A STUDY OF "SPREAD-F" IONOSPHERIC ECHOES AT NIGHT AT BRISBANE

III. FREQUENCY SPREADING

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Summary

Virtual range versus frequency ($P'f$) records of the ionosphere made at Brisbane (lat. 27·5 °S., long. 152·9 °E.) during 1952 and 1953 have been examined. It is found that occasionally neither the o nor the x mode of propagation penetrates the F_2 layer at a unique frequency, the upward sweeping traces either being blurred out over a range of penetration frequencies (diffuseness) or possessing a fine structure (penetration-frequency multiplicity). Temporal analysis of the occurrence of these effects reveals that they occur only at night; penetration-frequency multiplicity appearing more frequently in the hours before dawn, while the diurnal distribution of diffuseness has a maximum between 0100 and 0500 hr in summer and represents a more even distribution between 2100 and 0500 hr in winter. The seasonal distribution has a pronounced peak in the winter months and minima in the equinoctial months. These data are compared with the world-wide picture of these variations as it has emerged from the recent literature.

The observations are interpreted in terms of scattering from the clouds of enhanced ionization near the F_2-layer maximum which are believed to be responsible for the scintillation of radio stars. It is suggested that there is a seasonal vertical movement of these clouds, the extent of which increases with latitude.

I. INTRODUCTION

When the echoes of short pulses of radio-frequency radiation reflected from the F_2 region of the ionosphere at night are examined by means of the familiar radar A-scan technique, they are often found to have a configuration not unlike that of a mountain range. The duration of the echo is much longer than that of the transmitted pulse; the successive peaks of echo amplitude may or may not move relative to each other, and may fluctuate in amplitude independently as time proceeds or as the frequency of the radiation is varied. This phenomenon reveals itself on virtual range versus frequency ($P'f$) records as a spreading of the F_2-region trace in range, or penetration frequency, or both, and has consequently become known as "spread-F". In the greater number of occurrences, the spreading is predominantly one of range only (Plate 1, Fig. 1) or of penetration frequency only (Plate 1, Fig. 2), while on a lesser number of occasions both effects are observed simultaneously.

Spreading in range usually manifests itself as a multiplicity of discrete F-region traces all of closely similar range-frequency characteristics. The

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general behaviour and nature of range multiplets, as revealed by a wide variety of observational techniques, have been discussed in Part I (McNicol, Webster, and Bowman 1956), while Part II (McNicol and Webster 1956) has been devoted to a discussion of the physical significance of these observations. The present part discusses the spreading of F-region $P'f$ traces in penetration frequency.

II. Equipment

The analysis presented here is largely based on $P'f$ (virtual range versus frequency) measurements obtained at Brisbane. The equipment (Higgs 1943) employed incorporates a broad band superheterodyne receiver which is arranged to be tuned continuously to a variable frequency pulse transmitter whose power is approximately 500 W. The transmitter frequency is varied in a logarithmic manner from 1 to 16 Mc/s in 2 min and is pulsed 50 times a second with pulses of 100 μ sec duration. The transmitter pulse length and receiver bandwidth are such as to allow echoes differing in range by about 25 km to be resolved. Delta aerials, whose radiation patterns are predominantly upwards over the range of frequencies employed, are used for both transmitting and receiving.

The received pulses are applied to a 6-in. cathode-ray tube in such a way as to black out a linear time-base which is applied to the tube. This black-out modulated time-base, which is started when the transmitter is pulsed and which has a duration such that echoes of range up to 800 km are displayed, is photographed on 35-mm film moving in a direction perpendicular to that of the time-base. The result is a plot, with range as ordinate and frequency as abscissa, of the range-frequency characteristics of the ionospheric layers.

Reference will also be made in what follows to observations made with the fixed-frequency recording system described in Part I.

III. Experimental Results

(a) *General Characteristics of Frequency Spreading*

The widening of $P'f$ traces near the penetration frequency is sometimes resolved into fairly distinct upward-sweeping traces which are usually four in number (Plate 1, Fig. 3), though on occasion six and more have been observed. These traces, which in general have the same low frequency range characteristics, are here called penetration-frequency multiplets. An " o-ray " and an " x-ray " for each of the satellites of a multiplet can usually be identified, these being separated by $0 \cdot 7$–$0 \cdot 8$ Mc/s, as expected at the latitude of Brisbane.

The difference in penetration frequency between the o-rays of the main trace and its satellite in a penetration-frequency doublet is usually of the order of $0 \cdot 2$ Mc/s, while occurrences with separations up to $0 \cdot 6$ Mc/s have been observed. This quantity varies not only from one occurrence to another, but also during any one occurrence, though the latter variation is usually smaller than the former. The satellites may appear with penetration frequencies higher or lower than those of the pre-existing trace, while a multiplet may or may not replace the previously existing trace as the new main trace at the end of an occurrence.

Spreading in penetration frequency is often the result of the penetrating F-region trace assuming a more continuous configuration than that described in the preceding paragraphs. Here the broadening of the trace at and above the critical frequency usually has a speckled appearance in which it is impossible to discern connected traces (Plate 1, Fig. 2). The suitably descriptive term "diffuseness" is employed when referring to this effect. Diffuseness may cause the penetration frequency of both modes of propagation to be spread $0 \cdot 5$ Mc/s or less or it may result in the whole of the space between the o- and x-rays, and a considerable distance beyond, being filled with a confusion of echoes.

On the average, penetration-frequency multiplets have a much shorter lifetime than diffuseness has. The majority of occurrences of penetration-frequency multiplicity have a duration of less than 1 hr; indeed many occurrences appear on only one or two records (which are made at 10 min intervals). On the other hand, diffuseness, although it may have a short duration, usually persists for periods of several hours.

While diffuseness and penetration-frequency multiplicity, as defined above, are observed quite commonly, they represent the limits of a whole range of frequency-spreading phenomena, the gradations of which often appear on a sequence of records (Plate 2, Fig. 1). Sequences of this type are usually associated with the disappearance of diffuseness, a process which invariably occurs at sunrise, but they are also often observed as the forerunners of periods of pronounced diffuseness (Plate 2, Fig. 2).

As the critical frequency of the F_2 layer approaches the operating frequency of a fixed-frequency $P't$ recorder, the frequency-spreading effects described above may appear on its records. As Figures 3 and 4 of Plate 2 show, the penetrating F_2 trace is broadened considerably in range and the period over which penetration occurs is prolonged. The trace may be in the form of a speckled strip (Plate 2, Fig. 3) or it may reveal considerable structure (Plate 2, Fig. 4). In either case it is evident that deep multiple fading is occurring; a conclusion which has been borne out by independent observations of the amplitude fluctuations of the echoes at such times.

