EVENING–TYPE TRANSEQUATORIAL PROPAGATION ON JAPAN–AUSTRALIA CIRCUITS

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Abstract

The correlation between the reception in the evening of v.h.f. signals on Japan–Australia circuits and the presence of spread F along the circuits is examined. The correlation is found to be highly significant and leads to the conclusion that spread F is a necessary but not sufficient condition for such reception. The fact that the presence of spread F is not a sufficient condition is explained in terms of either breaks in its distribution along the circuits or of plasma frequencies which are too low to support the proposed propagation mode.

I. Introduction

The initial studies of transequatorial propagation (TEP) were made by radio amateurs (Tilton 1947*a*, 1947*b*, 1951; Southworth 1960), who reported numerous and reliable transequatorial contacts in the 6 m band at frequencies usually far in excess of the predicted maximum usable frequencies (MUF) for the circuits considered. The observed signal strengths often approached and sometimes exceeded free-space values, in marked contrast to those normally obtained. Circuit lengths ranged from about 3000 to 10 000 km, the circuits usually being approximately bisected by the magnetic equator and at right angles to it. Seasonal occurrence rates showed pronounced equinoctial maxima which decreased with decreasing solar activity.

The last two decades have seen greatly increased understanding of TEP and its causes although there are still many unsolved questions (for further details, see reviews by McCue and Fyfe 1965; Nielson 1968; Harrison 1972*a*, 1972*b*). There appear to be two types of TEP, characterized by the times of peak occurrence, fading characteristics, and modes of propagation. The first type, which we shall call the afternoon type, has the characteristics:

(1) a peak occurrence around 1700–1900 hr LMT, the time being measured at the point where the circuit cuts the magnetic equator;

(2) normally strong steady signals with a low fading rate and a small Doppler spread (about ± 2–4 Hz);

(3) path lengths of about 6000–9000 km and sometimes longer.

It has been shown by Gibson-Wilde (1969) that, in the Australasian zone at least, these signals probably travel by the "super-mode" or FF mode proposed by Villard *et al.* (1957). Propagation by this mode involves two F-region reflections without an intervening ground reflection.

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The second type of TEP, which we shall call the evening type, generally supports higher frequencies than the afternoon type and has very different characteristics:

(1) a peak occurrence around 2000–2300 hr LMT;

(2) high signal strengths but with deep and rapid fading at rates up to about 15 Hz and a large Doppler spread which sometimes exceeds 40 Hz;

(3) path lengths usually shorter than for the afternoon-type mode, being about 3000–6000 km.

This propagation mode of TEP is the main subject of the present paper. Except when confusion could arise we shall omit the words "evening type" and refer simply to TEP.

II. TEP on Japan–Australia Circuits

The circuits considered in this paper are from Darwin (12·3° S., 130·8° E.) to Yamagawa (30·2° N., 130·6° E.), Yamagawa to Townsville (19·3° S., 146·7° E.), and Okinawa (26·3° N., 127·8° E.) to Townsville, which will be denoted hereinafter by D–Y, Y–T, and O–T respectively. Four fixed frequency sounders are operated on the D–Y circuit at approximately 48, 72, 88, and 102 MHz and signal strengths are recorded every 10 min. For the other two circuits, Granger stepped-frequency sounders (4–64 MHz) are used and oblique ionograms are recorded every 1 hr, the maximum observed frequency (MOF) being scaled from the ionograms.

It is generally conceded that the evening-type mode is somehow related to the presence of spread *F* along the circuit. It has been suggested by Cohen (1967) that the spread *F* might be just a masking phenomenon, simply impressing the observed signal characteristics on signals propagating by an ordinary or *FF* mode. However, this seems unlikely in view of the observations by Washburn and Johnson (1962) and by Bowen *et al.* (1968) of two distinct time delays during the period just after *F*-layer sunset. Washburn and Johnson found that one time delay was associated with signals exhibiting substantial fading while the other was associated with signals of good short-term stability.

The general association of evening-type TEP with spread *F* has been reviewed by McCue and Fyfe (1965). Both phenomena exhibit equinoctial maxima, at least in periods of high solar activity, and are strongly correlated with that activity. The papers by Kuriki *et al.* (1968) and Tao *et al.* (1970) both briefly discuss the association of TEP on the D–Y circuit with the presence of spread *F* at Manila but do not attempt any detailed analysis. Nielson (1969), while recognizing the need for spread-*F* data along the circuits considered, was unable to obtain these data. Attempts were made to use topside sounders to measure the corresponding spread-*F* distribution but this could not give reliable results without a detailed knowledge of the association between topside and bottomside spread *F*. An analysis of data obtained from the O–T and D–Y circuits for the period 1964–8 has also been given by Fyfe (1968), although his report does not consider possible propagation modes or the effect of spread *F* along the circuits.

