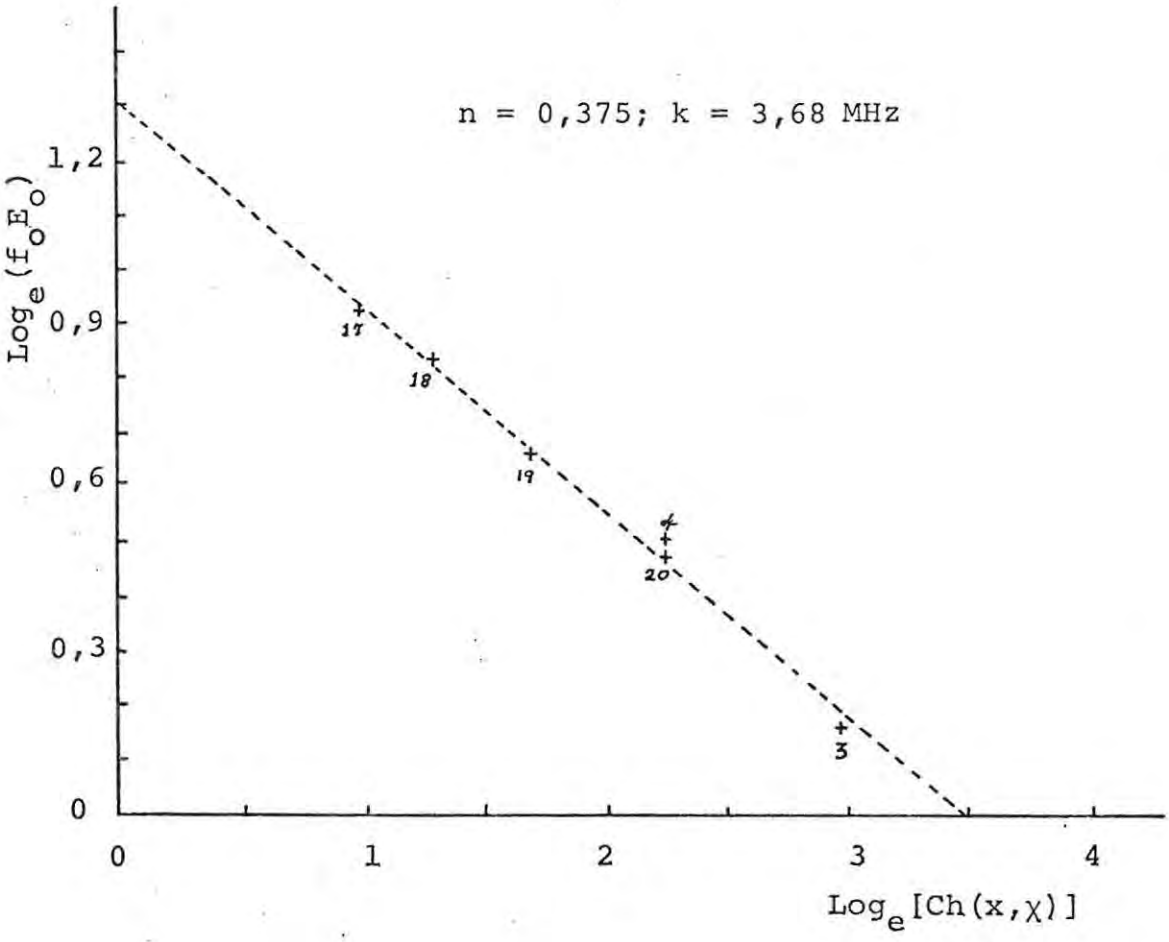


Fig. 4.6 A plot of $\log_e f_oE_o$ against $\log_e Ch(x,\chi)$ from which we may obtain values for the parameters n and k . The numbers 17 , 18 , 19 , 20 , 3 and 4 indicate the time of day in hours for which the corresponding points are plotted .

The recalculated values for n and k are

$$n = 0,364 \quad ; \quad k = 3,60 \text{ MHz}$$

Substituting these two different sets of parameters into equation 4.3 introduces a discrepancy of only 0,006 MHz in the calculation of f_oE_o for $Ch(x,\chi) = 5,36$. Thus both these sets may be considered to give a fairly consistent representation of the parameters which determine the relation between f_oE_o and $Ch(x,\chi)$. Using these parameters we are able to determine the relation between f_oE_o for each time and day within the period of analysis. The difference between the calculated value of f_oE_o and the observed critical frequency at a certain time may be taken as a measure of the increase in the ionization density which is caused by the precipitation of electrons in the E-region if no other than the normal solar production source is present.

The possible effect of the day-to-day change in the Zürich sunspot number, R_z, on the values for the critical frequency, has as yet not been considered. Beynon and Brown (1959) have shown on occasions a close correlation between day-to-day variations of R_z and f_oE. Relationships between f_oE and R_z have been suggested from analyses of monthly mean values of $(f_oE)^2$ and R_z. However it is felt that there is little justification for assuming that these relationships will apply to the day-to-day correlations of f_oE and R_z. For this reason and also because R_z remains consistently low ($\sim$10) for most of the period of investigation no correction was made to the f_oE data for possible sunspot effects.

The formula suggested by Swenson (1969) relating the long term variation of f_oE with R_z was used to calculate the increase in f_oE corresponding to $R_z = 50$. This was found to be less than 0,05 MHz. Since R_z is close to

50 on only three days, it seems reasonable to expect that the effect of the daily variation of R_z on the observed correlations of f_oE with flux may be minimal.

Plots of Δf_oE, the difference between observed f_oE values and f_oE_o, against flux are shown in fig. 4.7 where for reasons mentioned above the plots corresponding to 0200 and 0500 L.T. have been excluded. These diagrams are very similar to those in fig. 4.5 since the small difference between the parameters, n and k, used for the two figures is found to have an insignificant effect on the relative variation of f_oE with the solar zenith angle. These plots will be useful later for a comparison with theoretical predictions.

4.34 A Possible Relationship between f_oE and Flux

From table 4.2 it may be noticed that, if we may neglect the values listed corresponding to 0400 and 0500 L.T. due to the poor linear relationship which plots for those times exhibit, the change in f_oE per unit flux, m, increases consistently with solar zenith angle except for 1900 L.T. where m is found to be high. This relationship between m and χ is not surprising since for smaller values of χ the ionization density of the E-layer will be greater and thus a higher flux of electrons will be required to produce a unit increase in f_oE.

A graph of the values of m against $Ch(x,\chi)$ is plotted in fig. 4.8. If the point corresponding to 1900 L.T. with coordinates (5,4 ; 0,38) is neglected the remaining points seem to indicate a linear relationship between m and $Ch(x,\chi)$.