Plate 2, Figure 5, shows a $P't$ recording of a diffuse penetration made with the aid of the variable-gain technique described in Part I. It will be noted that, in general, the signal strength across the diffuse echo falls off gradually as the range increases.

(*b*) *Temporal Variations*

In order to examine the temporal variations of the several frequency-spreading effects, two methods of obtaining data from the $P'f$ records have been employed. The first of these is based on an hourly index which is allotted in the course of routine scaling to records from which it is difficult to obtain a determination of f_0F_2; the index, ranging from one to four, gives a measure of the degree of uncertainty in the value of the quoted critical frequency. This inability to read f_0F_2 may result from some degree of penetration-frequency multiplicity or diffuseness. The penetration-frequency multiplicity may, or may not, be accompanied by range multiplicity. However, in the case of range spreading the main trace and its satellites usually penetrate in one well-defined trace, in which case no index is allotted. A comparison of the index allocations with the records for three typical winter, summer, and equinoctial months shows that 60 per cent. of allocations are due to frequency spreading alone and that all cases of frequency spreading receive an index figure. The remaining 40 per cent. of allocations are due to penetration-frequency multiplicity which is accompanied by range multiplicity or to range multiplicity alone, of such severity that it precludes the possibility of determining f_0F_2. These occurrences of range spreading amount to less than half of the total occurrence of this phenomenon. Obviously then, statistics calculated in terms of these index allocations will, in the main, reveal the behaviour of the frequency-spreading phenomena and will be influenced only in a second-order manner by the behaviour of range multiplicity. Reber (1954*a*, 1954*b*) has used a method of count based on similar premises and consequently the data presented here are comparable with those gathered by him.

In the second analysis the records were re-examined in order to determine the temporal variations of penetration-frequency multiplicity when the effect is separated from the more frequently occurring diffuseness.

Figure 1 presents the diurnal distributions of penetration-frequency multiplicity and diffuseness taken together for each of the 12 months of the year 1952. The several histograms are plotted in cumulative fashion, the lower dark-shaded portions represent the distribution of strong spreading (index 3 and 4), while to these are added the moderately shaded and blank portions which represent the distributions of moderate (index 2) and weak (index 1) spreading. These histograms reveal that the frequency-spreading phenomena occur only at night, peaking between 0100 and 0500 hr in summer, while in winter the maximum is quite broad, existing between 2100 and 0500 hr. The shape of the distribution averaged over 12 months is therefore somewhat similar to that of the summer distribution. These features of the diurnal distribution are roughly independent of the degree of spreading.

It is also evident that there is much more frequency spreading in the winter than in the summer months, while the occurrence of the phenomena is a minimum in the equinoctial months.

The variation of the total annual occurrence of frequency spreading at Brisbane has been discussed by Gipps, Gipps, and Venton (1948) and Gipps (1954), who have shown that the number of occurrences and their intensity varies inversely with the sunspot number. This result is depicted in Figure 2, which also serves to further illustrate the seasonal variation of the phenomena.

The Brisbane observations are consistent with the world-wide spread-*F* picture which has emerged from the recent literature (Reber 1954*a*, 1954*b*; Wells 1954) and which is summarized in Table 1. It is to be noted that, while the overall shape of the diurnal distributions, as judged from the positions of maxima, varies little from place to place for the respective seasons, the seasonal and sunspot cycle variations are subject to marked latitude effects. It would

