SPREAD-F AND THE PERTURBATIONS OF THE MAXIMUM ELECTRON DENSITY OF THE F LAYER

By D. G. SINGLETON*

[*Manuscript received November* 6, 1961]

Summary

An analysis has been made of spread-F data obtained from I.G.Y. f-plots for several ionosonde stations grouped about longitude 75° W. to establish whether there is any connection between the severity of frequency-spreading (Δf) and the time of day, season of the year, magnetic activity, height of the F layer, critical frequency of the F layer, and the latitude of the ionosonde station. The diurnal variations of the severity of frequency spreading are found to vary considerably with latitude and season and no clear pattern emerges. Magnetic activity affects the value of Δf but again in a complex way which varies with latitude. The magnitude of Δf seems to be greatest when the layer is high and descending at low and middle latitudes but not at high latitudes. At all latitudes the magnitude of Δf is greatest when the critical frequency is lowest. This is considered to be the dominant effect having a profound influence on the diurnal and seasonal distributions of Δf. These results are discussed in terms of the hypothesis that frequency spreading is due to the availability of a range of values of $N_{\text{max.}}$ at the maximum of the F_2 layer. This range of values is thought to correspond to a system of irregularities each involving an enhancement or a deficiency of electron density relative to the background ionization. The extra ionization involved in the irregularities is estimated to be of the order of 10^5 electrons/c.c. and is found to vary little with season, magnetic activity, and latitude.

I. INTRODUCTION

Several authors (Gipps, Gipps, and Venton 1948 ; Little 1951 ; Kasuya, Katano, and Taguchi 1955 ; Singleton 1957 ; Briggs 1958*a*, 1958*b* ; Martyn 1959) have suggested that the cause of frequency spreading is to be found in irregular spatial variations of the maximum electron density in the F_2 layer. The range of penetration frequencies involved f_0 to $f_0+\Delta f$ is considered to correspond to the range of values of maximum electron density N_m to $N_m+\Delta N$ within " view " of the ionosonde. It is of considerable interest, from the point of view of explaining the mode of formation of these perturbations in N_m, to consider their amplitude and how this might vary with such factors as the time of day, season of the year, magnetic activity, the height of the F layer, the critical frequency of the F layer, and the latitude of the ionosonde station. This paper reports the results of such a study carried out on data from several ionosonde stations at different latitudes.

II. SOURCE OF DATA

As pointed out in an earlier paper (Singleton 1960) the f-plots (Wright, Knecht, and Davies 1957) prepared by the ionosonde observatories during the I.G.Y. provided an accurate and convenient source of frequency-spreading data.

* Physics Department, University of Queensland, Brisbane.

From this data it is possible to obtain information concerning the range of frequencies over which the overall penetration through the F_2 layer is spread. However, the overlapping of *o*- and *x*-rays sometimes makes it impossible to determine unambiguously the spread in the penetration of the *o*-ray alone. In Figure 1, only in the first case illustrated can the *o*-ray's spread Δf_0 be determined. In the second case only the combined spread Δf can be determined. It might be argued that a reasonable estimate of Δf_0 could be obtained in the second case by subtracting from the total spread the normal separation $(f_x - f_0)$ between the *o*- and *x*-rays. This gives the spread (Δf_x) in the *x*-ray. Experience gained in examining many ionograms involving frequency spreading suggests, however, that the apparent *x*-ray spreading is often less than the *o*-ray spreading (presumably because of the difference in the absorption of the two rays).

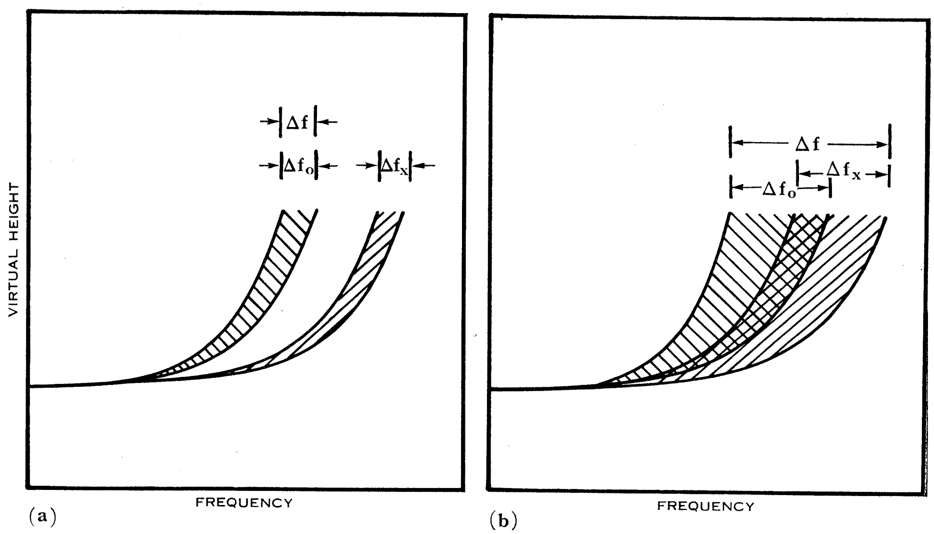

Fig. 1.—Sketches of ionograms which illustrate the manner in which Δf is related to Δf_0 and Δf_x.

Thus the *x*-ray spreading is not a reliable indication of the *o*-ray spreading. The *o*-ray spreading information is preferred because of the greater ease of interpretation. Consequently no attempt has been made to separate the *o*- and *x*-ray spreading in these cases in the initial analysis but, as will be seen later, due account of this effect is made when interpreting the results obtained.

Results from the group of stations listed in Table 1 have been analysed. These stations have similar longitudes but a wide range of latitudes. Comparison of results from such stations can be expected to yield information concerning the variation with latitude of any relationships found.

III. The Diurnal and Seasonal Variations

Typical stations in the three main zones of spread-*F* activity, the equatorial, middle latitude, and auroral zones (Singleton 1960) namely Huancayo, Ft. Monmouth, and Thule, have been chosen for detailed consideration as far as diurnal and seasonal distributions are concerned. In Figure 2 the diurnal variation of the monthly mean value of Δf is presented for each of these stations and for the months of July and September 1957 and January 1958. It is immediately obvious that there are considerable changes in the apparent diurnal distributions of spread-F activity, as measured in terms of Δf, from season to season and from latitude to latitude. In summer the values of Δf are low at Thule and Ft. Monmouth but peak sharply at 0200 at Huancayo. At the equinoxes night-time peaks occur at 2000 to 2200 h at Huancayo, at 0500 h at Ft. Monmouth, and between 1800 and 0600 h at Thule. In winter there is little activity at Huancayo, a small peak at 0200 at Ft. Monmouth, while Thule experiences a general increase in activity with a minimum at 0100.