McNamara (1971*a*) showed the existence of a high correlation between the presence of range-spreading at Vanimo, New Guinea, and the existence of TEP on the O–T and Y–T circuits but the data analysed covered a period of only 4 months which were all equinoctial. However, this analysis was later extended (McNamara 1971*b*) to an 18 month period and confirmed that there is a very high correlation between evening-type TEP on Japan–Australia circuits and the presence of range-spreading at Vanimo. The present paper further extends this work by including spread-*F* data from Manila. The analysis has been restricted to 1970 since spread-*F* data for Manila were obtained only for that year. The soundings from Okinawa started to become unreliable after July 1970, which was when the Yamagawa sounder commenced operation. Spread-*F* data have been obtained directly from the vertical incidence ionograms recorded at Manila (14·7° N., 120·6° E.), Vanimo (2·7° S., 141·3° E.), Port Moresby (9·4° S., 147·1° E.), and Cocos Island (12·2° S., 96·8° E.).

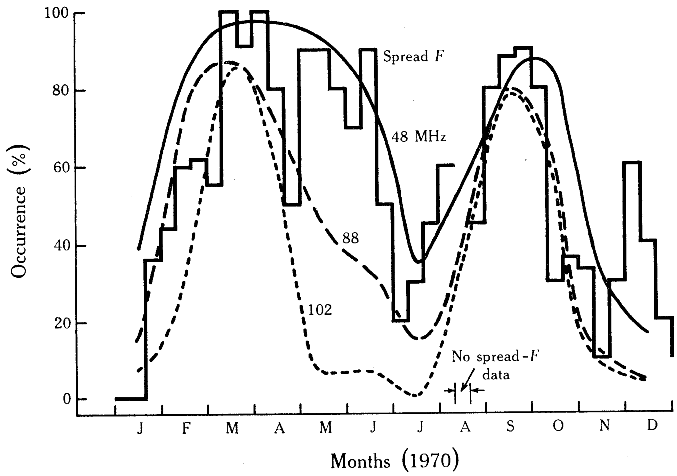

Fig. 1.—Occurrence rates for 1970 of spread *F* before 0000 hr LMT at Vanimo and of reception at Yamagawa of 48, 88, and 102 MHz transmissions from Darwin.

The association between the presence of spread *F* at Vanimo and the reception at Yamagawa of 48, 88, and 102 MHz transmissions from Darwin is shown in Figure 1. Since reception of the higher frequencies always stopped an hour or two after midnight, the histogram records only the spread *F* which started before 0000 hr. There should in fact be three slightly different spread-*F* distributions to take into account failures for the four sets of equipment, but the diagram is exact enough for present purposes as the data are analysed in much greater detail in following sections. It can be seen from Figure 1 that, although the 48 MHz reception has the same seasonal variation as spread *F* at Vanimo, it is not entirely confined to nights with spread *F*. The higher frequencies, on the other hand, are much more closely confined to such nights. In fact the equinoctial peaks at these frequencies are much narrower than the spread-*F* distribution, with spread *F* occurring far more often in May, June, and December than signal reception. The occurrence of TEP on the Y–T and O–T circuits follows a distribution similar to that of the 88 MHz reception for D–Y.

Figure 1 suggests the hypothesis that spread *F* at Vanimo is a necessary but not sufficient condition for the presence of TEP on Japan–Australia circuits. Further support for this hypothesis is given by the fact that the MOF is significantly higher on nights with spread F. For example, in October, which had 15 nights with spread F, the median MOF for the Y–T circuit at 2100 hr (135° E.) was 15 MHz higher for those nights with spread F than for those nights with no spread F. The correlation between TEP and spread-F data obtained at just one point along the circuit would not be expected to be exact, unless the data were exactly representative of all points along that circuit. Since this is not likely to be the case, and certainly cannot be assumed, we also consider spread-F data from other stations and especially Manila.

III. Spread F

As much work has been published on the various aspects of spread F (see e.g. reviews by Clemesha and Wright 1966; Hermann 1966), only those details which are of particular relevance will be considered here.

(*a*) *Nature*

The well-known controversy over the nature of spread F has been summarized by King (1970) who discussed two possible causes of the phenomenon which appears on vertical incidence ionograms. One school of thought is that spread F is due to scattering from field-aligned irregularities in the F region (e.g. Calvert and Cohen 1961; Clemesha and Wright 1966; Hermann 1966). The second school of thought is that the irregularities are not field-aligned but are large surfaces of the order of hundreds of kilometres in size and the spread-F echoes are caused by total reflection from these tilted surfaces (McNicol *et al.* 1956; Bowman 1960*a*, 1960*b*). King rejects the scattering hypothesis, largely on the basis of observed signal strengths which seem too large to be attributed to a scattering process, and points out that some irregularities causing spread F are definitely not field-aligned.