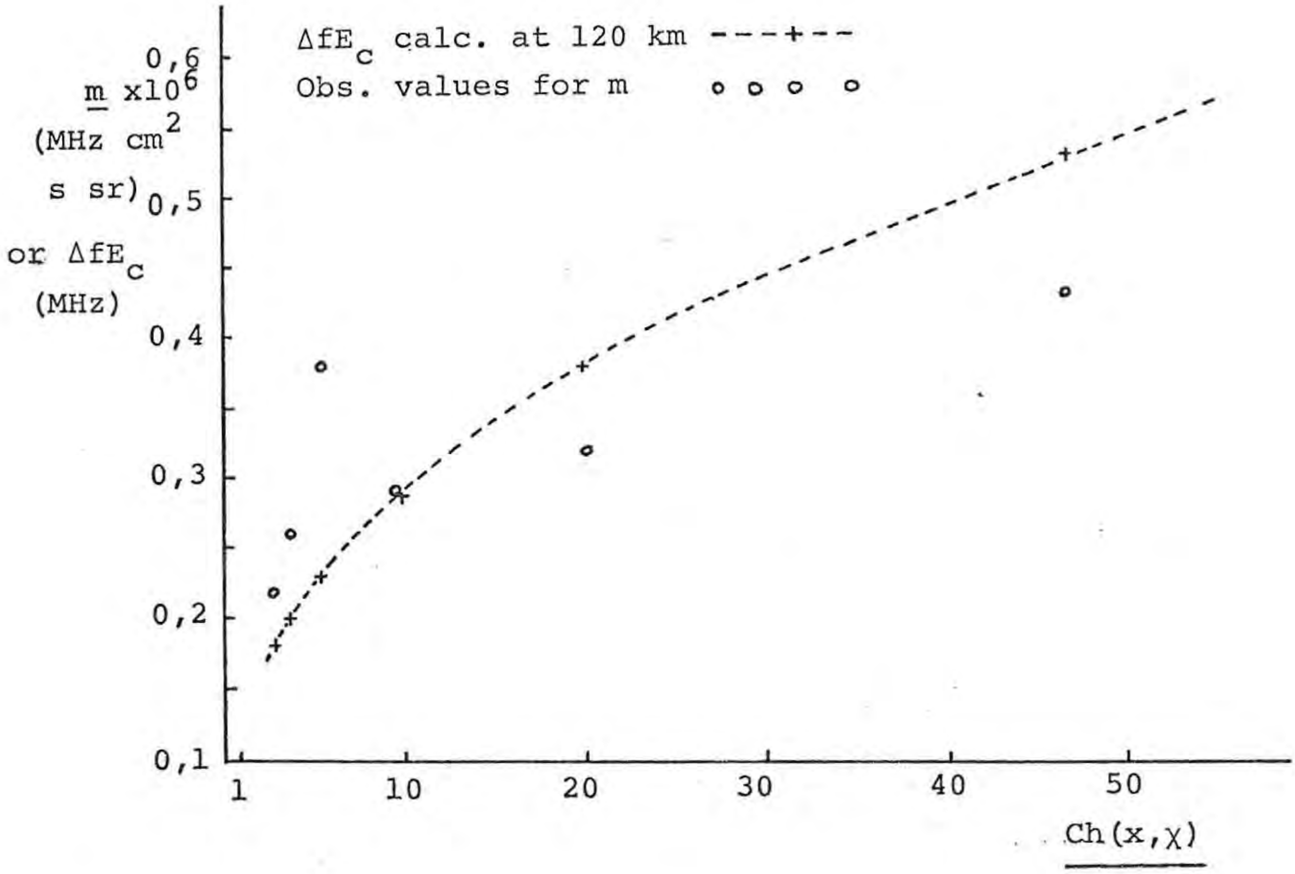


Fig. 4.8 A plot of the parameter m , the increase in f_oE observed per unit flux , as well as ΔfE_c , the computed increase in f_oE at 120 km due to a flux of 1×10^6 cm^{-2} s^{-1} sr^{-1} , versus Ch(x,χ).

This may be expressed in the form

$$m = 4,3 \times 10^{-9}(Ch(x,\chi) + 55) \text{ MHz cm}^{2} \text{ s sr} \qquad 4.8$$

where the numerical constants were determined by means of a regression analysis.

This relationship is only crude because of the sparseness of the data. Nevertheless if we take the relation 4.8 as being representative of the change of m with χ for the times plotted we may propose a general expression for the variation of f_oE with solar zenith angle and the directional flux density measured at roughly 1 000 km.

$$f_oE = f_oE_o + m J' \text{ MHz} \qquad 4.9$$

where m is given by the relation 4.8

J' is the directional flux density at 1 000 km in the energy range 40 - 250 keV

$$f_oE_o = 3,68 \left[Ch(x,\chi)\right]^{0,375} \qquad 4.9a$$

is the critical frequency for zero flux.

This expression may scarcely be used as an accurate description of the general relationship between f_oE, χ and J' in view of the many simplifying assumptions which have been made as well as the sparseness of the data but may be regarded as a rough representation of the behaviour of f_oE in terms of these variables during the period of the analysis.

In conclusion, we have shown that for the period 1st to 18th November 1963 a definite positive correlation exists between values of f_oE for the Argentine Islands corrected for the change of f_oE with χ , and the variation of the electron flux density in the energy range 40 - 250 keV as measured by Alouette I. A possible relationship between f_oE, χ and J' has been proposed as being representative of the data analysed.

Considering the short term fluctuations which are evident in the flux measurements and the time interval which may elapse between a flux reading and the recording of f_oE at the Argentine Islands as well as the longitude range ($\sim 55^o$) over which flux measurements were made, this analysis has given surprisingly good results. However the flux data which were used above are still in a rather elementary state as no account has been taken of the possible effect which a change in the orientation of the directional counter with respect to the magnetic field may have on the intensity measurements. If the electron intensities are not distributed isotropically with respect to their pitch angle, the counter will register different readings for a constant flux dependent on its direction of orientation. Thus in order to be able to compare the magnitude of directional flux densities measures for different pitch angles, a suitable correction must be made to the data.

4.35 The Pitch Angle Distribution of the Electron Flux Densities

From an analysis of Alouette I data for the complete period for which flux measurements were available for the Falkland Islands, J.G. Greener (private communication) has deduced the pitch angle distributions shown in table 4.3 for invariant latitude intervals of approximately 2^o within the range $2,2 \leq L \leq 2,8$. These distributions correspond to the median values of electron intensity measurements which are separated both in time and longitude and may suffer from the possible effects of a seasonal variation in the electron intensities.

TABLE 4.3

	PITCH ANGLE θ			
	$10^\circ - 30^\circ$	$30^\circ - 50^\circ$	$50^\circ - 70^\circ$	$70^\circ - 90^\circ$
Median	0,12	0,26	2,6	8,3
Electron Flux	0,06	0,29	1,5	5,9
Densities J_θ	0,08	0,29	1,4	5,1
$\times 10^{-5}\ cm^{-2}\ s^{-1}\ sr^{-1}$	0,06	0,19	1,4	3,9
	0,05	0,16	0,61	2,1

Normalising each of these distributions to the median flux value within the pitch angle range $10^\circ - 30^\circ$ and taking the mean of these normalised distributions, we will obtain the mean pitch angle distribution for this L-parameter range $2,2 \leq L \leq 2,8$ as shown in table 4.4.