While the possibility that these variations may be real and characteristic of season and latitude cannot be eliminated, the inconsistency of the overall

TABLE 1

THIS TABLE LISTS THE INFORMATION CONCERNING THE RANGE OF VALUES OF ΔN (el/c.c.) OBSERVED FOR THE SEVERAL STATIONS AND SEASONS. IT ALSO CONTAINS THE VALUES OF THE PARAMETER ($f_H \cos\theta$) CONSIDERED IN RELATION TO THE EFFECT WHICH ABSORPTION HAS ON Δf

Station	Geom. Lat.	Geog. Lat.	f_H at 200 km (Mc/s)	Dip ($90°-\theta$)	$f_H \cos\theta$ (Mc/s)	Season	ΔN derived from Δf (el/c.c.)
Thule ..	87·0° N.	76·6° N.	1·4	87·0°	1·40	Summer	5×10^4 to 2×10^5
						Equinox	5×10^4 to 3×10^5
						Winter	$7\cdot5\times10^4$ to 7×10^5
Baker Lake	73·7° N.	64·3° N.	1·5	86·6°	1·50	Summer	10^5 to 5×10^5
						Equinox	10^5 to 5×10^5
						Winter	10^5 to 5×10^5
Winnipeg	59·8° N.	49·9° N.	1·6	77·7°	1·56	Summer	5×10^4 to 2×10^5
						Equinox	5×10^4 to 2×10^5
						Winter	5×10^4 to 5×10^5
Ft. Monmouth	51·0° N.	40·3° N.	1·5	72·0°	1·43	Summer	$3\cdot5\times10^4$ to 2×10^5
						Equinox	5×10^4 to 2×10^5
						Winter	5×10^4 to 2×10^5
White Sands	41·2° N.	32·3° N.	1·3	62·0°	1·15	Summer	5×10^4 to 2×10^5
						Equinox	5×10^4 to 2×10^5
						Winter	5×10^4 to 2×10^5
Talara ..	6·6° N.	4·6° S.	0·8	13·0°	0·18	Summer	10^5 to 5×10^5
						Equinox	10^5 to 10^6
						Winter	2×10^5 to 10^6
Huancayo	0·6° S.	12·0° S.	0·7	1·0°	0·01	Summer	2×10^5 to 10^6
						Equinox	10^5 to 10^6
						Winter	10^5 to 5×10^5

picture presented suggests that any real temporal distribution is probably being modified by the variation of some factor or factors which influence the value of Δf observed. One factor which is believed to play a part in the occurrence of spread-F is the state of disturbance of the Earth's magnetic field and the possible influence of magnetic activity on the magnitude of Δf is considered in the next section.

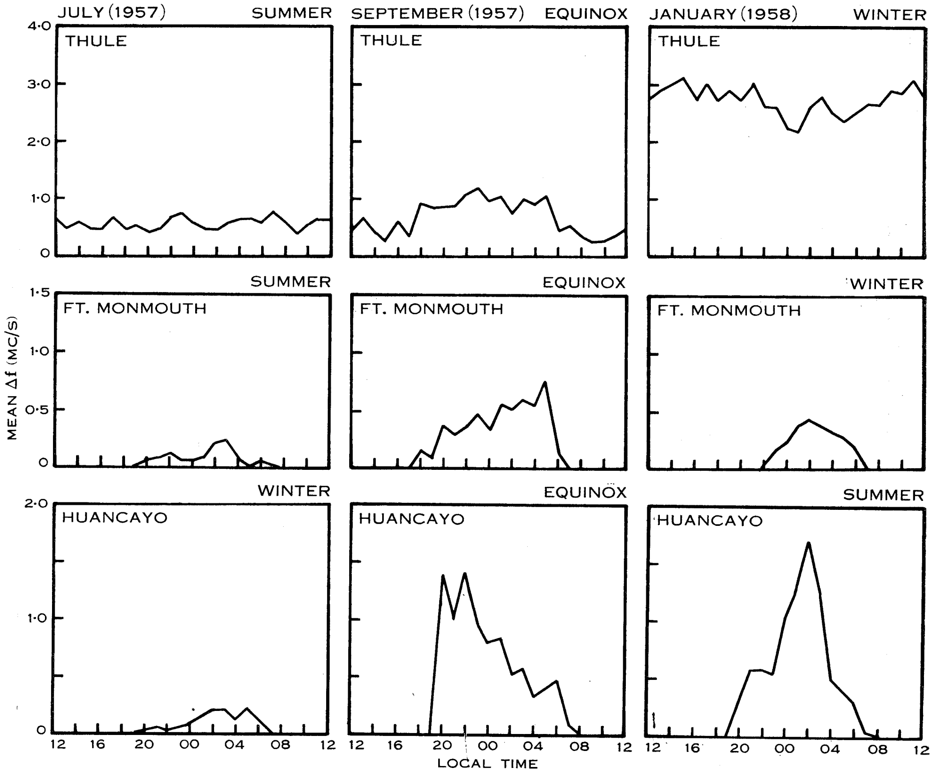

Fig. 2.—The diurnal variations of the monthly mean values of Δf for Huancayo, Ft. Monmouth, and Thule and for each of the months July and September 1957 and January 1958.

IV. The Effect of Magnetic Activity

The lower graphs (c) of Figures 3, 4, and 5 represent the diurnal distributions of the mean value of Δf for the five magnetically quiet days (full lines) and five magnetically disturbed days (broken lines) for each of the months July and September 1957 and January 1958 and for the three stations Huancayo, Ft. Monmouth, and Thule. For all three stations and for all three seasons there are differences in the diurnal distributions for magnetically quiet and disturbed days. For Huancayo (Fig. 3) and disturbed days the activity peaks after midnight for all seasons but on quiet days the activity is mainly before midnight in the winter and equinox and after midnight in summer. At Ft. Monmouth (Fig. 4) the activity during disturbed days is mainly after midnight in the solstices but before midnight in the equinox. For quiet days at this location the situation is just the reverse of that for the disturbed days, the activity peak coming after midnight in the equinox and before midnight in the solstices. An interesting difference between Ft. Monmouth and Huancayo is that in general the activity peaks at larger values on disturbed days than on quiet days at Ft. Monmouth but on quiet rather than disturbed days at Huancayo. In the case of Thule (Fig. 5), the lack of diurnal distribution in summer is independent of magnetic activity. The diurnal distribution in the equinox peaks before midnight on

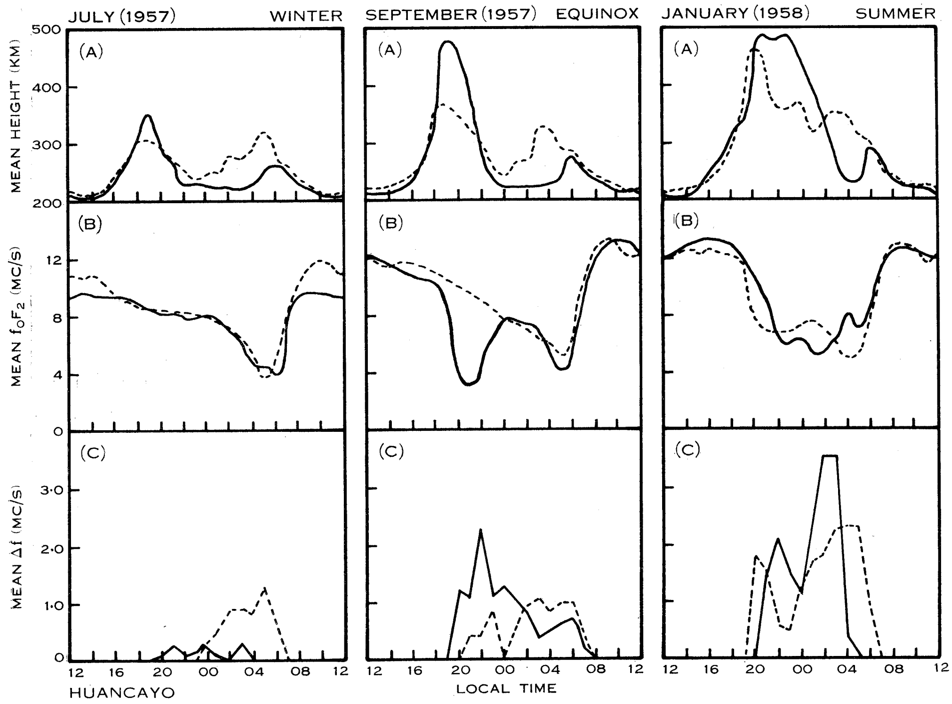

Fig. 3.—The diurnal variations of layer height (group A), critical frequency (group B), and Δf (group C) for Huancayo and each of the months of July and September 1957 and January 1958. The full-line curves correspond to magnetically quiet conditions while the broken-line curves correspond to magnetically disturbed conditions.

quiet days and after midnight on disturbed days. Also the apparent midday maximum noted previously for winter conditions at Thule is only recognizable on magnetically quiet days, there being little diurnal distribution on disturbed days. For this station the overall level of activity seems to change little from magnetically quiet to magnetically disturbed days.