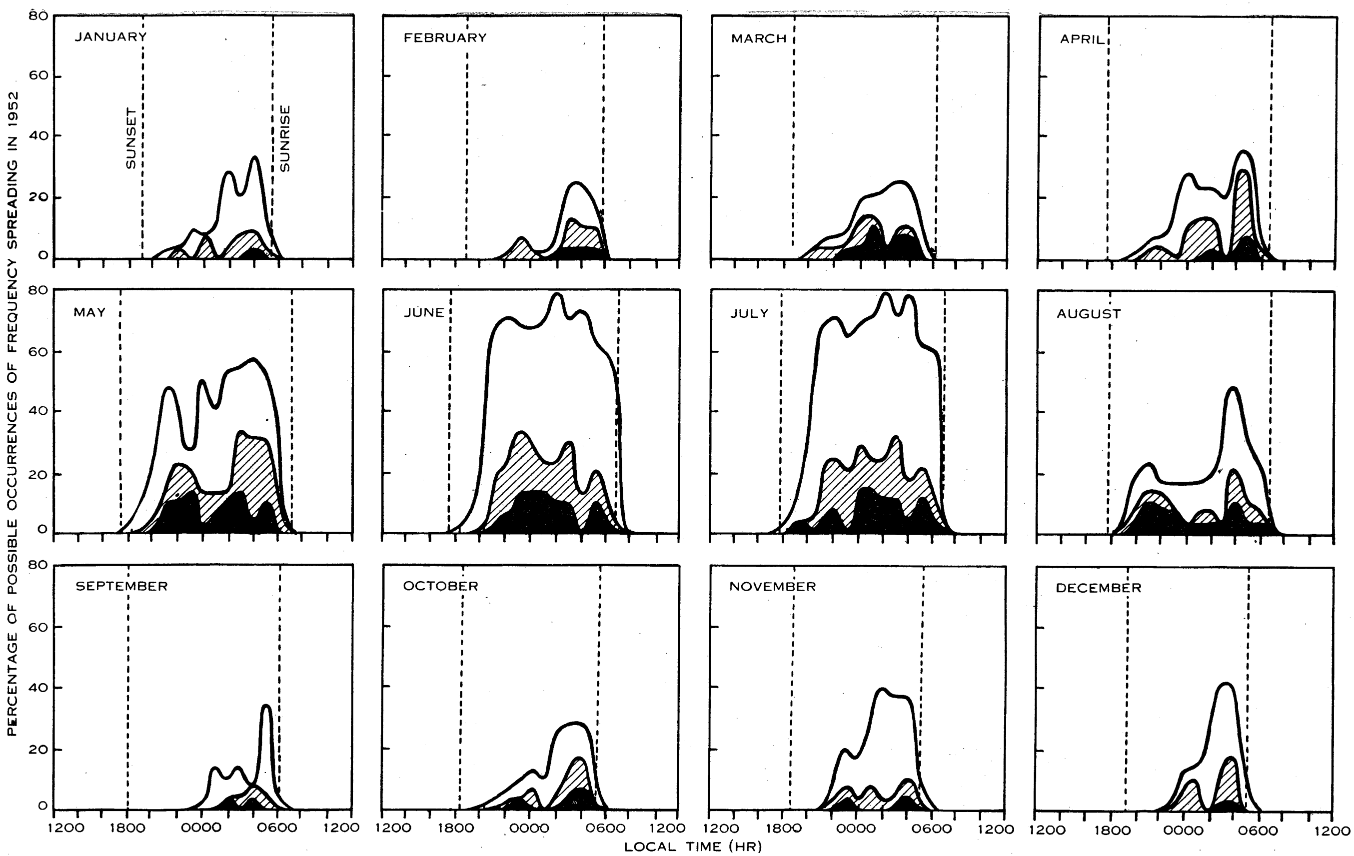
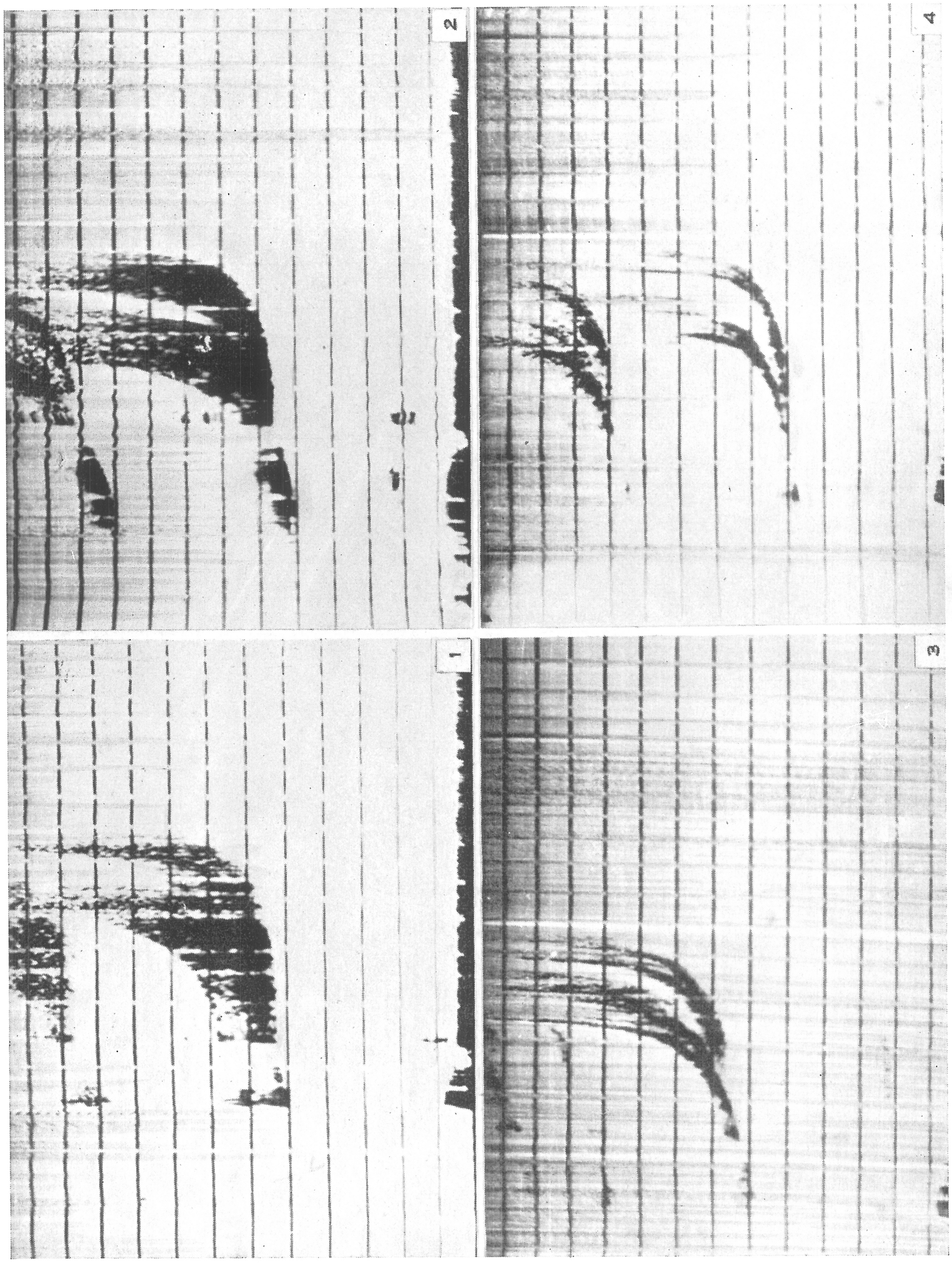
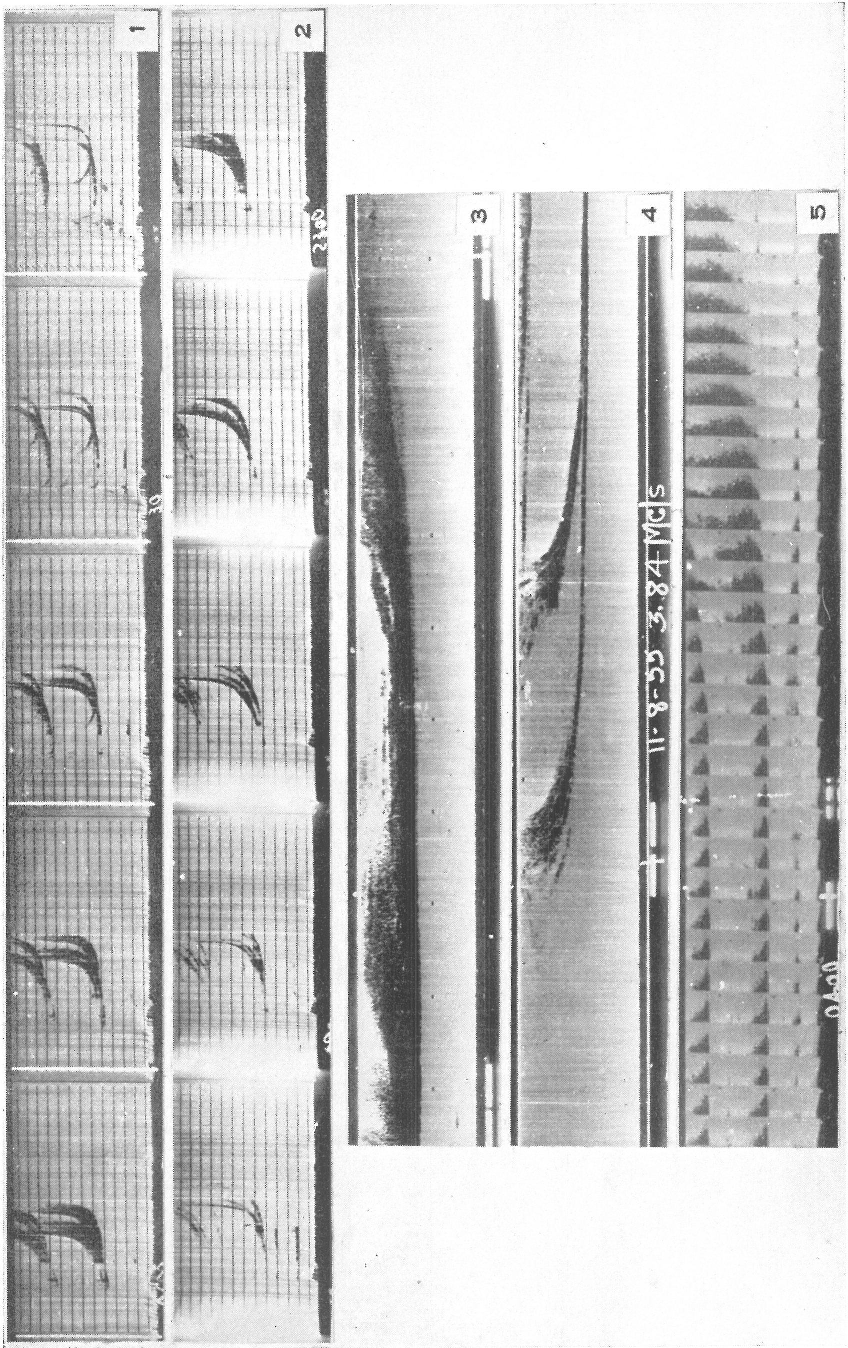