TABLE 4.4

PITCH ANGLE θ	NORMALISED MEAN FLUX J_θ'
$10^\circ - 30^\circ$	1
$30^\circ - 50^\circ$	$3,4 \pm 0,5$
$50^\circ - 70^\circ$	$19,5 \pm 2,3$
$70^\circ - 90^\circ$	$67,6 \pm 10,5$

Fig. 4.9 shows the variation of this normalised mean flux, J_θ', with the pitch angle (in radians) in the middle of the ranges indicated in table 4.4. An examination of this variation suggests that we may be able to fit an exponential relationship to these points for $\theta < \pi/2$. Fig. 4.10 shows that within the error limits $\log_e J_\theta'$ is linearly related to θ. By means of a

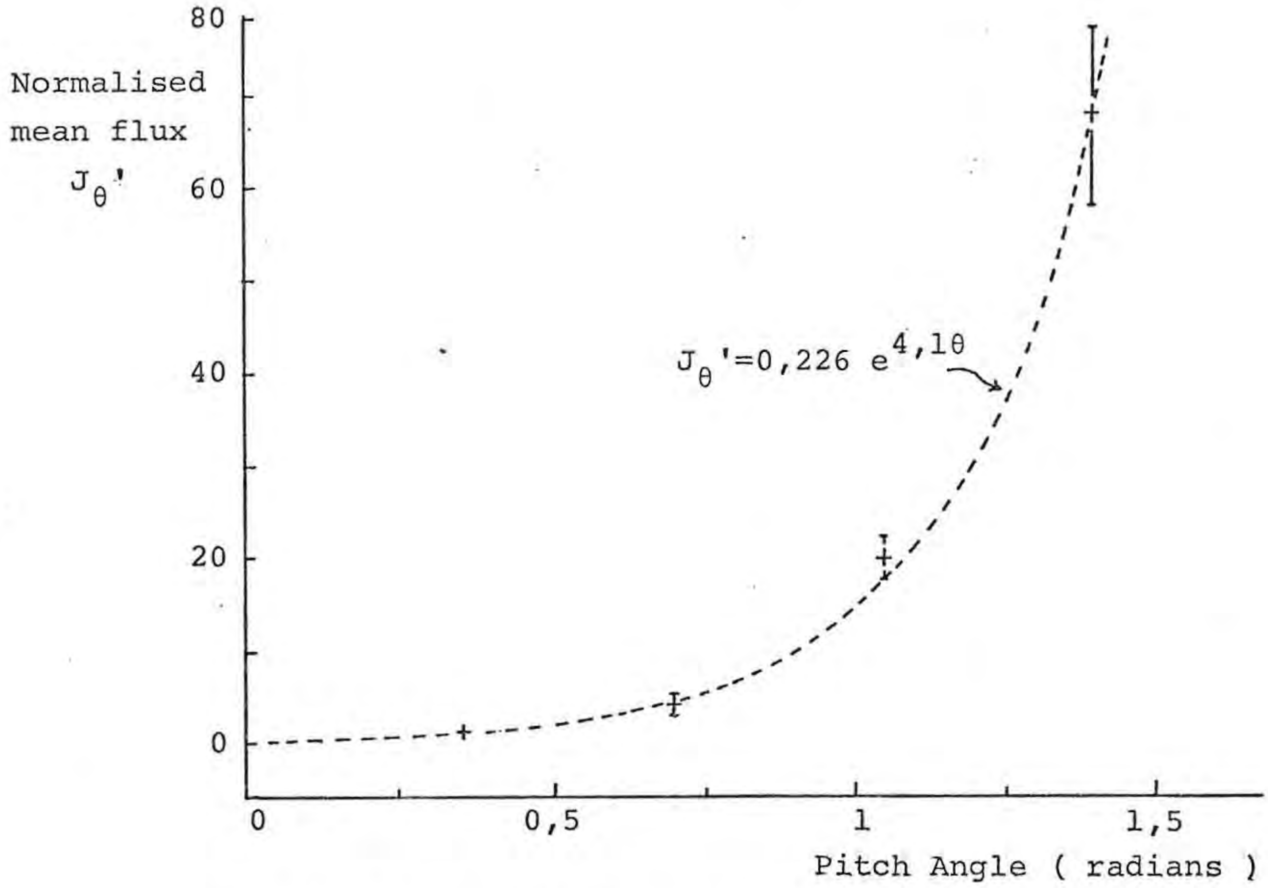


Fig. 4.9 A plot of the observed normalised mean flux J_{θ}' against the pitch angle, θ . The estimated exponential relationship agrees within the error limits to the points plotted .

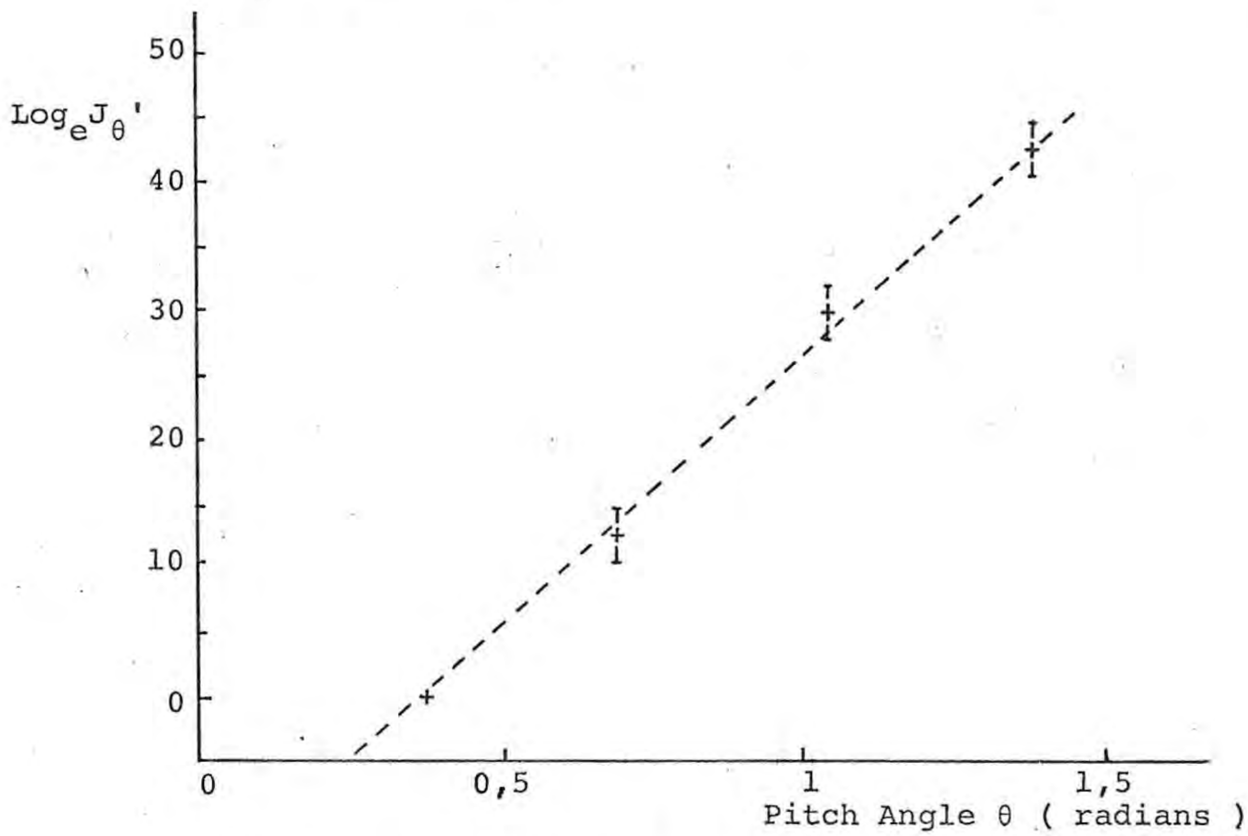


Fig. 4.10 A plot of $\log_e J_{\theta}'$ vs θ , indicating a linear relationship within the error limits .

regression analysis we have deduced the following expression for the pitch angle distribution

$$J_\theta' = 0,226\ e^{4,1\ \theta} \qquad 4.10$$

where J_θ' is the normalised median flux for $E \geqslant 40$ keV

θ = pitch angle in radians.