It appears from this that considera tion of the distributions for magnetically quiet and disturbed days separately does little to systematize the results. This analysis suggests, however, that magnetic activity does have an influence on Δf possibly through its influence on some other factor which plays a major part in determining the magnitude of Δf.

V. The Effect of F-layer Height on the Magnitude of Δf

It has been suggested (Booker and Wells 1938; Osborne 1952; Kasuya, Katano, and Taguchi 1955; Bowman 1960*a*, 1960*b*; Lyon, Skinner, and Wright 1960*a*, 1960*b*, 1961) that the height of the F layer plays a part in the occurrence of spread-F. In general the incidence is found to be greater the higher the layer. Consequently it is of interest to examine what role, if any, this property of the layer has in determining the magnitude of Δf. The most appropriate height

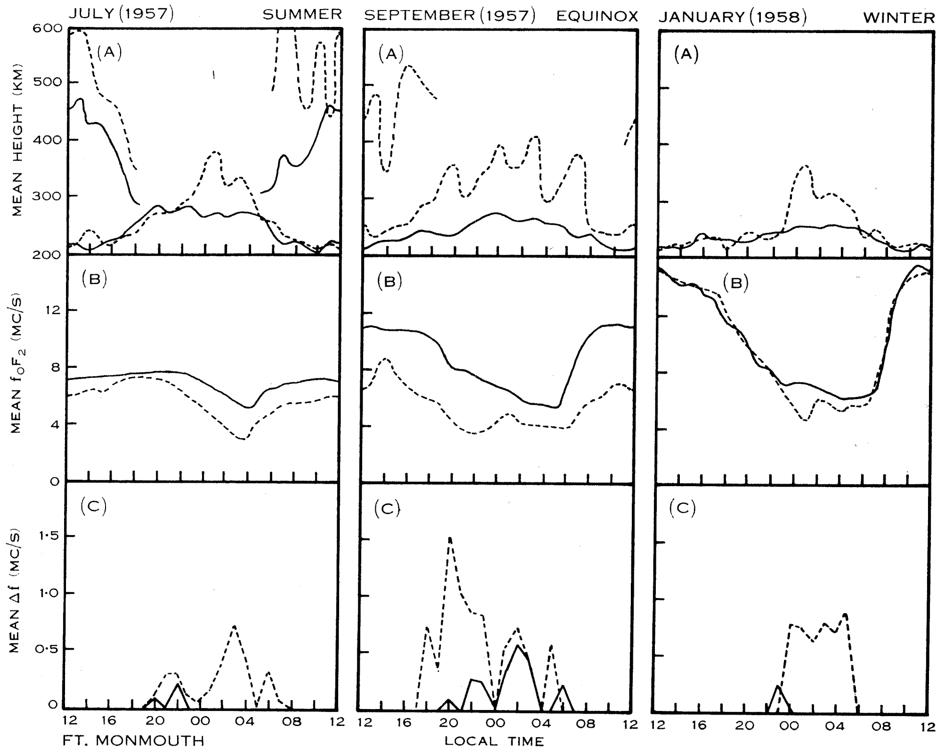

Fig. 4.—The diurnal variations of layer height (group A), critical frequency (group B), and Δf (group C) for Ft. Monmouth and each of the months of July and September 1957 and January 1958. The full-line curves correspond to magnetically quiet conditions while the broken-line curves correspond to magnetically disturbed conditions.

parameter to use in an analysis of this sort would be the true height of the ionization density maximum of the F_2 layer. However, this parameter is not readily available and the published values of the virtual height of the bottom of the F layer have been used. Lyon, Skinner, and Wright (1961) have shown that this quantity tends to follow the height of the layer maximum in equatorial latitudes and it will be assumed here that this is true at all latitudes.

The curves (a) of the upper parts of Figures 3, 4, and 5 show how the mean value of the virtual height of the bottom of the layer for the five magnetically quiet days (full lines) and five magnetically disturbed days (broken lines) varies with time of day for each of the three seasons and for each of the three stations considered. The lower curves of this group, which persist throughout the whole

24 hr, correspond to the $h'F$ values, whereas the upper curves, which are only present in some cases, correspond to the $h'F_2$ values. These latter cases correspond to those times when the bifurcation of the F layer into F_1 and F_2 layers is complete enough to make the determination of $h'F_2$ practicable.

Considering Huancayo (Fig. 3), it is seen that on quiet days the layer height is a maximum at 1900 to 2000 and at 0600 in each of the seasons and that the frequency-spreading activity appears between these times. The activity peaks do not correspond to the peak in the layer height distribution but occur when

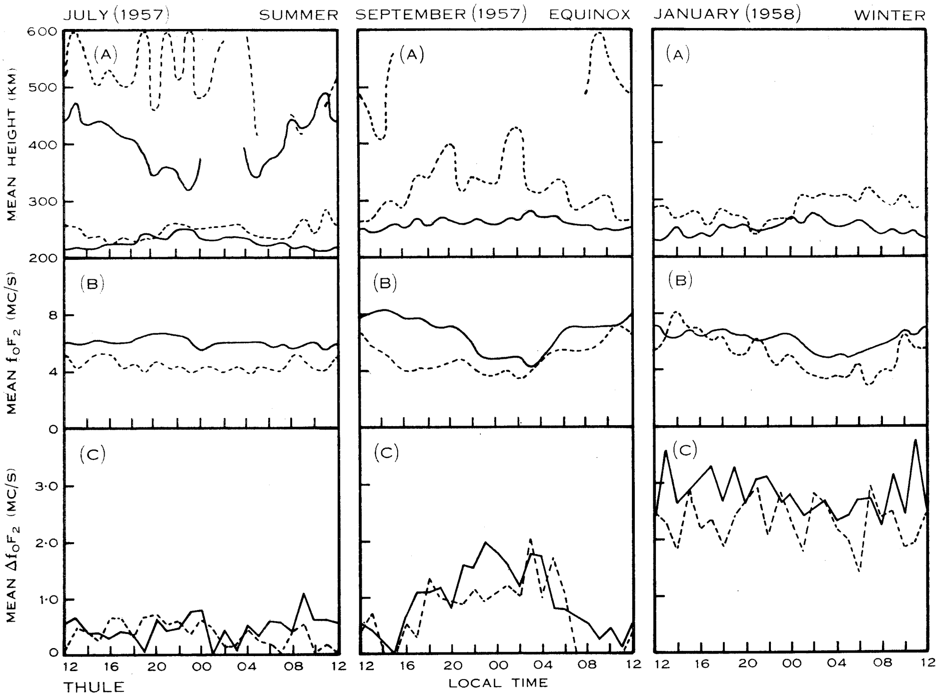

Fig. 5.—The diurnal variations of layer height (group A), critical frequency (group B), and Δf (group C) for Thule and each of the months of July and September 1957 and January 1958. The full-line curves correspond to magnetically quiet conditions while the broken-line curves correspond to magnetically disturbed conditions.

the layer is moving down. This effect is particularly noticeable in the equinox and in summer. The major activity peak in each case corresponds to the centre of the downward height trend following the earlier of the two height peaks. On magnetically disturbed days at Huancayo the height distribution again involves double peaks the earlier of which occurs at much the same time as that for quiet days whereas the later peak occurs two or so hours earlier than its quiet day analogue. Here we find that the peaks in the Δf distribution occur much closer in time to the peaks in the height distribution than is the case for magnetically quiet days.