Fig. 1.—Diurnal distributions of strong (dark-shaded), moderate (light-shaded), and weak frequency spreading for each month of the year 1952.

SPREAD-F IONOSPHERIC ECHOES AT NIGHT AT BRISBANE. III



SPREAD-F IONOSPHERIC ECHOES AT NIGHT AT BRISBANE. III



appear that the winter takes over from the summer as the season of maximum occurrence at latitudes greater than 20°, while for latitudes greater than about 40° the correlation of the variation of the total annual occurrence with sunspot number changes from inverse to direct.

On separating penetration-frequency multiplicity from the more frequently occurring diffuseness, the former is found to have a diurnal distribution which is substantially different to that of the two effects lumped together. The full-line curves of the histograms of Figure 3 are the monthly diurnal distributions for the 12 months of the year 1952. It will be noticed that, without exception, these curves peak sharply 2 hr before the monthly average local sunrise time even though this time fluctuates over a 2-hr period during the year. In the summer months the pre-dawn peak accounts completely for all the occurrences. In

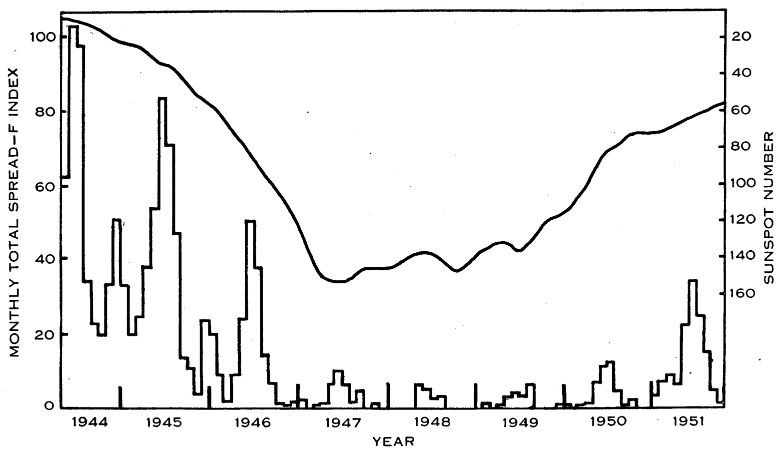


Fig. 2.—Inverse correlation between the occurrence of spread-F (lower histogram) and sunspot number (upper curve).

each of the remaining months, however, there is a considerable number of occurrences earlier in the night, but, except for the equinoctial months of May and August, these occurrences distract little from the prominence of the pre-dawn peak. This is not the case with diffuseness for which the winter diurnal distributions are more or less independent of time throughout the night. These differences in the distributions are due at least in part to the fact, already pointed out, that the majority of occurrences of penetration-frequency multiplicity appear as diffuseness decays at dawn.

The upper broken-line curves of Figure 3 represent the variation of the monthly median critical frequency with time. It will be noted that the frequency of occurrence only becomes appreciable when the median critical frequency curves drop to or below 4 Mc/s. Indeed, during the years 1952 and 1953 only 5 per cent. of occurrences of penetration-frequency multiplicity appeared when the critical frequency of the F_2 layer was above 4 Mc/s, which, for this period, is about the average value of the night-time F_2-layer critical frequency.

TABLE 1

VARIATION OF FREQUENCY-SPREADING CHARACTERISTICS WITH LATITUDE

Station	Huancayo	Hawaii	Rarotonga	Brisbane	Watheroo	Baton Rouge	San Francisco	Washington	Christ-church	Winnipeg
Latitude										
Geographic	—12·0°	20·8°	—22·0°	—27·5°	—30·3°	30·5°	37·4°	39·0°	—43·5°	49·9°
Geomagnetic	— 0·4°	20·9°	—21·7°	—35·7°	—41·7°	41·0°	43·6°	50·3°	—48·0°	59·5°
Diurnal distribution										
Winter max. between ..	0300–0500	0000–0500	0000–0600	2100–0500	2100–0500	0000–0600	0000–0600	0000–0600	2100–0200	0300
Summer max. between ..	2000–0400	0200–0300	0200–0400	0100–0500	0200–0400	0200–0400	2300–0000	0200–0400	0300	0300
Seasonal distribution										
Winter ..	Minimum	Minimum	No variation	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum
Summer ..	Maximum	Maximum		Sub-max.	Minimum	Sub-max.	Minimum	Minimum	Minimum	Minimum
Equinox ..	Midway	Midway		Minimum		Minimum		Midway	Midway	
Sunspot cycle distribution	Inverse correlation	Inverse correlation		Inverse correlation		Inverse correlation		No variation		Direct correlation