This relation yields a normalised pitch angle distribution which agrees closely with the observed distribution as shown in fig. 4.9.

Thus in order to correct the flux data used in the analysis for the effect of this variation in the pitch angle, the level of the directional flux may be adjusted to the value that it would have at some fixed pitch angle θ assuming the distribution 4.10.

If the directional flux J_{θ_c}' is measured at some pitch angle θ_c say, then the normalised flux at this pitch angle would be

$$J'_{\theta_c} = 0,23\ e^{4,1\ \theta_c} \qquad 4.11$$

and thus the corrected flux density at the fixed pitch angle θ would be

$$J_\theta = \frac{J_{\theta_c}\ J_\theta'}{J'_{\theta_c}} \qquad 4.12$$

$$= J_{\theta_c}\ e^{4,1(\theta - \theta_c)} \qquad 4.13$$

Using this relation 4.13 we may calculate what the flux measured at any pitch angle θ_c would be at some fixed θ. Correcting all the flux data used in the analysis to this fixed θ, would give a much better measure of the relative magnitude of the flux which reaches the ionosphere.

However this method suffers from one main drawback and that is that we cannot assume that particles will always conform to this average distribution. As mentioned in chapter 2 various experimenters have shown that where high fluxes of electrons are measured, their distribution tends towards isotropy and this would make any correction according to the above method totally inaccurate.

A further complication arose in the attempt to correct the data for the effect of the change in angular distribution in that values for the pitch angle for the Falkland Islands data were only given for roughly 50% of the occasions where flux readings were recorded. This meant that any correction to the values of the flux would be unsatisfactory as a 50% reduction in the amount of data would render the correlation plots of f_oE versus flux statistically insignificant. The values of the pitch angle which were available for the data used in the analysis were found to vary roughly between 45 to 75^o and on occasions showed an approximate 10^o variation per pass. Thus an accurate correction for the pitch angle effect for individual cases did not seem justifiable.

Nevertheless this relationship 4.13 will be useful in the consideration of the average long term effects of the electron flux in particular with respect to calculations of the expected increases in the ionization density due to fluxes measured by Alouette I.

4.4 Calculation of Expected Increases in f_oE with Flux

In this section we will attempt to calculate the increase in f_oE caused by the flux densities used in the above analysis at those solar zenith angles for which the correlation plots of f_oE versus flux have been constructed in fig. 4.5. The method of computation is identical to that described in chapter 2 except that here the ionization density increments due to the flux are calculated for a constant ionization density distribution with altitude. This value of the constant ionization density corresponds to the values of f_oE_o which have been estimated for each of the plots in fig. 4.7.

In order to effect the calculation of the ionization density increases we are required to know the IDH flux at 300 km. For our purposes the flux density has been assumed to conform to the pitch angle distribution as given by the relation 4.10 and not to the unrealistic isotropic case. Thus from the directional intensities measured at 1 000 km an estimate of the omni-directional flux density over the downward hemisphere at 300 km must be made.

From magnetic field considerations it is a simple matter to estimate the pitch angle range within which particles measured at 1 000 km will mirror below 300 km. The Alfvèn mirror equation (Heikkila and Axford, 1965) gives a relation between the pitch angle of a particle and the magnetic field

$$\sin^2 \alpha = \frac{B}{B_m} \qquad 4.14$$

α = pitch angle at the value of the magnetic field B

B_m = magnetic field at the mirror point.

Since $$B \propto \frac{1}{r^3}$$ 4.15

we may write 4.14 as

$$\sin^2\alpha = \left(\frac{r_e + h_a}{r_e + h}\right)^3$$ 4.16

where h = height of the particle with pitch angle α which will mirror at the altitude h_a,

r_e = earth radius.

In order that particles measured at 1 020 km should mirror below 300 km their pitch angles at 1 020 km must be less than

$$\alpha = \arcsin \left(\frac{6,680}{7,400}\right)^3 \qquad r_e = 6,380 \text{ km} \quad h = 1\ 020 \text{ km}$$

$$\simeq 59^\circ$$

Thus electrons at 1 020 km within the pitch angle cone of 59° will mirror below 300 km. In order to calculate the electron flux density with pitch angles less than 59° we must integrate the directional flux density over the range of pitch angles 0 to 59°. The integral is of the form (A. Wulff, 1972)

$$J = 2\pi \int_{0^\circ}^{59^\circ} J_\theta \sin\theta \cos\theta \, d\theta$$ 4.18

where J is the omnidirectional flux over the downward hemisphere at 300 km, elec cm^{-2} s^{-1}

θ = pitch angle

J_θ = the directional flux at the pitch angle θ at 1 020 km, elec cm^{-2} s^{-1} sr^{-1}

If we may express J_θ in terms of the pitch angle and the directional flux J_{θ_c} measured at the angle θ_c by the relation 4.13, 4.18 becomes

$$J = 2\pi \int_{0^\circ}^{59^\circ} J_{\theta_c} \; e^{4,1(\theta - \theta_c)} \sin\theta \cos\theta \, d\theta \qquad 4.19$$

$$= 2\pi \, J_{\theta_c} \; e^{-4,1\,\theta_c} \int_0^{59^\circ} e^{4,1\,\theta} \sin\theta \cos\theta \, d\theta \qquad 4.20$$

Integrating by parts 4.20 becomes

$$J = \frac{2\pi J_{\theta_c}}{e^{4,1\theta_c}} \left[\frac{e^{4,1\theta}}{4,1^2 + 4} \left(2 \sin^2\theta + 4,1 \cos\theta \sin\theta - 1\right) \right]_0^{59^\circ}$$

$$= 50,4 \;\; J_{\theta_c} \; e^{-4,1\,\theta_c} \qquad \text{elec cm}^{-2}\ \text{s}^{-1} \qquad 4.21$$

where J_{θ_c} is the directional flux density at 1 020 km measured at the pitch angle θ_c in radians, (elec cm^{-2} s^{-1} sr^{-1}).

J is as defined above.

Using the simple relation, 4.21, we may estimate the omnidirectional flux over the 'downward hemisphere' at 300 km from the measurements of the directional flux density at 1 020 km, assuming the pitch angle distribution given by the equation 4.13.

4.41 The Computation of Δf_oE

In order to determine the changes in f_oE which the fluxes used in the above correlation analysis would be expected to produce, we have followed directly the method of computation described in chapter 2 of this thesis. In this case the increase in the ionization density has been estimated for the constant ionization density - height profiles corresponding to the values of f_oE_o calculated from the relation 4.9a for each of the plots in fig. 4.7. Values for the spectral parameters, E_o and J_o, of the electron flux are required to perform this computation.