Turning to Ft. Monmouth (Fig. 4) we see that the post sunset and dawn rises in $h'F$ experienced at Huancayo do not exist here and that on magnetically quiet days the distributions of $h'F$ are quite smooth involving heights below 300 km. On magnetically disturbed days however, the night-time values of $h'F$ do undergo fairly sudden increases and subsequent decreases and again it is found that the severity of frequency spreading takes on high values when the layer is moving down. This effect is ,particularly noticeable in the solstices. For Ft. Monmouth F_1–F_2 bifurcation occurs mainly during the day when the spread-F activity is zero.

In the case of Thule (Fig. 5) the bifurcation of the F layer in summer particularly and also in the equinox confuses the situation as far as the effect of layer height on Δf is concerned. In the winter the general high level of frequency-spreading activity regardless of magnetic activity is accompanied by generally smooth distributions of $h'F$ involving heights not much greater than 300 km. This suggests that at these latitudes the layer need not necessarily be high nor be moving down in order that frequency spreading should occur.

The general conclusion to be drawn from the discussion of this section seems to be that frequency-spreading activity, as measured by Δf, is greatest when the layer is high and moving down in low and middle latitudes, but that this possible effect is not operative at high latitudes.

VI. The Effect of F-layer Critical Frequency on the Magnitude of Δf

It has been shown (Singleton 1957) that at Brisbane the incidence of frequency spreading is high when the critical frequency of the F_2 layer is low. This result was later confirmed by Bowman (1960*b*) and extended to include Townsville and Hobart. It is of interest therefore to examine the present data for a possible connection between Δf and f_0F_2. The central set of curves (*b*) in Figures 3, 4, and 5 show how the mean value of f_0F_2 for the five magnetically quiet days (full lines) and five magnetically disturbed days (broken lines) varies with time of day for each of the three seasons at the three stations considered.

Considering Huancayo (Fig. 3) it is immediately obvious that at times when the critical frequency is low the mean value of Δf is high. A particularly striking example of this is to be found in the equinox quiet day situation where an unusually deep minimum in f_0F_2 occurs at 2100 and this is associated with a strong peak in the mean value of Δf. Another example exists in summer where on quiet days the minimum value of f_0F_2 occurs at 0200 and is associated with the major peak in Δf, whereas on disturbed days the minimum value of f_0F_2 is not attained until 0400 and this also corresponds to the peak of Δf. It can be said that in general when f_0F_2 drops below 8 Mc/s Δf rises above zero to a value which increases as the depression below 8 Mc/s increases.

In the case of Ft. Monmouth (Fig. 4) the situation is similar to that at Huancayo. For instance, in the equinox on disturbed days the minimum value of f_0F_2 is attained at 2100 to 2200 and the peak of frequency-spreading activity is at 2000, whereas on quiet days the f_0F_2 minimum is between 0300 and 0600 and Δf maximizes at 0200. Again depressions of f_0F_2 below about 8 Mc/s are in general accompanied by roughly proportionate increases in Δf.

For the solstices at Thule (Fig. 5) the critical frequency is below 8 Mc/s on both quiet and disturbed days and in summer there is little variation in f_0F_2 from hour to hour. This is matched by the absence of a significant diurnal variation in Δf for both quiet and disturbed conditions. For September, however, there is an appreciable diurnal variation in f_0F_2 for both quiet and disturbed conditions and in both cases the night-time depression of f_0F_2 is accompanied by increases in frequency-spreading activity.

The general conclusion to be drawn from this discussion is that, independent of latitude, the lower the critical frequency the higher the value of Δf likely to be experienced in an occurrence of frequency-spreading. Since f_0F_2 is a measure of the maximum electron density of the F_2 layer (N_m) and Δf depends on the perturbation of this (ΔN), it is of considerable interest to examine this Δf and f_0F_2 association to see what type of association is implied between ΔN and N_m.

In Appendix I the penetration of radio waves through a system of irregularities of maximum electron density $N_m+\Delta N$ embedded in a layer of maximum density N_m is considered. It is shown that the relationship between N/N_m, Δf, f_0 (i.e. f_0F_2), and the gyrofrequency (f_H) is

$$\frac{\Delta N}{N_m}=\frac{1}{f_0}\left\{\Delta f+\Delta f\left(1+\frac{\Delta f}{f_0}\right)\right\},$$

when there is no overlap of the o-ray and x-ray spreading (Fig. 1 (a)) and

$$\frac{\Delta N}{N_m}=\frac{1}{f_0}\left\{\Delta f+(\Delta f-f_H)\left(1+\frac{\Delta f}{f_0}\right)\right\},$$

where there is overlap (Fig. 1 (b)). With the aid of these equations it is possible to obtain a family of curves showing how Δf varies with f_0 for various constant values of the parameter $\Delta N/N_m$. This family of curves for the gyrofrequency of Ft. Monmouth appears in Figure 6 (a). The part of this figure below the lower dashed curve represents values of Δf which are possible for the case of no overlap of the o-ray and x-ray spreading. The part above the upper dashed curve represents the values of Δf associated with overlapping o- and x-ray spreading.

Also in Appendix I it is shown that the relationship between ΔN, Δf, f_0, and f_H is

$$\Delta N=\frac{\pi m}{e^2}f_0\left\{\Delta f+\Delta f\left(1+\frac{\Delta f}{f_0}\right)\right\},$$

where there is no overlap of the o-ray and x-ray spreading, and

$$\Delta N=\frac{\pi m}{e^2}f_0\left\{\Delta f+(\Delta f-f_H)\left(1+\frac{\Delta f}{f_0}\right)\right\},$$

where there is overlap. Figure 6 (b) has been drawn with the aid of these two equations for constant values of the parameter ΔN and Ft. Monmouth conditions. Again the part of the figure below the lower dashed curve represents those values of Δf which are possible in the case of no overlap of the o-ray and x-ray spreading. The part above the upper dashed curve represents the values of Δf associated with overlapping o- and x-ray spreading.

Comparison of Figures 6 (*a*) and 6 (*b*) shows that the two families of lines represent two completely different trends. The general trend of the lines in Figure 6 (*b*) is toward increasing Δf as f_0 decreases while the trend exhibited in Figure 6 (*a*) is for Δf to decrease as f_0 decreases. The conclusion has been reached above that Δf increases as f_0 decreases therefore it seems more likely that ΔN rather than $\Delta N/N_m$ should remain constant, or at least roughly so, as f_0 varies.

More evidence to this effect is obtained by constructing scatter diagrams, of Δf *versus* f_0. Figures 7, 8, and 9 are scatter diagrams of this type for Huancayo, Ft. Monmouth, and Thule for the five magnetically quiet and five magnetically disturbed days in each of the months July and September 1957 and January

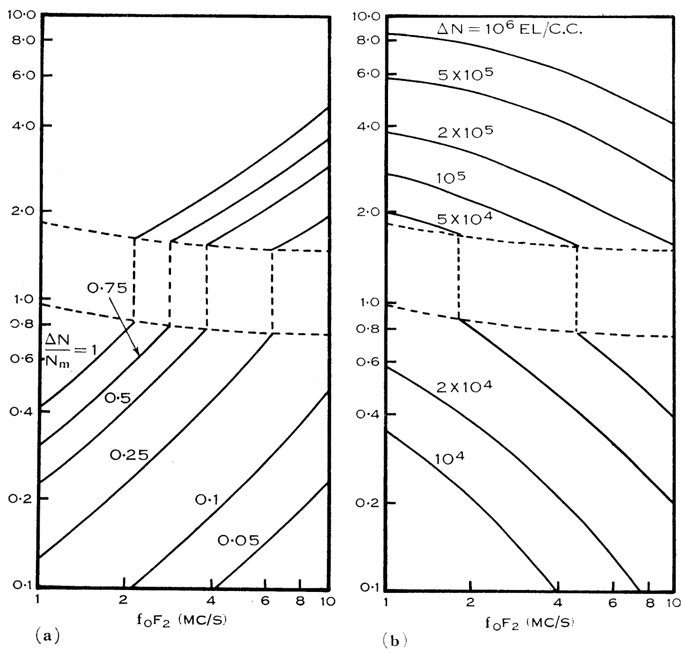

Fig. 6.—This diagram illustrates how Δf varies with f_0F_2: (*a*) when the parameter $\Delta N/N_m$ is held constant and (*b*) when the parameter ΔN is held constant.