Following the publication of King's (1970) paper, Bates (1971) re-examined backscatter records obtained at College, Alaska, and agreed that the spread F on the vertical incidence ionograms could be caused by total reflection from gross structures in the F layer. However, he also deduced that within these large-scale structures there always existed small-scale irregularities that were definitely field-aligned. In another investigation, Skinner and Kelleher (1971) agreed with King that oblique total reflections from inclined surfaces could contribute to the broadening of the F-layer trace but did not feel that this was the major factor in producing the typical equatorial spread-F pattern on Nairobi ionograms. They interpreted the stratified structure frequently seen on these ionograms as scattering from patches of irregularities at different oblique ranges which were detected because of the wide-angle antenna used. Their backscatter observations at 27·8 MHz (Kelleher and Skinner 1971) supported this view and further indicated that scattering was predominantly from F-layer irregularities which were field-aligned. Mathews and Harper (1971), on the other hand, have interpreted their observations of spread F at Arecibo in terms of specular reflection from tilted surfaces.

Although the question of the nature of spread F is thus clearly not resolved, it seems likely that both large-scale non-field-aligned irregularities and small-scale field-aligned irregularities coexist in the F layer when spread F is observed on vertical incidence ionograms at Manila, Vanimo, and Port Moresby. It is possible, however, that only the large-scale structures are observed on the ionograms. The presence of the small field-aligned irregularities, on which the proposed propagation mode for TEP is based, could then only be inferred. The presence of both types of irregularities is presumably the cause of the uncertainty as to the nature of spread *F*, since different experimental techniques would generally single out only one type.

The exact size of the small-scale irregularities is not important here, but it can be estimated that if they are the same ones which support 50 MHz forward scatter then they are possibly about 10 m wide and extend about 1 km along the magnetic field lines (Cohen and Bowles 1961). On the other hand, the macrostructure of spread *F* is important in the present context, since there is considerable evidence that the irregularities occur in patches rather than as a continuous distribution. According to Clemesha and Wright (1966) the east–west dimensions of these patches are probably about 300 km, while Hermann (1966) gives a similar value for the north–south dimensions. Once produced, these patches travel eastwards into the night-time hemisphere at speeds of about 100 $m\,s^{-1}$. The mechanism by which the irregularities themselves are produced is not understood (see e.g. Farley *et al.* 1970).

(*b*) *Morphology*

The typical development of spread *F* at Vanimo is as follows. At $\sim$ 1900 hr LMT ($\sim$ 1 hr after ground sunset) the base of the *F* layer starts to rise and reaches a maximum after about 1 hr when satellite traces begin to appear. Some time later the echoes diverge and assume the very distinctive form of equatorial spread *F*. Before midnight it is usually only the flat low frequency part of the trace which appears spread, but after about midnight spreading tends to occur in the whole trace while towards dawn it is only in the high frequency part. In terms of the descriptions "range-spreading" and "frequency-spreading" introduced by McNicol *et al.* (1956), pre-midnight spread *F* is almost exclusively range-spreading, post-midnight spread *F* is a mixture of the two types, while spread *F* near dawn is almost exclusively frequency-spreading. The development of spread *F* at Manila follows a similar pattern to that at Vanimo except that the satellite traces often appear before $h'F$ has attained its maximum value.

In the late evening the high frequency part of a trace is usually not visible because of the combined effects of retardation, absorption, noise, and also probably the irregular nature of the lower ionosphere. It is thus possible that this part of the trace, if it existed, would be spread also.

(*c*) *Diurnal Variation*

The earliest times at which spread *F* was first observed at Vanimo during a given month varied between 1845 and 1945 hr LMT. The earlier limit was reached during the September equinox, which showed slightly earlier starting times than the March equinox. The later limit was reached during both solstices. The corresponding range for Manila was 1830–1930 hr, with the same seasonal behaviour. The time of maximum occurrence rate was not well defined but was about 2000–2200 hr for Vanimo and about 1930–2130 hr for Manila. The half-hour difference was a consistent feature throughout the year.

It was very unusual for spread *F* to last continuously throughout the night at either Vanimo or Manila. The normal pattern of occurrence was an initial period of several hours followed by a break of varying time before its reappearance. Three well-separated periods of spread *F* were commonly observed on a particular night.

This pattern of behaviour can be readily understood in terms of the drift of patches of irregularities across the field of view of the observing station.

Only on about 5–10 % of occasions did spread F appear after midnight at either station without having first appeared before midnight. On these occasions there was presumably no generation of irregularities over the station itself but only at points well to the west. It was also not unusual for spread F to be present later than 0600 hr, i.e. well after the F-layer sunrise. However, as implied above, spread F was never observed during daylight hours apart from the short period after sunrise.