An E_o value of 50 keV was taken as being typical of the measurements made within the period of analysis. The total integral flux density J_o was estimated from the directional fluxes, measured by Alouette I, by combining relation 4.21 with the expression for the exponential energy spectrum. This gives

$$J_o' = 50{,}4\ J(>E)_{\theta_c}\ e^{(E/E_o\ -\ 4{,}1\ \theta_c)} \qquad 4.22$$

where J_o' is the total energy omnidirectional flux density over the downward hemisphere.

E = 40 keV.

$J(>E)_{\theta_c}$ is the directional integral flux measured by Alouette I with energy greater than E.

Thus for the conversion of the directional flux at 1 020 km to the omnidirectional flux at 300 km, J_o', it is necessary to know the pitch angle θ_c of the observations of flux. For our purposes the mean value of the pitch angle data, which was available for the flux measurements used in the correlation studies, was adopted. The estimated mean value of 62^{o} may be regarded as a reliable representation of θ_c for the data as θ_c was seldom found to lie outside the range 50 to 75^{o}.

Using the calculated values for J_o', corresponding to specified values for the observed directional flux $J(>40)_{\theta_c}$ within the range 0 to 1×10^{6} cm^{-2} s^{-1} sr^{-1}, for E_o = 50 keV and $\theta_c = 62^{o}$, we have determined the production rate profiles and have subsequently estimated the changes which would be produced by these fluxes in the 'constant' ionization density altitude distributions. The magnitude of the increment in f_oE, Δf_oE, which should result from these increases in the ionization density, will depend on the height, h_m, of the maximum ionization density of the E-layer at the time of the influx of electrons. Since the production rate for 50 keV electrons shows a sharp variation with altitude particularly in the E- and D-regions (A. Wulff, 1972), we should expect that relatively small changes in h_m would cause a large effect on the predicted increment of f_oE. Thus in order to estimate Δf_oE from the calculated ionization density increases, a representative value for h_m must be chosen for the times being considered. Unfortunately no virtual height data for the E-layer was available for this period from bulletins. Hourly median values for h'E for November 1965 were available and are given in table 4.5. These values display a variation of h'E from 160 to 100 km over the period of the analysis which would suggest that different values for h_m should be used in the estimation of Δf_oE at different times. Since we cannot assume that the h'E values quoted in table 4.5 accurately represent the virtual heights for the period being considered, a constant value for h_m of 120 km was chosen and the effects on the correspondence between the calculated and observed results due to a variation of h_m were noted. A detailed analysis of the h'E data for this period would be most satisfactory. This constant value for h_m, however, gave very encouraging results.

The calculated increment in the ionization density or in this case the plasma frequency, Δ fE, at 120 km was plotted against the directional flux for each of the correlation diagrams in fig. 4.7 (the variations are indicated by dotted lines). The values of Δf_oE, which are obtained from a regression analysis for each of the plots in fig. 4.5, corresponding to a flux of 1×10^6 cm^{-2} s^{-1} sr^{-1} are compared with calculated values in table 4.5

TABLE 4.5

L.T.	χ	Ch(x,χ)	Δf_oE_r (regression)	ΔfE_c (calc.) for 120 km	$fE_c - f_oE_r$	h'E-120	h'E (median)
h	Degrees		MHz	MHz	MHz	km	km
0200	95.00	46,5	0,43	0,53	0,1	40	160
0300	91.34	19,77	0,32	0,38	0,06	15	135
2000	86.57	9,38	0,29	0,29	0	5	125
1900	81.00	5,36	0,38	0,23	- 0,15	- 10	110
1800	74.91	3,56	0,26	0,20	- 0,06	- 15	105
1700	68.95	2,64	0,22	0,18	- 0,04	- 20	100

From the results presented in table 4.5 and the graphs in fig. 4.7 reveal a surprisingly close agreement between the calculated change in the plasma frequency at 120 km with flux and the variation of the f_oE data with flux. It may be noted from these results that for larger solar zenith angles (greater than that corresponding to 2000 L.T.) the calculations have overestimated the increase in f_oE with flux whereas for smaller values for χ the increment of f_oE has been underestimated. This may easily be explained in terms of the variation of h_m with the solar zenith angle. The difference between the calculated ΔfE_c at 120 km and the Δf_oE_r estimated from the regression analysis of the plots in fig. 4.5 for $J(>40)_{\theta c} = 1 \times 10^6$ cm^{-2} s^{-1} sr^{-1} are shown in table 4.5. The variation of this difference with solar zenith angle shows a remarkable correspondence with the variation of the difference between the hourly median values of h'E for November 1965 and the value adopted for h_m of 120 km. This clearly indicates that the discrepancy between the calculated and the observed results is related to the fact that we have used a constant value for h_m.

The ionization production rate profile due to electron fluxes with E_o = 50 keV has a negative slope for altitudes above 100 km. If the height of maximum ionization density for the E-layer is below the altitude of 120 km assumed for the calculations, we may expect the observed increase in f_oE for a particular flux to be greater than that which would be estimated at 120 km. Similarly if h_m is greater than 120 km the estimated value for Δ f_oE should be greater than the observed Δ f_oE. This is clearly substantiated by the results presented in table 4.5. For values of h'E less than 120 km the magnitude of Δ f_oE has been underestimated, whereas for h'E greater than 125 km Δ f_oE has been overestimated. Thus in order to obtain more realistic estimates of the increase in f_oE due to the electron flux, an accurate determination of h_m is necessary at each solar zenith angle for which the calculations are performed. Nevertheless the use of the constant value for h_m of 120 km for the above calculations has provided a close agreement between the calculated and observed values for Δ f_oE. Where the hourly median value for h'E approaches 120 km the difference between the observed and calculated values for Δ f_oE becomes negligible (see table 4.5).

Finally, the calculated values of Δ fE at the constant height of 120 km (table 4.5) were plotted versus $Ch(x,\chi)$ in fig. 4.8. The variation of m (the value of Δf_oE per unit flux which was estimated from the regression analysis of the plots in fig. 4.5) with $Ch(x,\chi)$ is plotted on the same set of axes. These plots show clearly the discrepancy between the observed and calculated values of Δf_oE both for high and low values of $Ch(x,\chi)$. For high values of $Ch(x,\chi)$ both the Chapman theory and the h'E values (given in table 4.5) suggest that the height of maximum ionization density in the E-layer will be relatively high and thus the calculations for a constant height have overestimated the values for Δf_oE. Similarly for lower values of $Ch(x,\chi)$, Δf_oE has been underestimated.

The calculations of the variation of Δf_oE at the constant height of 120 km indicate a non-linear relationship between Δf_oE and $Ch(x,\chi)$, (fig. 4.8). The quantity m has been linearly related to $Ch(x,\chi)$. For values of $Ch(x,\chi)$ approaching the value of one, h_m will tend to a constant level (Rishbeth and Garriot, 1966) and we may expect the observed and calculated variations of Δf_oE to agree more closely. The hourly median values for h'E for November 1965 are found to be constant ($\sim$100 km) for $Ch(x,\chi) < 3$. If we may regard the point in fig. 4.8 with coordinates (0,22 ; 2,64) as significant, the linear relationship between m and $Ch(x,\chi)$ may be considered to break down for $Ch(x,\chi) < 3$. This would tend to indicate that the observed linear relationship between m and $Ch(x,\chi)$ may only hold for times when $Ch(x,\chi)$ and correspondingly h_m is changing rapidly. For a constant h_m the variation of Δf_oE with $Ch(x,\chi)$ is predicted from the calculations to be non-linear.