1958. They are based on the measurements made on the hour. The crosses correspond to the simple situation where there is no overlap of the *o*- and *x*-ray spreading and the points correspond to those cases where Δf results from an overlap of the *o*- and *x*-ray spreading. The full lines on these figures correspond to the expected variation of Δf with f_0 for the indicated constant values of ΔN. These lines vary slightly in shape from one figure to another because the values of f_H are different at the various stations.

On these diagrams there are some points which obviously correspond to occurrences of frequency-spreading which involve overlap and others which do not involve overlap. Besides these there are points which fall into the region between the two dashed curves. These points correspond to cases where the *o*-ray penetration appears to be spread right up to the *x*-ray penetration but

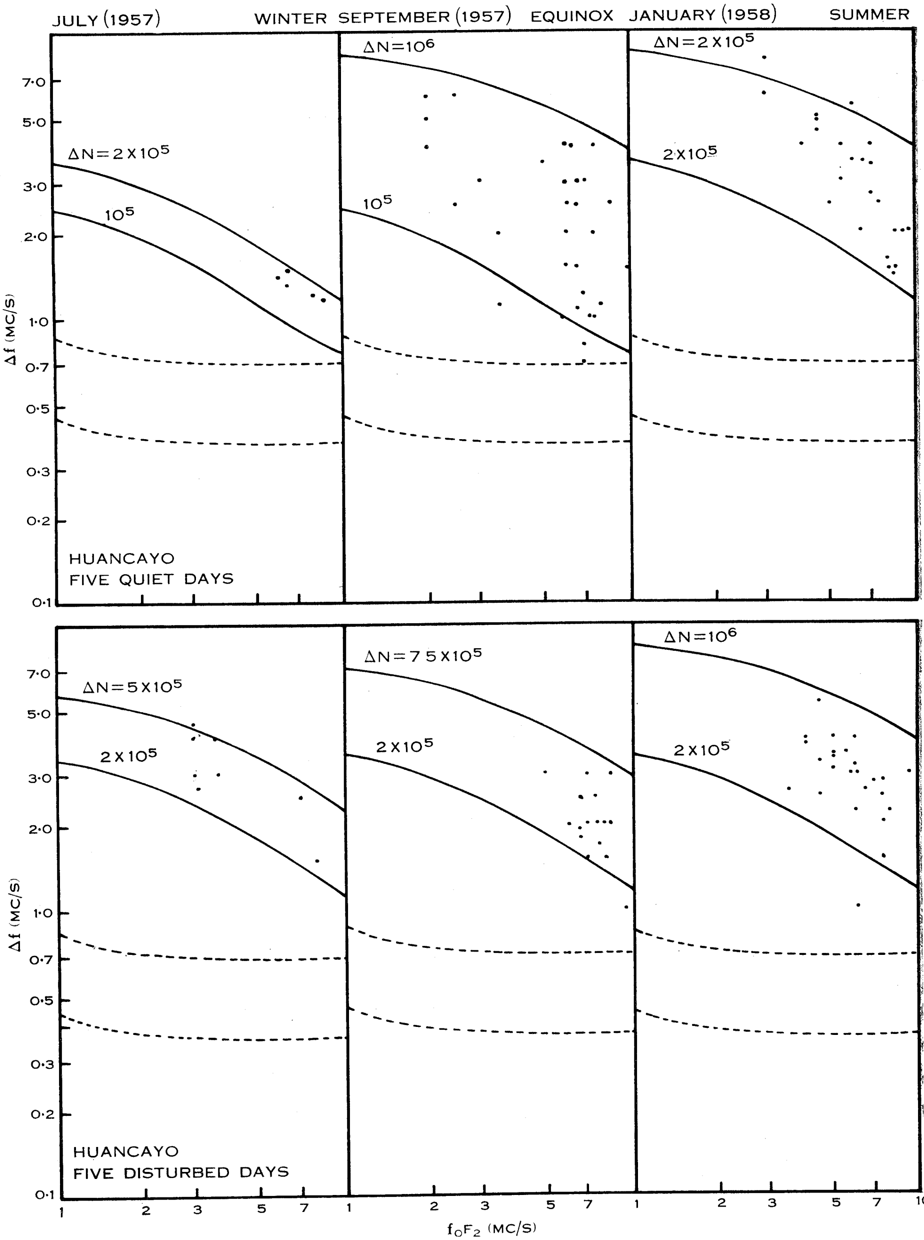

Fig. 7.—Scatter diagrams of Δf *versus* f_0F_2 for Huancayo on magnetically quiet and disturbed days during the months of July and September 1957 and January 1958. The full lines represent the expected variation of Δf with f_0F_2 for the indicated constant values of ΔN.