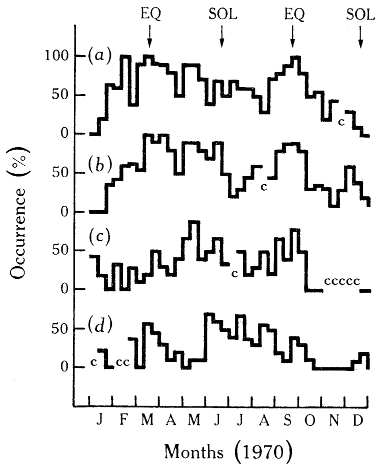

Fig. 2.—Occurrence rates for 1970 of spread F before 0000 hr LMT at: (*a*) Manila (dip = 14°), (*b*) Vanimo (dip = 22°), (*c*) Port Moresby (dip = 34°), (*d*) Cocos Island (dip = 39°). Arrows indicate the times of equinox (EQ) and solstice (SOL). Missing data are denoted by c.

(*d*) *Seasonal, Solar Cycle, and Latitudinal Variations*

The seasonal and solar cycle variations of the spread-F occurrence rate at Vanimo, Port Moresby, and Cocos Island have been considered by D. G. Cole and McNamara (to be published). The seasonal and latitudinal variations depend in fact on the epoch of the solar cycle. During periods of high solar activity, these three stations and Manila exhibit equinoctial peaks which seem to become smaller as the magnetic latitude increases. This is illustrated in Figure 2 which also shows the presence of an extra submaximum in May at Manila, Vanimo, and Port Moresby. During periods of low solar activity, the overall occurrence rate of spread F at Vanimo decreases and has a maximum during June–July. Port Moresby and Cocos Island exhibit a similar seasonal behaviour in periods of low solar activity, but the maximum is much more pronounced than at Vanimo.

(*e*) *Correlation with Post-sunset Height Rise*

Although the post-sunset rise in $h'F$ at Vanimo was only of the magnitude of the estimated error in measuring $h'F$ during June and July, it seems likely (Booker and Wells 1938; Rao *et al.* 1960) that such a rise is a necessary but not sufficient condition for the appearance of spread F. The height rise is certainly not a sufficient condition, as indicated by the fact that the rises are most pronounced at Vanimo in December and January, which show the lowest spread-F occurrence rate for the year. The work of Hanson and Sanatani (1971) suggests that the presence of Fe^+ ions in sufficient concentration may also be a necessary condition.

As mentioned in subsection (*b*) above, spread *F* appears at Vanimo just as or after $h'F$ reaches its peak value whereas at Manila it often appears before $h'F$ reaches its peak. This difference is probably due to the fact that the height rises are significantly larger at Manila than at Vanimo, typical equinoctial rises being 80 and 40 km respectively. For the three stations Manila, Vanimo, and Port Moresby, it has been found that the start times for spread *F* become later as the distance from the magnetic equator increases, while the size of the post-sunset height rise decreases. This agrees with the observation of Rao and Rao (1961) that the time of maximum spread *F* is strikingly delayed on nights associated with smaller values of $\Delta h'F$.

(*f*) *Duration of Initial Period of Spread* F

The presence of equatorial spread *F* on an ionogram usually precludes accurate scaling of $f_0 F_2$ or a true height analysis. Indeed probably the only feature which can be reliably determined is the presence or absence of spread *F*. With these restrictions in mind, the duration of the initial period of spread *F* was analysed in the hope that it would yield some useful information.

The seasonal variation of the average monthly duration at both Vanimo and Manila has been found to be very similar to that of the occurrence rate. A probable cause of this similarity is the fact that the irregularities tend to occur in patches. A high occurrence rate would indicate that patches of irregularities were probably produced at all points along a line of latitude as the sunset line moved along it. As the patches moved eastwards, they would then successively replace the one over the station. A higher probability of occurrence would lead to a larger number of patches drifting eastwards and a higher probability that there would always be at least one patch of irregularities in the field of view of the station. The converse would hold for low occurrence rates. It was found that average monthly durations at Vanimo in 1970 ranged from 90 min in December to 6 hr in September.

(*g*) *Correlation between Spread* F *at Vanimo and Manila*

In view of the fact that it is possible to obtain spread-*F* data only at particular points which do not lie exactly on the circuits considered, it is of some interest to attempt to derive some measure of the area characterized by the data obtained at a given station. Spread *F* occurred before 0000 hr LMT at both Vanimo and Manila on 46% of nights during 1970. (This time limit was chosen because TEP always commenced before then and often finished soon after.) On 27% of the nights there was no spread *F* at either station before this time. It occurred only at Manila on 16% of occasions and only at Vanimo on 11% of occasions; thus at least in 1970 there was marginally more spread *F* at Manila than at Vanimo.