4.5 Summary and Conclusions

Clear evidence for the electron flux densities, measured by Alouette I, causing observable increases in the critical frequency of the E-layer for the Argentine Islands has been presented in this section. Some pertinent results of the investigation are summarized below.

Correlation plots of f_oE at constant local times versus the electron flux for the period 1st - 18th November 1962 have shown an association between the magnitude of f_oE and the flux. These plots were corrected for the effect of the seasonal variation of the solar zenith angle at a constant local time. The association was found to improve on correction. The correlation coefficients for the plots showed a high degree of association between the flux and f_oE. An expression has been suggested for the relationship between f_oE, the solar zenith angle and the electron flux measured by Alouette I.

A simple formula involving the average pitch angle distribution of the flux was determined in order to estimate the omnidirectional flux at 300 km from Alouette I measurements. Using this formula, calculations were made of the change in plasma frequency with flux at the constant altitude of 120 km. These calculations show good agreement with observations. The variation with $Ch(x, \chi)$ of the difference between the observed and calculated values for f_oE was found to correspond with the variation of the median values of h'E. This difference is explained in terms of a change in the height of the maximum ionization density of the E-layer with solar zenith angle. The relationship between the observed change in Δf_oE per unit flux and $Ch(x, \chi)$ is proposed as being linear for times where the value of $Ch(x, \chi)$ and correspondingly h_m, is changing rapidly. Where h_m is constant the change in Δf_oE per unit flux with $Ch(x, \chi)$ should follow the non-linear variation calculated for a constant height.

The increase in f_oE with flux shows an agreement with the calculations for which an E_o of 50 keV has been assumed. Computations by A. Wulff (1972) have shown that in fact electrons with E_o values between 2 and 10 keV will deposit most of their energy at E-region altitudes. If these low energy electrons were to accompany the measured fluxes of electrons with energies greater than 40 keV, the calculations for E_o = 50 keV would underestimate markedly the increase in f_oE. Any increases in f_oE due to this low energy source would not be registered by a corresponding increase in the J(>40 keV) flux reading. This possible accompanying flux may help account for certain uncorrelated inhancements of f_oE values.

In conclusion we may suggest that along with solar phenomena, ionospheric currents and possibly drifts, energetic electrons may not be neglected as a cause of ionization changes in the E-region.

CHAPTER 5: Electron Effects on Ionograms

In the previous chapters we have examined the possible effects of electrons on F-, E- and D-region parameters. In this section we will investigate briefly the effect which precipitating electrons with assumed spectral characteristics may have on the virtual height of the E-layer. Other changes in the ionograms which could be caused by these electrons are also considered.

5.1 Introduction

In chapter 2 it has been suggested that retardation of the sounding pulse in the low lying ionization produced by high energy electrons (greater than 40 keV) may give rise to changes in the virtual height of the E-layer. These changes would probably be indicated by retardation of the lower end of the E-layer reflection.

The availability of both ionogram to N(h) profile and N(h) profile to ionogram conversion computer programs, made possible a study of the effect on an ionogram of changes in the corresponding N(h) profile. Using the method described in chapter 2 we may calculate the changes which would be produced by electrons with specified spectral characteristics in an N(h) profile and hence calculate the change in the corresponding ionogram due to these electrons. It is of particular interest to know whether the electron fluxes measured by Alouette I would exhibit any effect on h'E.

5.2 The Method

For this investigation the ionogram corresponding to 1430 L.T. on 11th January 1963 at Sanae was used. This is the same ionogram which was used in chapter 2 for the calculations of ionization density increases due to fluxes. The ionogram was converted to an N(h) profile by means of Titheridge's method of ionogram reduction. By use of the method described in chapter 2, the ionization production rate - altitude distribution corresponding to this N(h) profile was calculated. Upon addition of the production rate estimated for electrons with an exponential energy spectrum, the final N(h) profile and corresponding ionogram were computed. This computed ionogram may be compared to the original ionogram and any changes due to the electron flux noted.

5.3 The Results

Initially an arbitrary block of ionization was inserted below the E-layer in the N(h) profile corresponding to the selected ionogram. This inserted ionization which corresponds to a layer approximately 8 km thick with a maximum plasma frequency of 2,18 MHz at 90 km, resulted in an increase in h'E of roughly 7 km. Retardation at the lower end of E-layer reflection was also caused by this low lying ionization.

The effect on the ionogram which would be caused by low lying ionization produced by fluxes of electrons typical of the measurements made by Alouette I was now computed. A representative value for E_o of 50 keV and a value for J_o of 3×10^5 cm^{-2} s^{-1} sr^{-1} was chosen. The calculated N(h) profile with electron effects included, corresponds closely to that shown in fig. 2.2 for $J_o = 4 \times 10^5$. As may be noticed from this figure, the ionization density below 90 km has not been computed. An arbitrary variation of the plasma