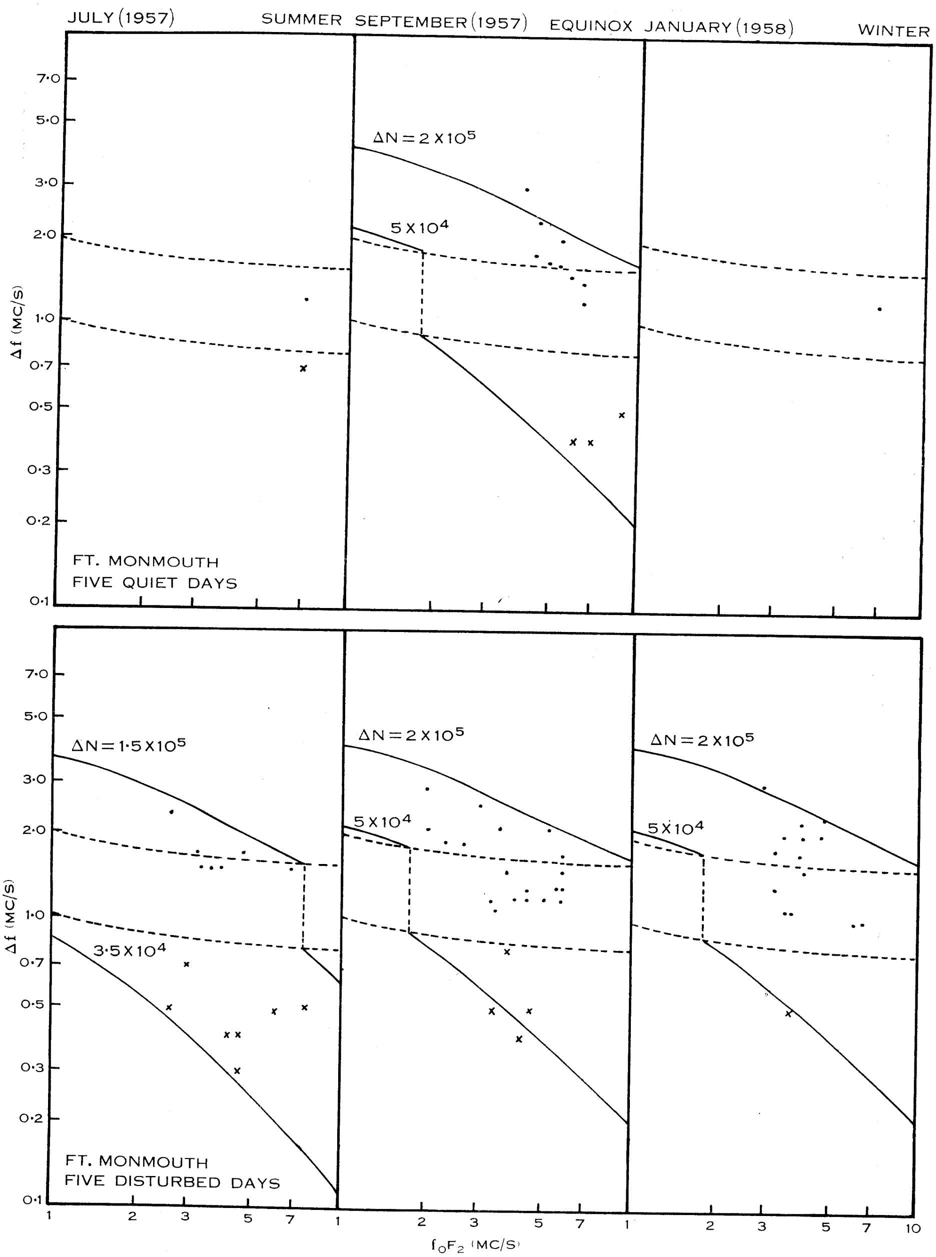

Fig. 8.—Scatter diagrams of Δf *versus* f_0F_2 for Ft. Monmouth on magnetically quiet and disturbed days during the months of July and September 1957 and January 1958. The crosses correspond to spreading of the type indicated in Figure 1 (*a*), while the points correspond to overlapping *o*- and *x*-ray spreading (Fig. 1 (*b*)). The full lines represent the expected variation of Δf with f_0F_2 for the indicated constant values of ΔN.

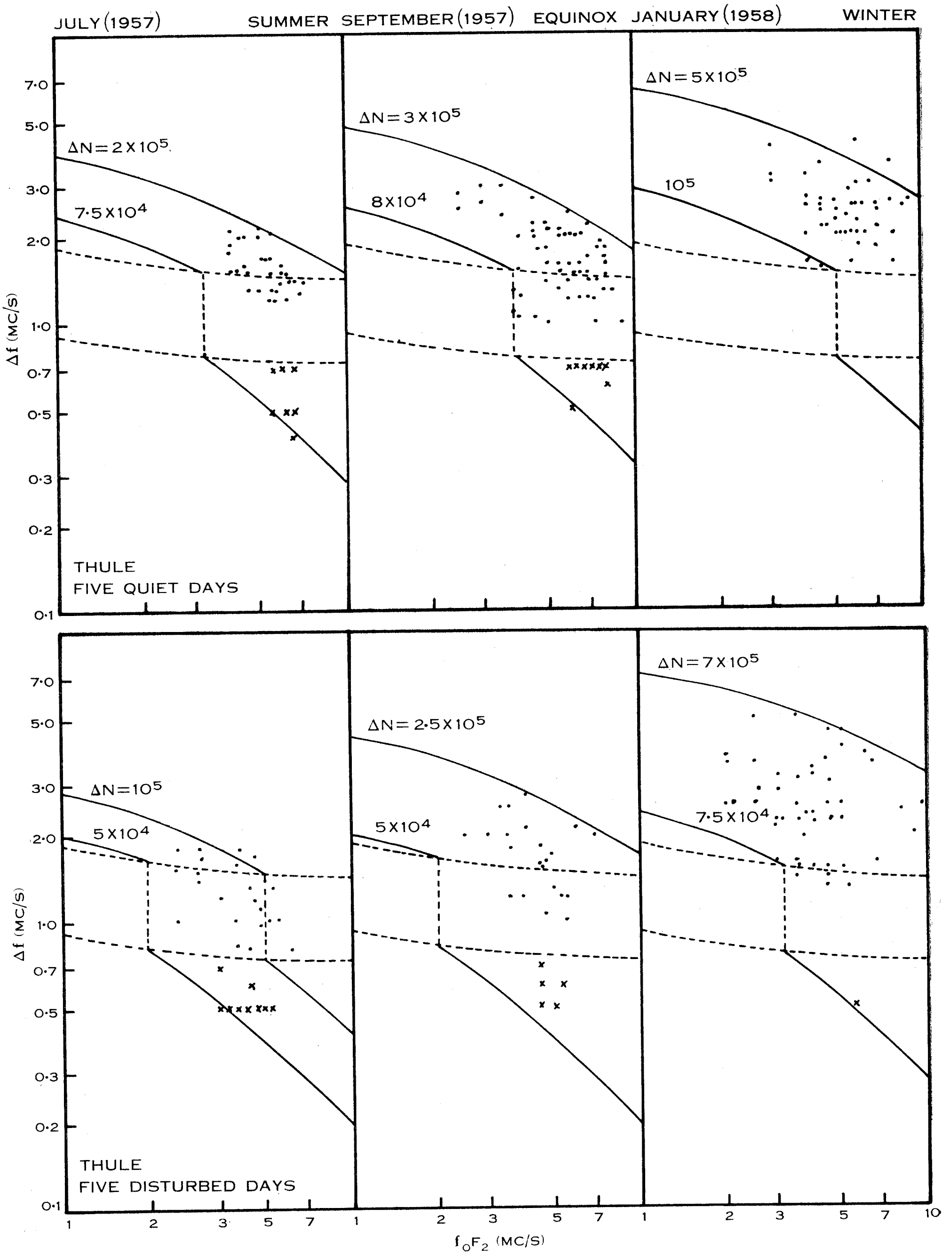

Fig. 9.—Scatter diagrams of Δf *versus* f_0F_2 for Thule on magnetically quiet and disturbed days during the months of July and September 1957 and January 1958. The crosses correspond to spreading of the type indicated in Figure 1 (*a*), while the points correspond to overlapping *o*- and *x*-ray spreading (Fig. 1 (*b*)). The full lines represent the expected variation of Δf with f_0F_2 for the indicated constant values of ΔN.

where the x-ray is not spread to the same extent. Neglecting these points for the moment, it is seen that the other two groups of points for each season and station confirm that there is a tendency for Δf to increase as f_0 decreases. The scatter is such that the upper limiting value of ΔN is never more than 10 times greater than the lower limiting value. In most cases the range of values of ΔN is considerably less than this. The ranges of values of ΔN involved are listed in Table 2.

A possible explanation of why points should fall within that region of each of the scatter diagrams bounded by the dashed lines has been foreshadowed in Section II. There it was suggested that in general the x-ray spreading is not as severe as the o-ray spreading. The reason for this is believed to be the difference in absorption for the two modes of propagation. Details of the mechanism involved here are discussed in Appendix II.

While this absorption effect possibly explains the appearance of points in the otherwise forbidden zones on the scatter diagrams for the higher latitude stations, it also means that the points above the forbidden zones may need to be moved up in these cases. There is then some uncertainty as to the value of the upper limit placed on ΔN. Comparison of equations (7) and (9) of Appendix I shows that, in the extreme case where there is overlap but no x-ray spreading, the application of equation (7) instead of (9) leads to a value of ΔN which is half of the true value. In most cases the error will be much less than this.

The lower limit placed on ΔN is, in general, set by the lower group of points, that is, those corresponding to occurrences not involving overlap of o- and x-ray spreading. The lower limit consequently is not subject to the type of uncertainty associated with the upper limit.