The correlation between spread-*F* observations at Vanimo and Manila is quite high ($\chi^2 = 62$, $N = 323$, $r = 0 \cdot 44$), indicating that the observations at either of these stations are characteristic of conditions that exist over a wide area at least in directions towards the magnetic equator. Although no limit can be placed on the radius of this area, it is possibly at least of the order of 500 km, since Vanimo and Manila are about 2000 km apart. This observed correlation probably stems from the correlation between the post-sunset height rises at the two stations. Although the actual sizes of these rises showed no correlation, it was found that if the layer height fell rather than rose at one station then it usually fell at the other as well, or at least experienced only a small rise, and, as we have noted above, a height rise seems to be a necessary condition for the appearance of spread *F*.

The durations of the first period of spread *F* at the two stations are also correlated, although not as highly as the simple occurrence of spread *F*; for 1970, the values were $\chi^2 = 9\cdot4$, $N = 147$, and $r = 0\cdot25$.

(*h*) *Correlation between Spread* F *at Vanimo and Port Moresby*

The interesting correlation in this case is between the duration of the first period of spread *F* at Vanimo and the appearance of spread *F* at Port Moresby. The data analysed were for 1970 only and the correlation would not necessarily be as high in other years, especially when the June maximum at Port Moresby became significant. However, it is felt that the deduction made here is generally true.

When the spread-*F* duration at Vanimo for each night was compared with the yearly average of that value, it was found that spread *F* was more likely to be observed at Port Moresby on days when the duration at Vanimo was longer than average. On 64% of such days spread *F* was also observed at Port Moresby. On the other hand, spread *F* was observed at Port Moresby on only 26% of the occasions when the duration at Vanimo was less than average. It will therefore be assumed in this paper that the duration of the first period of spread *F* at Vanimo is some measure of the latitudinal extent of the spread *F*, at least in the direction of Port Moresby.

(*i*) *Effect of Magnetic Activity*

According to Clemesha and Wright (1966), the occurrence of spread *F* in equatorial regions is reduced on magnetically disturbed days, with the magnetic control being much more marked at sunspot minimum conditions. The occurrence of spread *F* at Vanimo for 1970 is not very highly correlated with the magnetic activity as measured by the *K* index observed at Port Moresby. By dividing nights into those with $K < 4$ or $K \geqslant 4$ and noting whether spread *F* was present or not, a correlation coefficient of $r = -0\cdot02$ only was obtained. However, a much higher coefficient was obtained for particular months (e.g. $r = -0\cdot24$ for March), indicating that the effect of magnetic activity may be masked in some months by other more dominant effects.

The correlation of the duration of the first period of spread *F* at Vanimo with magnetic activity is somewhat higher ($r = -0\cdot06$) than the correlation of the occurrence of spread *F*, although it is still very small. The correlation between spread *F* at Port Moresby and magnetic activity is in fact positive, but again very small ($r = 0\cdot02$).

IV. Proposed Propagation Mode

The observed correlations between spread *F* and TEP are considered here in terms of a guided propagation mode similar to that suggested by Bowen *et al.* (1968) and Nielson (1968, 1969). Bowen *et al.* studied 77 MHz transmissions from Okinawa to Darwin and measured both the elevation angle of the incoming rays and the group time delay, from which they deduced that the propagation mode was probably a field-guided mode with an apogee of about 470 km. No attempt was made to explain the details of the guiding process. Nielson, on the other hand, discussed the guiding mechanism in detail and explained at least some propagation in terms of guidance between field-aligned irregularities. For frequencies below about 50 MHz, the signal strengths seemed to be far too high to attribute to a scattering process and Nielson suggested that propagation at or below about this frequency takes place essentially by a guiding process. However, at frequencies above about 60 MHz Nielson has shown that the observed signal strengths and their variation with frequency can equally as well be interpreted in terms of scattering provided there is at least partial coherence between different scattering surfaces.