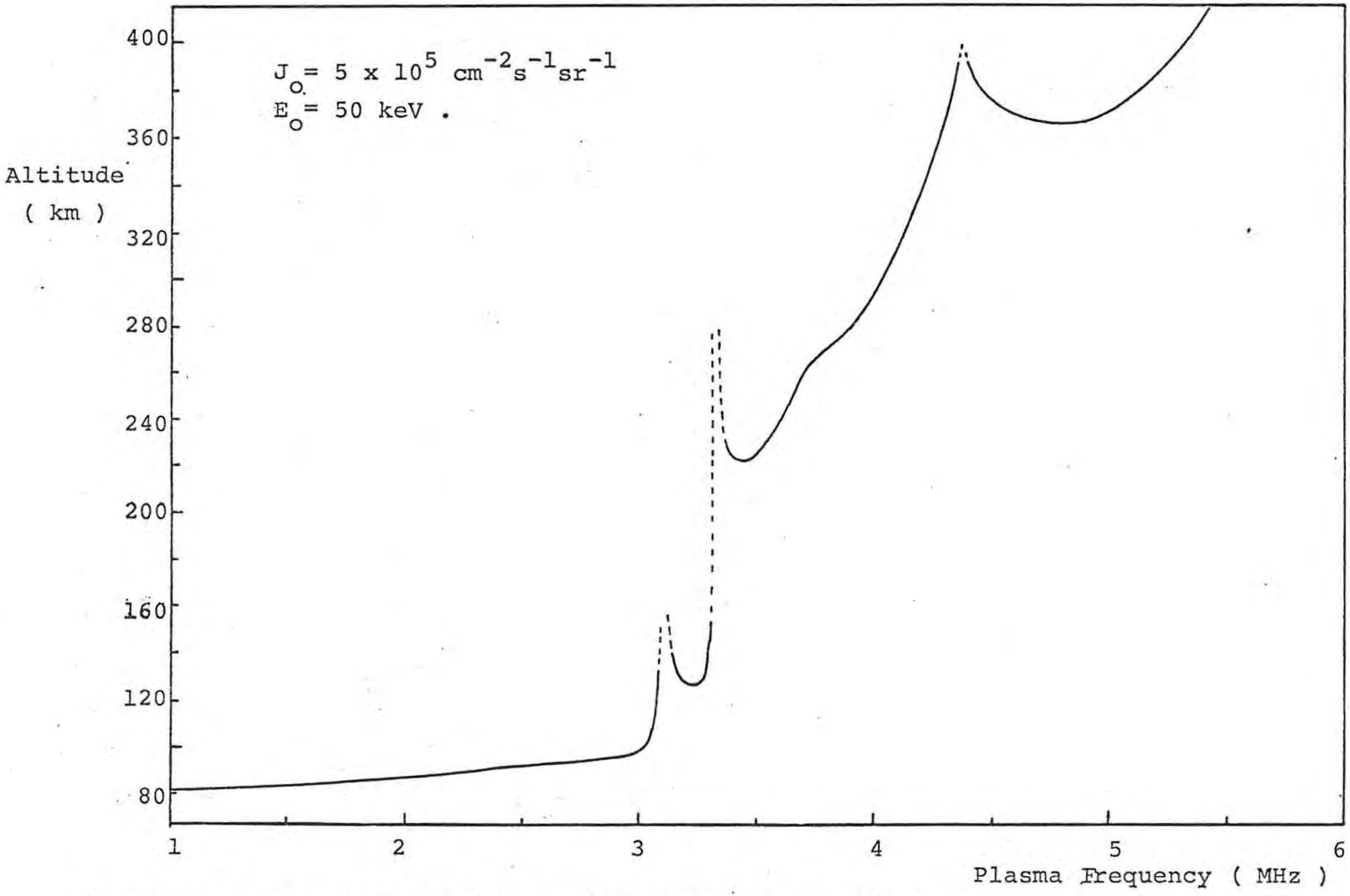


Fig. 5.1b A computed ionogram illustrating the formation of a double cusp in the E-region on the influx of electrons .

frequency which decreases slowly to zero at 84 km has been inserted in this case. The ionogram corresponding to this N(h) profile is shown together with the original ionogram in fig. 5.1.

The virtual height of the E-layer shows an increase of roughly 6 to 10 km with a very clear retardation cusp near the maximum plasma frequency of the low lying ionization. The critical frequency of the E-layer is found to increase notably. Increasing J_o to 5×10^5 has the effect of bringing the retardation cusp and f_oE closer together. This ionogram corresponds closely to ionograms observed on a number of occasions at Sanae and the Argentine Islands where double cusps are observed in the E-region. Little or no effect due to these electrons is observed at F-region altitudes.

Decreasing the value for E_o to 20 keV and increasing J_o to 1×10^6 yields the ionogram shown in fig. 5.2. Where dotted lines are drawn, absorption would probably result in these areas not being observed in actual soundings. The intermediate layer in the E-region in this ionogram resembles very closely a blanketing sporadic E-layer showing retardation on the low frequency end. This type of sporadic E-layer occurs on a number of occasions at Sanae and the Argentine Islands and typical examples are shown in the IGY manual (1956) fig. 90 and 78 for the station Maui.

Reducing E_o to 10 keV, keeping J_o at 1×10^6 cm^{-2} s^{-1} sr^{-1} produces the ionogram shown in fig. 5.3. In this case the only observable changes that have occurred are an increase in f_oE and a slight increase in $h'F_2$ and f_oF_2. The retardation cusp produced by the electron fluxes is still present but occurs at much lower frequencies.

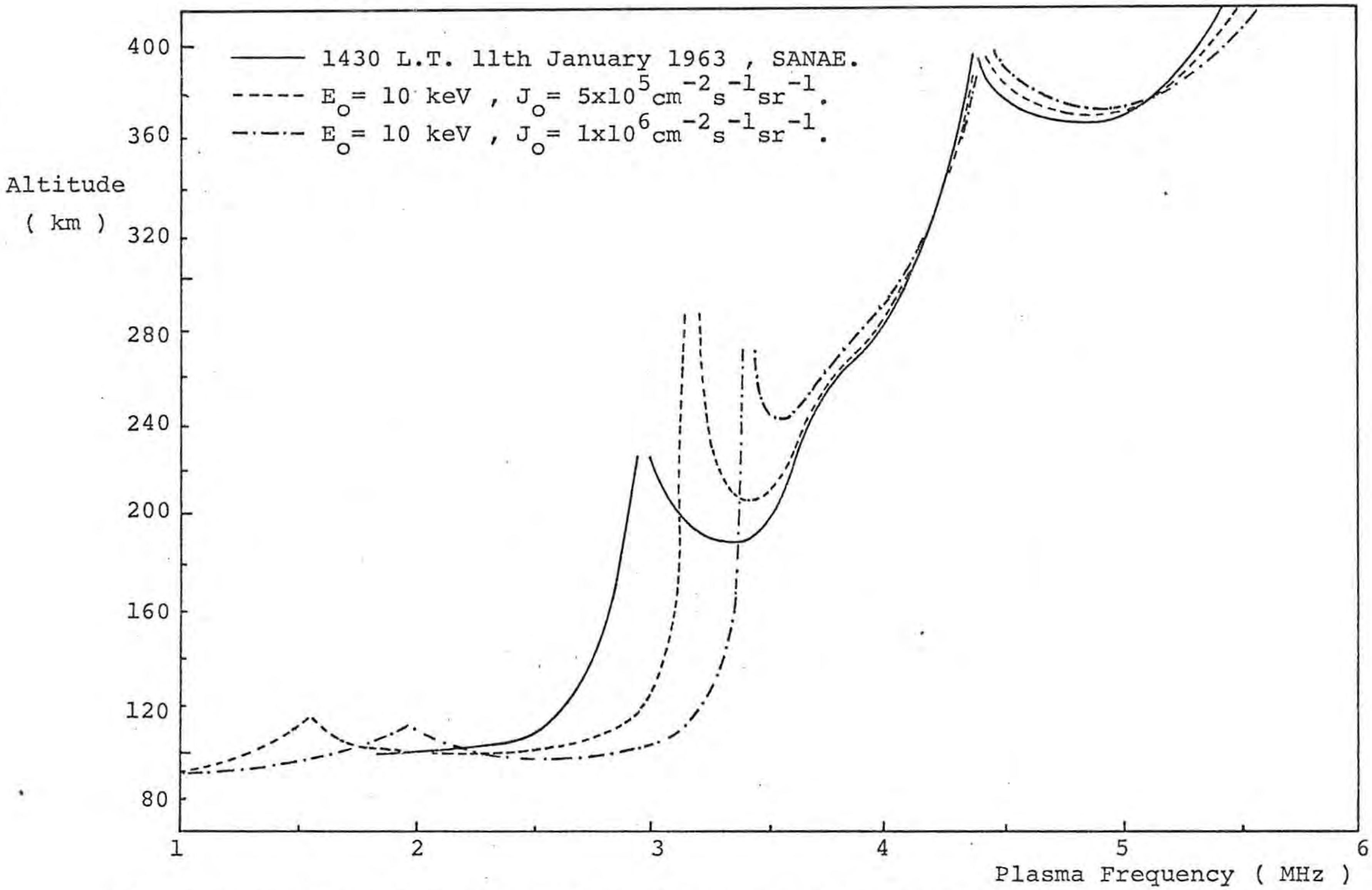


Fig. 5.3 The computed change in an ionogram due to an influx of electrons , E_o= 10 keV.

We may expect that as we decrease E_o further the ionizing effect at F-region altitudes will become more and more predominant and that at E-region altitudes less noticeable.