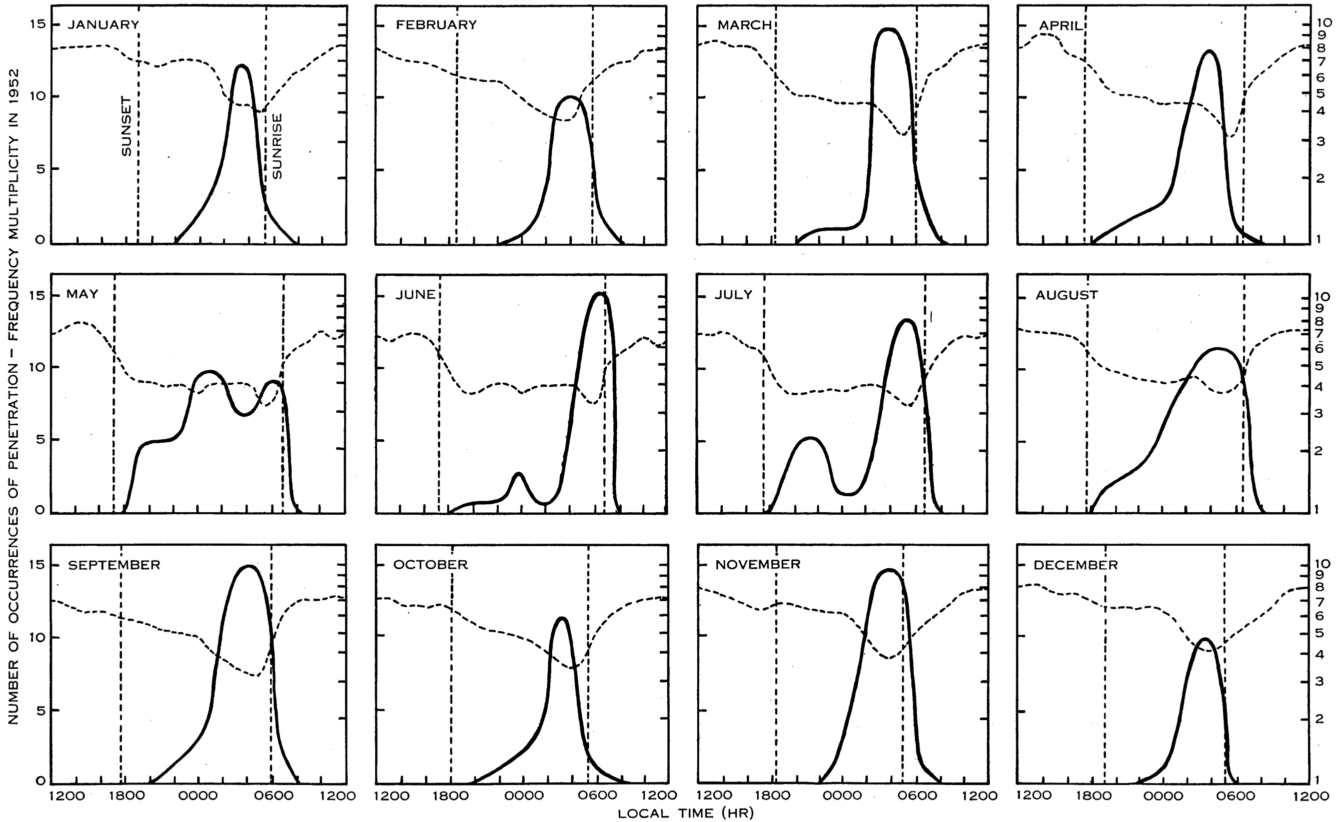


Fig. 3.—Diurnal distribution of penetration-frequency multiplicity (full-line curves) together with the variation of the median critical frequency for each month of the year 1952.

IV. Interpretation

(a) *Existing Hypotheses*

Eckersley (1937) suggested that the spreading of echoes from the F layer in range, or penetration frequency, or both, could be due to scattering from irregularities in the E_s region, followed by regular reflection at the F layer. The possibility that a mechanism of this type may be responsible for range multiplicity has been discussed in Part II. Dieminger (1951) has examined this hypothesis in relation to penetration-frequency multiplicity and diffuseness, and concluded that the explanation is untenable for the majority of occurrences. The present investigation adds support to this conclusion, for it is observed that a large number of occurrences of penetration-frequency multiplicity and diffuseness are unaccompanied by measurable echoes from the E_s region.

That scattering by the F layer should be responsible for spread-F, was first suggested by Booker and Wells (1938). These authors invoked a mechanism involving Rayleigh scattering by irregularities or clouds in the upper F region. They considered the diurnal distribution of the scattering centres to be only apparent, attributing it to the formation of a strong lower layer at dawn which masks off the irregularities during the daylight hours.

Recent investigations of radio star scintillations have renewed interest in the possibility of the existence of clouds in the upper F layer. Indeed, the high correlation between scintillations and spread-F (Little and Maxwell 1951) has resulted in the suggestion that the same system of irregularities gives rise to both effects. However, the scintillation investigations have led to the conclusion that the clouds responsible for the twinkling of radio stars have lateral dimensions of the order of 5 km (Little 1951 ; Hewish 1952). Consequently, if these clouds are also to be responsible for spread-F, it becomes impossible to retain the Booker and Wells hypothesis, for Rayleigh scattering requires that the scattering centres should have dimensions less than the wavelength of the incident radiation. (The range of wavelengths over which spread-F is observed is 30–300 m.) To overcome this difficulty an alternative mechanism for the production of spread-F involving diffraction from large clouds will be put forward in the next section.

Further evidence in favour of the hypothesis that the one system of irregularities is responsible for both effects is provided by the fact that the two effects require for their explanation irregularities of electron density of the same order of magnitude. For the particular case of irregularities which exist at the F-layer maximum and whose excess electron density increases linearly with height to the maximum and then decreases linearly, it is possible to show (following Little (1951)), that the following expression gives a necessary condition for the production of scintillations :

$$(f_I^2-f_L^2)(z_2-z_1)\leqslant 2cf. \qquad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

Here f_L and f_I are the critical frequencies of the layer and the irregularities respectively, f is the frequency at which the scintillation observations are made, z_2-z_1 the vertical extent of the irregularities, and c the free-space velocity of light.