Examination of Table 2 shows that the Thule quiet day values of ΔN are at the most 50% higher than the disturbed day values, the Huancayo disturbed day values in winter are twice as large as the quiet day values, and that there is otherwise no change in the range of values of ΔN when proceeding from mag-

TABLE 2

THIS TABLE LISTS THE RANGES OF VALUES OF ΔN (el/c.c.) FOUND AT THULE, FT. MONMOUTH, AND HUANCAYO IN THE THREE SEASONS UNDER MAGNETICALLY QUIET AND DISTURBED CONDITIONS

Station	Season	Five Quiet Days ΔN (el/c.c.)	Five Disturbed Days ΔN (el/c.c.)
Thule	Summer (July 1957)	$7\cdot5\times10^4$ to 2×10^5	5×10^4 to 10^5
	Equinox (Sept. 1957)	8×10^4 to 3×10^5	5×10^4 to $2\cdot5\times10^5$
	Winter (Jan. 1958)	10^5 to 5×10^5	$7\cdot5\times10^4$ to 7×10^5
Ft. Monmouth	Summer (July 1957)		$3\cdot5\times10^4$ to $1\cdot5\times10^5$
	Equinox (Sept. 1957)	5×10^4 to 2×10^5	5×10^4 to 2×10^5
	Winter (Jan. 1958)		5×10^4 to 2×10^5
Huancayo ..	Summer (Jan. 1958)	2×10^5 to 10^6	2×10^5 to 10^6
	Equinox (Sept. 1957)	10^5 to 10^6	2×10^5 to $7\cdot5\times10^5$
	Winter (July 1957)	10^5 to 2×10^5	2×10^5 to 5×10^5

netically quiet to disturbed conditions. Similarly the seasonal variation in ΔN is small. There is some suggestion that ΔN might be slightly greater in winter in Thule whereas at Huancayo ΔN is a maximum in summer. There is also no gross variation in ΔN with latitude. Table 2 shows that the Thule and Huancayo values are slightly larger than those for Ft. Monmouth, there being no more than a factor of five involved. The general lack of a seasonal variation and the very slight variation with latitude are further illustrated by Table 1. This lists along with the Thule, Ft. Monmouth, and Huancayo results those for four further stations intermediate in latitude to these. These values of ΔN were obtained by the above scatter diagram technique without regard to any possible effect of magnetic activity.

VII. Discussion

In terms of the hypothesis that frequency-spreading is due to irregular spatial variations of maximum electron density in the F_2 layer, it has been possible to draw the following conclusion concerning the nature of the irregularities. The maximum deviation of the ionization density in the irregularities from the background density is of the order of 10^5 electrons/c.c., and does not vary by more than a factor of five from season to season or from station to station.

As a result of this consistency of ΔN, low values of f_0F_2 are associated with high values of Δf and hence the apparent diurnal distribution of Δf is markedly influenced by the diurnal distribution of f_0F_2. This throws some doubt on the significance of the conclusion of Section V that in low and middle latitudes, Δf is large when the F_2 layer is moving down. The conclusion that low critical frequency is the prime requirement for the production of high Δf rather than downward movement, stems from the fact that the former requirement gives a consistent picture covering all latitudes, whereas the latter would only explain the facts for low and middle latitudes. It may be that while low values of f_0F_2 ensure high values of Δf when the irregularities are present, such values of f_0F_2 are not a prerequisite for the production of irregularities. Indeed the downward movement may be such a prerequisite. (The question of the effect of layer height and critical frequency on the occurrence of irregularities responsible for frequency spreading will be discussed elsewhere.) If this is the case, then a different mechanism must be responsible for the production of the irregularities at high latitudes than that which is operative in the middle and low latitudes. The differences in diurnal distribution for magnetically quiet and for magnetically disturbed days also undoubtedly finds explanation in differences in the diurnal distribution of f_0F_2 at these times.

VIII. Acknowledgments

The author would like to thank Professor H. C. Webster, Dr. J. A. Thomas, Dr. R. W. E. McNicol, and Mr. J. Crouchley for their helpful discussion during the preparation of this paper. Thanks are also due to the I.G.Y. Data Centre A (C.R.P.L. of the N.B.S.) and the Ionospheric Prediction Service for supplying the f-plot data. The Radio Research programme of the University of Queensland is assisted by the Radio Research Board, C.S.I.R.O.

IX. References

Booker, H. G. (1958).—*Proc. Inst. Radio Engrs. N.Y.* **46**: 298.

Booker, H. G., and Wells, H. W. (1938).—*Terr. Mag. Atmos. Elect.* **43**: 249.

Bowman, G. G. (1960*a*).—*Planet. Space Sci.* **2**: 133.

Bowman, G. G. (1960*b*).—*Aust. J. Phys.* **13**: 69.

Briggs, B. H. (1958*a*).—*J. Atmos. Terr. Phys.* **12**: 34.

Briggs, B. H. (1958*b*).—*J. Atmos. Terr. Phys.* **12**: 89.

Gipps, G. de V., Gipps, D. I., and Venton, H. R. (1948).—*J. Coun. Sci. Industr. Res. Aust.* **21**: 215.

Kasuya, I., Katano, S., and Taguchi, S. (1955).—*J. Rad. Res. Labs. Japan* **2**: 329.

Little, C. G. (1951).—*Mon. Not. R. Astr. Soc.* **111**: 289.

Lyon, A. J., Skinner, N. J., and Wright, R. W. H. (1960*a*).—*Nature* **187**: 1086.

Lyon, A. J., Skinner, N. J., and Wright, R. W. H. (1960*b*).—*J. Atmos. Terr. Phys.* **19**: 145.

Lyon, A. J., Skinner, N. J., and Wright, R. W. H. (1961).—*J. Atmos. Terr. Phys.* **21**: 100.

Martyn, D. F. (1959).—*Proc. Inst. Radio Engrs. N.Y.* **47**: 147.

Osborne, B. W. (1952).—*J. Atmos. Terr. Phys.* **2**: 66.

Singleton, D. G. (1957).—*Aust. J. Phys.* **10**: 60.

Singleton, D. G. (1960).—*J. Geophys. Res.* **65**: 3615.

Wright, J. W., Knecht, R. W., and Davies, K. (1957).—*Ann. I.G.Y.* **3**: 133.

Appendix I

The Variation of Δf *with* f_0F_2 *for the Models* ΔN *Constant and* $\Delta N/N_m$ *Constant*

For ordinary-mode propagation the refractive index of the ionosphere for a radiowave of frequency f is given by

$$\mu^2=1-Ne^2/mf^2,$$

where N is the number of electrons/c.c., m and e are the electronic mass and charge respectively. From this it follows that a wave of frequency f_0 will penetrate when

$$f_0^2=N_m e^2/\pi m, \tag{1}$$

where N_m is the maximum electron density of the layer. If the irregularities involve a maximum density $(N_m+\Delta N)$ and consequently do not allow penetration until a frequency $(f_0+\Delta f_0)$ is reached then

$$(f_0+\Delta f_0)^2=(N_m+\Delta N)e^2/\pi m. \tag{2}$$

For the extraordinary mode of propagation it is well known that reflection occurs for a frequency f given by

$$\frac{N_e^2}{\pi m}=f^2-ff_H,$$

where f_H the gyrofrequency $=He/2\pi mc$, H being the Earth's magnetic field strength. It follows that the x-ray penetrates the background layer (maximum density N_m) at a frequency f_x given by

$$f_0^2=f_x^2-f_xf_H, \tag{3}$$

and the irregularities (maximum density $N_m+\Delta N$) at a frequency $(f_x+\Delta f_x)$ given by

$$(f_0+\Delta f_0)^2=(f_x+\Delta f_x)^2-(f_x+\Delta f_x)f_H. \tag{4}$$

Consideration of Figure 2 (*b*) shows that in the case where the *o*-ray spreading overlaps the *x*-ray spreading, Δf, the total range of penetration frequencies, is given by

$$(f_0+\Delta f)=(f_x+\Delta f_x). \tag{5}$$

Combination of equations (4), (5), and (2) leads to

$$(N_m+\Delta N)e^2/\pi m=(f_0+\Delta f)^2-(f_0+\Delta f)f_H. \tag{6}$$

With the aid of equation (1) this reduces finally to

$$\Delta N=\frac{\pi m}{e^2}f_0\left\{\Delta f+(\Delta f-f_H)\left(1+\frac{\Delta f}{f_0}\right)\right\}, \tag{7}$$

or

$$\frac{\Delta N}{N}=\frac{1}{f_0}\left\{\Delta f+(\Delta f-f_H)\left(1+\frac{\Delta f}{f_0}\right)\right\}. \tag{8}$$