5.4 Discussion and Conclusions

These results indicate that we may expect an increase in h'E to accompany fluxes of high energy electrons. This increase in h'E is small - of the order of 6 km - and may hardly be regarded as a reliable estimate owing to the simple approach which has been adopted.

For high fluxes of electrons with E_o = 50 keV we may expect a double cusp to occur near the E-critical frequency. A blanketing, or perhaps a partially blanketing sporadic E-layer could be caused by high fluxes of electrons with E_o = 20 keV. For lower values of E_o, the fluxes might only cause an increase in f_oE, with F-region effects becoming more important.

These different effects which are observed for different values of E_o are not absolutely related to the E_o value but depend also on the height of the original E-layer. If we were to increase the height of the E-layer for the N(h) profile used in the analysis, lower energy electrons ($<$ 50 keV) may exhibit the same effect which was previously observed for the 50 keV electrons.

In conclusion the results in this chapter suggest that electron fluxes should be considered as a possible cause of effects such as double cusps, blanketing or partially blanketing sporadic E-layers and increases in the virtual height of the E-layer.

Unfortunately owing to a lack of time, an investigation of the data for a possible correspondence between these effects and high fluxes of electrons could not be undertaken. It may be of interest to future researchers to determine whether these effects show a correspondence with electron fluxes, and if so , to what extent they relate to different spectral characteristics of the fluxes.

The above analysis could also be extended to F-region altitudes for which a solution of the continuity equation would be required in order to predict realistically any possible changes.

Summary

In this investigation of electron effects in the ionosphere, we have dealt with parameters relating to the D-, E- and F-regions.

In chapter 1 we have shown that electron fluxes in the range 40 to 250 keV exhibit a significant correlation with disturbances in the F-region parameters at Sanae and the Argentine Islands. Temperature effects are thought to be predominant in disturbances at Sanae. Ionization may be the main effect at the Argentine Islands. Accompanying high fluxes of low energy electrons (~ 2 keV) are suggested as causing the disturbances. The level of the flux for the Falkland Islands data shows a correlation with K_p indices for $3,75 \leq L \leq 4,25$ but exhibits no significant correlation with K_p for $2,26 \leq L \leq 2,63$.

The calculations in chapter 2 of changes in the ionization density of the ionosphere due to particular fluxes of electrons have shown that electron fluxes measured by Alouette I should exhibit observable effects in the E- and D-regions. Neglecting diffusion effects, high fluxes of low energy electrons (≤ 2 keV)were shown to cause noticeable increases in the F-region ionization density. An observed increase in the ionization density in the ionosphere at Sanae was explained in terms of double exponential spectra of electrons.

The parameter f_{min} was also found to show a correlation with the electron flux density. Ionospheric-stratospheric coupling effects are suggested as being more evident at the Argentine Islands as compared to Sanae.

Correlation plots of the critical frequency of the E-layer for a constant solar zenith angle versus the electron flux have shown a clear association between these two variables.

A mathematical relationship has been suggested between f_oE, the solar zenith angle and the electron flux.

A simple formula has been determined in order to convert the directional flux densities measured by Alouette I at 1 000 km to the omnidirectional fluxes which would be observed at 300 km.

Calculations of the change in f_oE with flux at a constant height have shown a good agreement with the observations.

Calculations have also indicated that electron fluxes should exhibit observable effects on ionograms. The production of a double cusp, a blanketing E_s layer and increases in h'E are shown to be caused by fluxes with different spectral characteristics.

APPENDIX A

L - coordinate range for the Argentine Islands:-

The parameter L is related to the geomagnetic latitude by the equation (Roederer, 1970).

$$L = \frac{1}{\cos^2\theta} \qquad \text{A.1}$$

where θ = geomagnetic latitude.

$$dL = \frac{2\sin\theta}{\cos^3\theta}\, d\theta$$

$$dL = 2L \tan\theta \, d\theta$$

$$\int_{L_o}^{L} \frac{dL}{L} = 2 \int_{\theta_o}^{\theta} \tan\theta \, d\theta$$

$$\log_e L - \log_e L_o = 2(\log_e \cos\theta_o - \log_e \cos\theta) \qquad \text{A.2}$$

The geomagnetic latitude for the Argentine Islands $\theta_o = 53,8^o$ and L_o is 2,45 at approximately 200 km

Substituting these values into A.2 we obtain

for $\theta = 55,4^o$ $\quad L = 2,63$

for $\theta = 52,2^o$ $\quad L = 2,26$

where this $3,2^o$ range in latitude corresponds to a distance of roughly 350 km.

APPENDIX B

The count rate in the 223-type counter-on board Alouette I-due to particles penetrating the side shielding is given by the rate of the 302-type counter multiplied by the ratio of the omnidirectional geometric factors and the ratio of the solid angles for which the shielding of the two counters is a minimum. (The 223-type counter measured electrons with energies greater than 40 keV and protons greater than 500 keV.)

$$\text{Corrected 223 count rate} = \text{observed 223 count rate} - 302 \text{ count rate} \times \frac{0{,}27}{0{,}55} \times \frac{2{,}0}{2{,}4}$$

$$= \text{observed 223 count rate} - 1/3 \times 302 \text{ count rate.}$$

The corrected rate was converted to directional flux density by means of the directional geometric factor and counting efficiency suggested by McDiarmid (private communication).

$$\text{Directional flux density} = \frac{\text{corrected 223 count rate}}{5{,}05 \times 10^{-4} \times 0{,}9}$$

$$= 2\ 200 \times \text{corrected 223 count rate.}$$

APPENDIX C

The linear regression correlation coefficient used in the analysis is defined by

$$r' = \frac{v(x,y)}{[v(x,x)\ v(y,y)]^{\frac{1}{2}}} \qquad C.1$$

where

$$v(x,y) = \Sigma\, xy - \frac{\Sigma x\, \Sigma y}{N}$$

$$v(x,x) = \Sigma\, x^2 - \frac{(\Sigma x)^2}{N}$$

$$v(y,y) = \Sigma\, y^2 - \frac{(\Sigma y)^2}{N}$$

APPENDIX D

The product moment correlation coefficient for a 2 x 2 contingency table is defined by Kendall (1952).

For the table

a	b	a + b
c	d	c + d
a+c	b+d	N

where N = a + b + c + d the correlation coefficient

$$r = \frac{Na + (a+b)(a+c)}{\left[(a+b)\ (b+d)\ (c+d)\ (a+c)\right]^{\frac{1}{2}}} \qquad D.1$$

APPENDIX E

The mirror altitude for St. Johns data over Sanae:-

For a dipole field

$$B \propto \frac{1}{r^3} \qquad \text{E.1}$$

The magnetic field at the conjugate point to Sanae at the surface

$$B_o = 0{,}530 \text{ gauss.}$$

For Sanae at the surface

$$B = 0{,}425 \text{ gauss.}$$

Thus B at 1 000 km over the conjugate area (using E.1) will be

$$B_{1\,000} = \left(\frac{6\,380}{7\,380}\right)^3 B_o$$

$$= 0{,}342 \text{ gauss.}$$

B over Sanae = 0,342 gauss at an altitude of 476 km.

Thus electrons measured at 1 000 km over the conjugate St. Johns area will mirror below $\sim$450 km at Sanae.

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