By considering the equality it is possible to plot $f_I - f_L$ against f_L and thereby obtain information about the upper limit of the critical frequency increase in the clouds. The curves of Figure 4 depict this relationship (observing wavelength 5 m) for clouds of several different vertical extents of which 5 and 10 km are, for reasons already pointed out, the most important. For the range of layer critical frequencies which are of interest (2–6 Mc/s) the upper limit of the critical frequency of the clouds is always greater than that of the layer by 0·3 Mc/s, while the difference may be as great as 1 Mc/s. This is in good agreement with the range of critical frequency observed in any occurrence of frequency spreading.

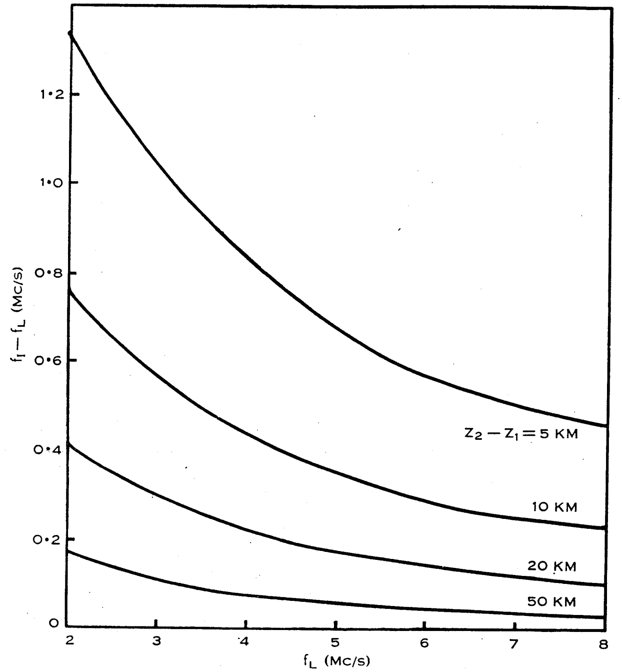


Fig. 4.—Variation of the difference between the critical frequencies in the clouds (f_I) and layer (f_L) with layer critical frequency for several different cloud sizes.

In the more general case, where the height of the maximum of the irregularity electron density is other than at the height of the layer maximum, the clouds will be required to have maxima of electron density which are less than those indicated above in order to produce comparable scintillation effects. The magnitude of the cloud electron density maximum will fall off as the separation between this maximum and that of the layer increases. It follows that there will be a range of heights, containing the height of the layer maximum, into which the entry of scintillation-producing clouds results in the critical frequency of the composite layer being raised above that of the background layer. The order of magnitude of the upper limit of this critical frequency increase in the clouds is indicated in Figure 4.

(b) Reflection from an Irregular Layer

If irregularities of the type discussed in the previous section are to be exploited in order to explain the anomalous penetration effects described in Section III, justification must be sought for the hypothesis that one or more of these irregularities are present in that region of the ionosphere which is directing the reflected probing radiation back to the recording site. It is evident that, since these irregularities have dimensions two orders of magnitude larger than the wavelength of the probing radiation, reflection from each irregularity may proceed in accordance with the simple magneto-ionic theory. However, interference must occur between the reflections from the several clouds and the background layer in which these are embedded to give rise to an irregular wave field immediately below the reflecting region. The subsequent behaviour of such an irregular wave field can be considered most conveniently in terms of its autocorrelation function and angular power spectrum (Booker, Ratcliffe, and Shinn 1950).

It has been demonstrated (Booker, Ratcliffe, and Shinn 1950) that, for plane wave illumination, the wave field of the reflected radiation contains irregularities whose dimensions are characteristic of those in the ionosphere and further that these irregularities persist as the wave field is propagated away from the ionosphere to eventually produce the observed diffraction pattern on the ground. It follows that, if the spatial autocorrelation function of the diffraction pattern across the ground is of Gaussian form (McNicol 1949), the spatial autocorrelation function $\rho(\xi)$ of the ionosphere irregularities is also Gaussian.

$$\rho(\xi)=\exp\,(-\xi^2/2a^2). \quad \dots\dots\dots\dots\dots\dots \quad (2)$$

Booker, Ratcliffe, and Shinn (1950) further show that the power spectrum $|\,P\,(\sin\theta)\,|^2$ of the diffracted radiation is proportional to the Fourier transform of the autocorrelation function. Thus

$$|\,P\,(\sin\theta)\,|^2 \propto \exp\,(-2\pi^2a^2\sin^2\theta), \quad \dots\dots\dots\dots \quad (3)$$

which is also Gaussian, the standard deviation being $1/2\pi a$. This leads to the conclusion that the distribution of power in the angular spectrum of plane waves falls off rapidly for large values of $\sin\theta$, and hence θ. Most of the power scattered from the layer is confined, consequently, within a " cone " whose semi-angle depends on the standard deviation a of the autocorrelation function of the wave field. If the cone is chosen to include all those waves of the angular spectrum whose intensities are greater than 0·14 times that of the wave of maximum intensity, then it follows from equation (3) that this cone has a semi-angle θ_0 given by

$$\theta_0=\sin^{-1}\,(1/\pi a). \quad \dots\dots\dots\dots\dots\dots \quad (4)$$

In the present investigation the ionosphere is irradiated, not by plane waves, but by waves more like those emitted from a point source and, consequently, the scattered radiation might be expected to be of a form different to that predicted above. This aspect has been investigated fully by Briggs and Phillips (1950), who show that a screen capable of scattering plane wave illumination according to a Gaussian angular distribution of power will, when irradiated from a point source, still scatter according to a Gaussian angular power spectrum, the standard deviation in the latter case being half that of the former. It follows that a system of ionospheric irregularities, distributed in the horizontal plane so as to have an autocorrelation function of Gaussian form of standard deviation a, will reflect radiation emitted from a point source back towards that point in the form of a cone of semiangle θ_0' where

$$\theta_0'=\sin^{-1}(1/2\pi a). \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

If the irregularities are at a height H km above the ground, this implies that the radiation received at the transmitting point emanates from a region immediately overhead which is on the average circular in horizontal cross section, the diameter being $2H \tan \theta_0'$, i.e. $H/\pi a$ for small values of θ_0'.