In cases where the frequency-spreading is less severe (Fig. 2 (*a*)) Δf has been taken to equal Δf_0 and in these cases equations (7) and (8) reduce to

$$\Delta N=\frac{\pi m}{e^2}f_0\left\{\Delta f+\Delta f\left(1+\frac{\Delta f}{f_0}\right)\right\}, \tag{9}$$

$$\frac{\Delta N}{N}=\frac{1}{f_0}\left\{\Delta f+\Delta f\left(1+\frac{\Delta f}{f_0}\right)\right\}. \tag{10}$$

Appendix II

The Effect of Absorption on Δf

For points to fall within the " forbidden zones " of the Δf *versus* f_0F_2 scatter diagrams the x-ray spreading must be less severe than the o-ray spreading. The reason for this is believed to be in the difference in absorption of the two modes of propagation. The plausibility of such a mechanism is examined in this Appendix.

Ionograms made in quick succession and at different receiver gains (Wright, Knecht, and Davies 1957) have shown that in any frequency-spreading patch, whether it be associated with an o-ray or an x-ray penetration, the signal strength falls off with increasing frequency. This can be demonstrated in a general way with the aid of Figure 10 in which only o-ray propagation is considered. Figure 10 (b) shows the electron density distributions in the background layer and in the irregularities which are responsible for the spread $h'f$ o-ray of Figure 10 (c). Figure 10 (a) represents the manner in which N_m might be expected to vary along any horizontal line at the level of the layer maximum. At the frequency f_a reflection occurs for some parts of the layer at and above the true height R_a while the ray penetrates at other places at the level P_a. Figure 10 (a) suggests that reflection occurs over a much wider area than does penetration in this case. R_b and P_b are the initial reflection and penetration levels for rays of frequency f_b and in this case it is seen that penetration occurs over a wider area than does reflection. Consequently if the reflecting areas are smaller than the first Fresnel zone, the energy returned would be expected to fall off within the spread patch as the reflecting areas get smaller, that is, as the frequency increases. In the frequency range 3 to 10 Mc/s the radius of the first Fresnel zone at 300 km changes from 5 to 3 km and the irregularities are thought to have a cross-sectional dimension of the order of 1 km (Booker 1958). This implies that the higher frequency components of a frequency-spreading patch will disappear first as the absorption is increased. If the x-ray absorption is considerably greater than the o-ray absorption, it would be possible to have a composite frequency-spreading patch involving overlap which is predominately o-ray spreading.

For quasi-longitudinal propagation the absorption coefficient $\varkappa$ is given by (e.g. Wright, Knecht, and Davies 1957)

$$\varkappa=\frac{e^2}{2\pi mc}\cdot\frac{1}{\mu}\,\frac{N\nu}{(\nu/2\pi)^2(f\pm f_H\cos\theta)^2},$$

where μ is the refractive index, ν the collision frequency, and θ the angle between the Earth's magnetic field and the direction of propagation. The positive sign applies to the ordinary wave, the negative sign to the extraordinary wave. At penetration $\varkappa$ is necessarily infinite, but near penetration $\varkappa$ depends on $(f\pm f_H\cos\theta)$. Thus at any frequency f, as $f_H\cos\theta$ increases, $\varkappa$ for the o-ray decreases, whereas $\varkappa$ for the x-ray increases. The values of $f_H\cos\theta$ for the several stations discussed here are listed in Table 1. This table suggests that the effect of higher x-ray absorption should be more marked for the high latitude stations than for the low and, indeed, calculation shows that for the typical frequency of 5 Mc/s the o-ray absorption coefficient is 25% of the x-ray coefficient at Baker Lake, while at Huancayo there is no significant difference in the two

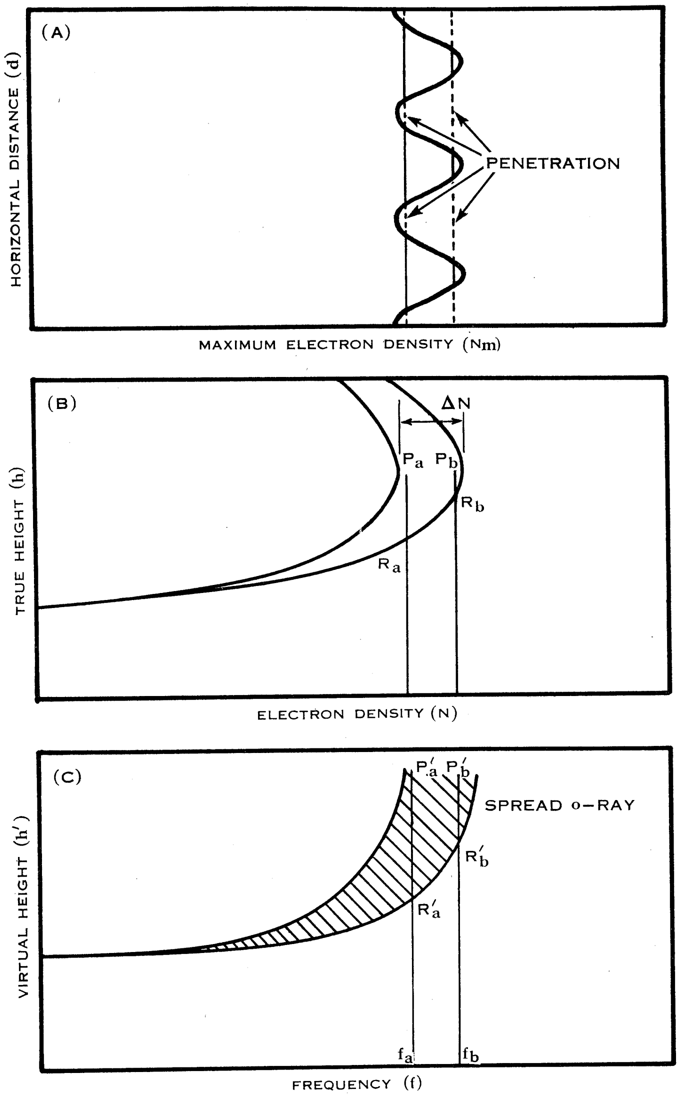

Fig. 10.—Diagram (B) represents the electron density (N) distribution with height (h) for the irregularities and background layer which give rise to the spread o-ray penetration sketched in diagram (C). Diagram (A) represents the manner in which the maximum electron density (N_m) might vary with distance (d) in the horizontal plane.

coefficients. Reference to Figures 7, 8, and 9 shows that this effect is not operative at Huancayo but occurs frequently for the higher latitude stations of Ft. Monmouth and Thule.