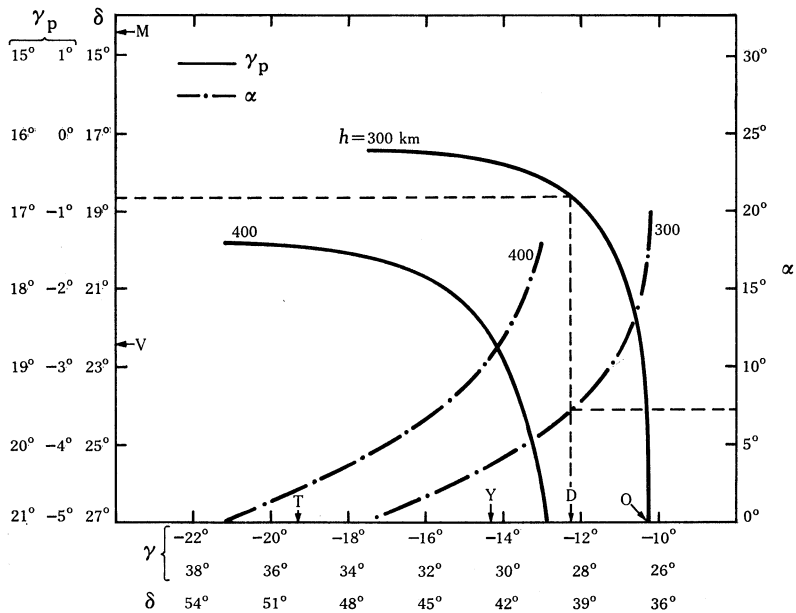

Fig. 3.—Latitudes γ_p with magnetic dip angles δ at which a ray leaving a transmitter at a geographic latitude γ and an elevation angle α would be tangential to the Earth's magnetic field at heights h of 300 and 400 km. The curves are for a geographic longitude of 135° E. Arrows indicate the positions of Manila (M), Vanimo (V), Townsville (T), Yamagawa (Y), Darwin (D), and Okinawa (O).

It is not the intention here to discuss the significance of a scatter mode of propagation (although it is very likely to be important at the three highest frequencies, 72, 88, and 102 MHz, on the D–Y circuit) but rather is it to show that the correlation of TEP with spread F is consistent with and readily explained in terms of guidance between field-aligned irregularities. It is only when other considerations such as signal strength are taken into account that the possibility of a scatter mode becomes evident. In point of fact, it is probable that propagation at the higher frequencies relies on both guiding and scattering processes. It is assumed that the ray path lies wholly beneath the peak of the F_2 layer since there is no evidence to suggest otherwise.

Although the concept of guidance along field-aligned irregularities is normally only applied to medium and lower frequencies, Nielson (1968, 1969) has shown that guidance at frequencies up to about 90 MHz is possible for reasonable density gradients in regions of high density. In general, the requirements for guidance are that (1) the ray curvature equals or exceeds that of the local magnetic field and (2) a suitable means exists for coupling energy into the region beneath (or between) the irregularities.

(*a*) *Coupling of Energy into* F *Region*

The condition for coupling of energy into the F region is probably one of obtaining the required incidence angle at the height where the irregularities exist. Since it is assumed here that the irregularities involved are field-aligned, the condition for coupling is that the incident ray should be approximately tangential to the Earth's magnetic field at the height and latitude where the ray encounters the irregularities.

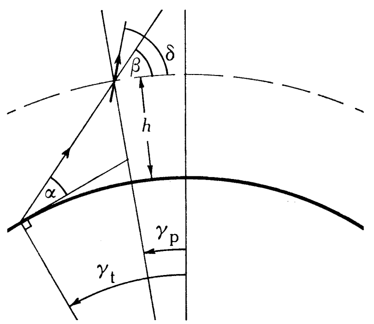

Fig. 4.—Geometry for determining at what elevation angle α a ray should leave a transmitter at a geographic latitude γ_t in order to strike the ionosphere at an angle β equal to the magnetic dip angle δ at a height h and latitude γ_p.

The angle of elevation at which a ray should leave the transmitter and the latitude at which that ray will strike the ionosphere at a given height can be derived from Figure 3. Thus, for example, a ray leaving Yamagawa at an elevation angle of 11° would encounter irregularities tangentially at a height of 400 km and at a geographic latitude of 18·7° N. Rays leaving transmitters at latitudes of either 26° or 38°, on the other hand, could never strike the irregularities tangentially, at least not between 300 and 400 km. Figure 3 is based on magnetic dip rather than geomagnetic dip because of the uncertainty of the effect of the differences between these two quantities. Accordingly the simple analytic procedure used by Nielson (1968, 1969) is not applicable and recourse has been made to graphical procedures. For simplicity the circuit has been taken to be in the magnetic meridian corresponding to a geographic longitude of 135° E.