Statistical examination (Rice 1944, 1945) of an irregular wave field of random form shows that the number of maxima (m) to be expected in any horizontal distance of one wavelength is given by

$$m=(1/2\pi)\{\rho_0(4)/\rho_0(2)\}^{\frac{1}{2}}, \quad \ldots\ldots\ldots\ldots\ldots \quad (6)$$

where $\rho_0(2)$ and $\rho_0(4)$ represent the second and fourth derivatives respectively of the autocorrelation function $\rho(\xi)$ with respect to ξ (measured in wavelengths) evaluated at $\xi=0$. If $\rho(\xi)$ is of Gaussian form, the standard deviation being a, the number of maxima occurring in a distance of one wavelength can thus be shown to be

$$m=\sqrt{3}/2\pi a. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Hence the average horizontal distance in kilometres between the irregularity centres (b) is given by

$$b=2\pi a\lambda/\sqrt{3}. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Some indication of the number of irregularities of such a system of irregularities contained within a sample of circular horizontal cross section is obtained in terms of the number of average irregularities (the distance between whose centres is b) which may be packed into the sample. Simple geometrical considerations show that the number of closely packed small circles of diameter q which are contained wholly or partly within a larger circle of diameter p, is of the same order of magnitude as $(p/q)^2$. Consequently, the number (n) of irregularities observable, in the sense that they are in that region of the ionosphere which directs radiation back to the receiver, is given by

$$n=\left\{\frac{H}{a}\,\frac{1}{b}\right\}^2.$$

Substituting for a this becomes finally

$$n=\frac{4}{3}\left\{\frac{Hc}{b^2f}\right\}^2. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

In Figure 5, the average distance between irregularity centres is plotted against frequency with the number of irregularities observable as parameter, for a screen range of 350 km. This reveals that irregularities of moderate size (average distance between centres of 6 km and less) are observable against their background in varying numbers for the range of frequencies normally reflected from the ionosphere at night. It is to be noted that, for a given irregularity separation, the number of irregularities under observation decreases as the frequency increases ; however, above 3 Mc/s the rate of decrease becomes small, especially where large numbers of irregularities are involved. The shaded part of the figure represents the conditions of irregularity-separation and frequency for which clouds are unobservable. This involves large frequencies, or large irregularity separations, or both.

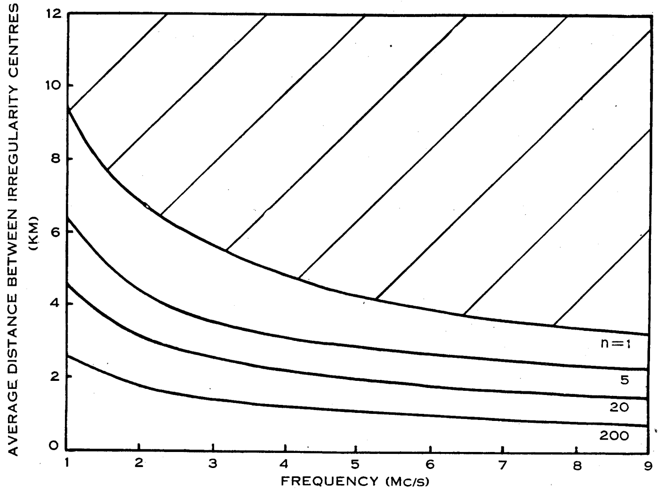


Fig. 5.—Relation between cloud separation, number of clouds observable (n), and layer critical frequency for clouds at a height of 350 km.

(*c*) *Discussion of the Observations*

The scintillation observations, referred to in Section IV (*a*), suggest that on occasions irregularities exist in the upper F layer which contain sufficient ionization to reflect radio waves of frequency by up to 1 Mc/s greater than those which penetrate the normal F-layer background. Further, it has just been shown that it is possible to observe a number of these irregularities, along with the associated background layer, over the range of frequencies employed, provided that the distance between the irregularity centres is not too great. The actual derivation of this result requires no knowledge of the nature of the horizontal configuration of the individual irregularities, and consequently any hypotheses regarding this configuration will not be restricted by what has gone before. Two horizontal configurations will be considered. In the first of these the irregularities are envisaged as clouds of enhanced ionization which involve a gradual decrease of electron density from the irregularity maximum in the centre of the cloud to the density of the background layer at the same height. The second involves clouds of enhanced ionization whose internal composition varies little in any horizontal direction and whose vertical boundaries consequently involve electron density changes of a more discontinuous nature than those visualized for the first cloud type.

(i) *Diffuseness.*—When clouds of the first type exist in that region about the F-layer maximum in which their maximum density takes on a value greater than that of the background layer a continuous variation of maximum electron density between that of the background layer and that of the centre of the irregularities will exist. Further, this range of values of maximum electron density will be accompanied by a range of vertical electron density gradients. The irradiation of such an irregular layer with pulses of radiation of gradually increasing frequency will result in recorded traces, corresponding to both modes of propagation, which sweep upwards over a broad band of frequencies to penetrate in a range of critical frequencies (Plate 1, Fig. 2). This is the effect called diffuseness whose observation was described earlier.

Figure 5 demonstrates that for a given irregularity system a decrease in the frequency of the incident radiation results in an increase in the number of irregularities under observation and hence an increase in the semi-angle of the scattered cone of radiation. If the irregularities extend down into the lower parts of the layer, then a considerable amount of the radiation reflected at low frequencies will be returned along non-vertical paths. For pulse transmissions, this will result in considerably lengthened echoes and broad low-frequency $P'f$ traces. Unresolved range spreading of this type is often observed to be associated with the more severe occurrences of diffuseness. The variable gain $P't$ observations (Plate 2, Fig. 5) indicate that there is a falling off of signal strength with increasing delay, both when the operating frequency is well below the critical frequency and when it is near it. This is the expected result if the components of the echo of greater delay are being returned from regions of the ionosphere remote from the zenith and if the angular power spectrum has the suggested Gaussian form.

The fading observations, referred to in Section III (*a*), suggest that a penetrating diffuse F-region trace is due to echoes composed of several peaks separated slightly in time and that the amplitude of each of these peaks fluctuates in an independent manner. This is consistent with the interpretation presented here, for each of the peaks corresponds to the radiation returned from one of the several clouds in the observable region. Since these clouds have considerable dimensions, it is reasonable to expect the radiation returned from each of them to fade in the normal manner as the result of the movement of small irregularities within them. The lack of a one-to-one correspondence between the amplitude fluctuations of the several peaks suggests that there is no detailed relation between the movement of such small irregularities. This, however, does not preclude the possibility that they possess the same average drift velocity.