The geometry of the problem is illustrated in Figure 4. The first step is to determine (for a given height h) the geographic latitudes γ_p at which a ray leaving the ground at an elevation angle α will strike the ionosphere at an angle β equal to the observed dip δ at γ_p. This involves solution for γ_p of the equation

$$\delta(\gamma_p) = \arccos\{R\cos\alpha/(R+h)\},$$

where $\delta(\gamma)$ is the observed variation of the magnetic dip with geographic latitude and R is the radius of the Earth. We thus obtain the curve $\gamma_p = F_1(\alpha)$ say. The next step is to find the difference in latitudes $\gamma_t - \gamma_p$ such that a ray leaving a transmitter at an elevation angle α and a geographic latitude γ_t will strike the ionosphere at height h and latitude γ_p. A little geometry shows that

$$\cos(\gamma_t - \gamma_p) = (R+h)\sin\alpha\,\{R^2+(R+h)^2-2R(R+h)\cos\alpha\}^{\frac{1}{2}}\,.$$

For a given transmitter at the latitude γ_t, we thus have a second curve $\gamma_p = F_2(\alpha)$. The curves in Figure 3 are constructed from the points of intersection of the curves $\gamma_p = F_1(\alpha)$ and $\gamma_p = F_2(\alpha)$ for different values of γ_t.

In terms of the field-guided mode, it is possible to appraise the merits of the D–Y, Y–T, and O–T circuits considered here even without reference to the details concerning the irregularities. This proposed mode leads to the conclusion that the MOF should be highest on those circuits best satisfying the tangency conditions. According to Figure 3, the highest MOF should thus be found on the D–Y circuit and the lowest MOF on the O–T circuit. These conclusions are in agreement with the TEP observations which show that the MOF on the Y–T circuit is about 10 MHz higher than on the O–T circuit but very rarely exceeds 60 MHz. The D–Y circuit MOF has been observed to be at least 102 MHz.

As far as the correlation between spread *F* and TEP is concerned, possibly the most important parts of the circuit are the entry and exit points in the ionosphere. For the maximum frequencies propagated on a circuit, these points are where the transmitted and received rays strike the irregularities tangentially. From Figure 3, it can be seen that the control points are at geographic latitudes of about $-1°$ and 16° to 18° for the D–Y circuit. Since Vanimo is at $-2\cdot7°$ and Manila at $14\cdot7°$, Vanimo lies just south of the southern control point and possibly not on the ionospheric part of the circuit while Manila lies south of the northern control point and is on the circuit.

Figure 3 shows that tangency conditions are satisfied over a large range of heights for rays leaving Yamagawa, which can therefore be regarded as ideally placed for injection of energy into the TEP mode. On the other hand, Townsville is not well placed and tangency conditions cannot be obtained at heights below about 400 km, which is probably where the important irregularities lie. A field line passing over Vanimo at an altitude of 400 km would penetrate the peak of the F_2 layer at smaller magnetic latitudes. Okinawa is also not well placed for injection of energy into the (evening-type) TEP mode. Tangency is possible at heights of about 300 km at a latitude of about 20°, but only for elevation angles of about 20°. Since most of the power is transmitted at much lower elevation angles than this, it seems likely that the power received at Townsville in fact enters the ionosphere mostly at a nonzero angle to the irregularities and at a latitude well south of the northern control point. Also, the field line on which tangency is possible reaches an altitude of 700 km over the magnetic equator whereas it is assumed here that the propagation path always lies below the peak of the *F* layer.

(*b*) *Conditions for Guidance by Irregularities*

The condition for guidance of a ray along a magnetic field line is that the ray curvature should equal or exceed that of the local magnetic field (Rao and Booker 1963). By using a centred dipole field, it is possible to determine the normalized density gradient transverse to the magnetic field line which is necessary before guidance can take place. For operating frequencies f much greater than the plasma frequency f_p, Nielson (1968, 1969) shows that

$$|\nabla_\perp N_e/N_e| \gtrsim 2(f/f_p)^2\{3(1+2\tan^2\theta)/r(1+4\tan^2\theta)^{\frac{3}{2}}\}, \tag{1}$$

where θ is the geomagnetic latitude, N_e the electron density, and r the distance of the ray from the centre of the Earth. At the equator, $\theta = 0$ and

$$|\nabla_\perp N_e/N_e| \gtrsim 6a^{-1}(f/f_p)^2, \tag{2}$$

where a is the radial distance to the field line over the magnetic equator. Equation (2) is approximately true for all points along the ionospheric part of the circuit since we have $\theta \lesssim 10°$.

The important thing to note is that, as the operating frequency increases, the size of the required density gradient increases. Clearly a point is reached above which guidance cannot take place for a given gradient. It should also be noted that the size of the required gradient decreases as the local plasma frequency increases. Thus conditions for guidance are more readily satisfied at low operating frequencies in the presence of high plasma frequencies. Nielson (1968, 1969) discussed the required normalized transverse gradients in terms of the ambient plasma frequencies and obtained estimates of the required gradients for guidance at frequencies up to 90 MHz. His estimates are quite reasonable in terms of the observed plasma frequencies along the circuit.