Penetrating diffuse F-region traces, whether $P't$ or $P'f$, may or may not reveal some suggestion of structure. The existence of structure in either type of record implies that the returned echo must, in fact, be a family of closely spaced, but nevertheless separate, echoes of relatively short duration which are capable of maintaining their identities as the appropriate parameter, time or frequency, is varied. This conclusion is consistent with that reached in the preceding paragraph and is therefore further evidence for the existence of several discrete reflecting zones within the observable region. Further, this evidence suggests that these reflecting zones may maintain their identity as time proceeds or as the level of reflection is raised in height. What then may be said of the penetrating diffuse traces which do not reveal structure ? Two alternative explanations suggest themselves ; either the component echoes are so closely spaced that the intermediate minima are above the recording threshold for the greater part of the time or the identities of the several maxima within the echo are not maintained as either time or frequency is varied. In either case the speckled appearance of the trace is easily accounted for. The first explanation is obviously consistent with the present hypothesis, while the second will be only if the individual irregularities have short lifetimes on these occasions. (Since, with the present experimental set-up, a considerable period of time is required for the examination of any variation with frequency, irregularities with small lifetimes may not be afforded the opportunity to reveal frequency structure.) There is no evidence to suggest that either of these hypotheses should be rejected and, indeed, both the mechanisms envisaged may at times be operative.

(ii) *Penetration-frequency Multiplicity.*—The presence of the second type of cloud near the layer maximum would result in two penetration frequencies for each mode of propagation, and such penetrations would have associated with them separate upward-sweeping $P'f$ traces. The satellites of a penetration-frequency doublet of this type may make their first appearance at the frequency at which the main trace o- and x-rays are just resolved (Plate 1, Fig. 3) or they may not appear until the main trace nears penetration (Plate 1, Fig. 4). This effect finds explanation in terms of different positions of the lower edges of the clouds relative to that of the layer maximum ; clouds whose density-increasing influence extends well down into the layer produce records such as that of Plate 1, Figure 3, while those whose lower boundaries are close to the background layer maximum give rise to records such as that of Plate 1, Figure 4.

The occasional observation of penetration-frequency multiplicity, which involves more than one pair of o-rays and one pair of x-rays, can be interpreted in terms of the present hypothesis if a number of clouds, some of which have a higher maximum electron density than others, are present simultaneously in the observable region.

While penetration-frequency multiplicity is often observed in a layer which is at other times undisturbed, it is more usually associated with the gradual decay of severe F-layer diffuseness (Plate 2, Fig. 1). In such occurrences successive records depict a whole range of frequency-spreading phenomena, the gradations of which are similar to other occurrences of frequency spreading which are not associated with decaying diffuseness. This implies that the two types of clouds postulated above are in fact the limits of a range of cloud configurations, any of the gradations of which occur either in a somewhat stable form for a long period or as the successive stages of a steadily changing configuration.

Until now the irregularities have been thought of as clouds of enhanced ionization, but the arguments remain valid if the irregularities are "holes" or regions where the ionization density is below that of the surrounding layer. Occasionally the satellite of a penetration-frequency doublet appears with a penetration frequency lower than that of the pre-existing main trace. In these cases it would appear that holes of reduced ionization rather than clouds of enhanced ionization are responsible for the observed effects.

(iii) *Temporal Variations.*—Before the temporal variations of the phenomena can be discussed in the light of the present hypothesis, it is essential to know something of the statistics of the clouds responsible for the production of the radio star scintillation effect. The limited amount of data available refers, in the main, to conditions in the ionosphere over the British Isles. This suggests that there is a marked diurnal variation in the occurrence of these clouds ; this variation shows a rapid rise from 2000 to 2200 hr, has a maximum at about 0100 hr and subsequently decays to small values at noon (Ryle and Hewish 1950). There appears to be little seasonal variation (Hewish 1952). Some observations of scintillations of point sources near the zenith have been made in Sydney by Shain and Higgins (1954). While their results are not sufficiently numerous to allow deduction of significant trends, they are by no means inconsistent with the results of the English workers. No data are available as to the variation of the height of the irregularities with time of night or season, nor is there any indication as to the type of variation, if any, of the occurrence of the scintillation phenomenon with latitude or during the sunspot cycle.

If it is assumed that the above diurnal distribution of the scintillation-producing clouds is approximately maintained over the whole ionosphere, then the several diurnal variations of frequency spreading (Table 1) are explained in terms of the movement of the layer at night (Booker and Wells 1938). The post-sunset elevation takes the layer maximum into the region where the clouds are situated, with the consequent possibility of the occurrence of frequency spreading, while the cut-off of the diurnal distribution of frequency spreading, at a time earlier than that of the scintillation-producing clouds, is due to the decrease in height of the F layer at this time, namely, dawn. Since the nocturnal height rise has such a marked effect on the diurnal distribution, the world-wide increase of this height rise in summer might be expected to be a factor controlling the seasonal distribution of frequency spreading, especially as the presence of the scintillation-producing clouds is independent of season. This is found to be the case for stations whose latitudes are less than 20°, where more frequency spreading is observed in summer than in winter, but for stations of higher latitude there is more frequency spreading in winter when the night-time layer is lower than it is in summer (Table 1). The conclusion is reached, therefore, that there must be a downward movement of the clouds in the winter months, the magnitude of which increases with latitude, being comparable with the winter layer movement at a latitude of 20° and larger than this at higher latitudes.

No satisfactory comment on the variation of the total annual occurrence of frequency spreading can be made without a knowledge of the variation of the occurrence of the scintillation-producing clouds throughout the solar cycle.

However, it is more than probable that the effect responsible for the change from inverse to direct sunspot cycle correlation, for latitudes greater than 40° (Table 1), is of auroral origin.

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Explanation of Plates 1 and 2

Plate 1

Examples of spread-F on $P'f$ records

Fig. 1.—Unresolved multiple traces, spread in range only.

Fig. 2.—Spreading in penetration frequency only, an example of diffuseness.

Fig. 3.—Penetration-frequency multiplicity, the satellites appearing at the point where the *o*- and *x*-rays are just resolved.

Fig. 4.—Penetration-frequency multiplicity, the satellites appearing where the main trace nears penetration.

Plate 2

The association of diffuseness and penetration-frequency multiplicity:

Fig. 1.—Diffuse echoes decaying to clean echoes via penetration-frequency multiplicity.

Fig. 2.—Penetration-frequency multiplicity developing into diffuseness.

Examples of penetration-frequency spreading on $P't$ records:

Fig. 3.—Penetrations spread in time which reveal no structure.

Fig. 4.—Penetrations spread in time which possess considerable structure.

Fig. 5.—Diffuse penetration recorded with the aid of the variable gain technique.