The real point at issue is whether the transverse gradients which exist in the irregularities are sufficiently large to permit guidance. On the assumption that the irregularities are more dense than the ambient ionosphere, it is clear that the gradients present in the irregularities must exceed those in the ambient ionosphere. The condition for guidance is thus possibly more readily satisfied than is indicated by equation (2), if f_p is taken as the ambient plasma frequency. It is not suggested, of course, that just one irregularity is involved in the guidance process. Since the irregularities are very short compared with the length of the circuit, it is obvious that any guidance achieved would be the integrated effect of many irregularities.

We have seen in the previous subsection that the most likely condition for coupling of energy into the F region is that the rays should strike the irregularities tangentially, and in this case we are able to determine the entry and exit points for the MOF. However, for frequencies below the maximum frequency which can be guided for a given $\nabla_\perp N_e$ and f_p (i.e. the MOF) it is quite possible for rays to be refracted into a condition of tangency with a field line. The localization of the entry and exit points to the so-called control points would not therefore be as great at frequencies below the MOF. Since the possibility of suitable refraction taking place would decrease with frequency, the size of the cone of incident rays which could be guided should decrease with frequency. This would lead to decreases with frequency of the received signal strength and time delay spread, in agreement with observation.

The tolerance of deviations from the tangency condition at lower frequencies also means that TEP could occur at these frequencies, even when the irregularities do not extend to the two control points. Thus lack of spread F at Vanimo, which is south of the southern control point, does not automatically preclude the presence of TEP along the circuits considered. The irregularities also need not form a continuous path for the rays at lower frequencies, although any breaks in the distribution of irregularities would probably lead to lower signal strengths.

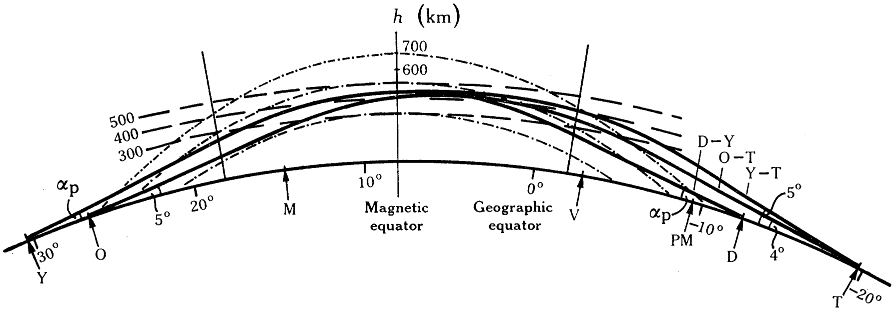

Fig. 5.—Suggested TEP propagation modes for the D–Y, O–T, and Y–T circuits. The dot-dash curves represent magnetic field lines while the dashed curves are equal-height contours. An elevation angle denoted by α_p indicates that the ray is tangential to a magnetic field line. Arrows show the positions of Yamagawa (Y), Okinawa (O), Manila (M), Vanimo (V), Port Moresby (PM), Darwin (D), and Townsville (T).

The geometry for the three circuits considered is illustrated in Figure 5, which shows suggested typical paths for the MOF on each circuit. It has been assumed that the signals remain below the peak of the *F* layer and that where possible the rays enter or leave the ionosphere tangentially to a field line. Since this is not possible for rays arriving at Townsville, the paths are based on an elevation angle of about 5° at this station. It is obvious that the geometry of the D–Y circuit is ideal for the existence of a field-guided mode, since tangency is obtainable by both stations on the same field line. It is also obvious that it is not possible for signals to travel to Townsville along a field line. Propagation along the southern half of the Japan–Townsville circuits may therefore rely on normal refraction as well as partial guidance by irregularities. Refraction cannot, of course, be the sole operative mechanism or even the dominant one, since we shall see in Section V that the presence of irregularities over Vanimo is crucial to the existence of TEP.

V. Correlation of TEP with Presence of Spread *F*

As vertical incidence soundings were made every 15 min in the present work, there were 49 observations of spread *F* (or lack of) for each night (1800–0600 hr LMT) and almost 18 000 potential observations for the year, and, in order to facilitate the analysis of this large amount of data, averages have been taken over both the diurnal and seasonal variations. The results showing the association of TEP with the presence of spread *F* at Vanimo and Manila are presented in Table 1.

The diurnal variation of the occurrence of reception at Yamagawa of 88 MHz transmission from Darwin is compared in Figure 6 with that of spread *F* at Vanimo for 1970. The curves represent averages over the year and tend to give a distorted picture. The seasonal variation of the occurrence rate has been given in Figure 1. An effective diurnal average has been obtained by characterizing each night as a spread *F* night if spread *F* appeared on at least one ionogram before 0000 hr LMT, with a similar procedure for TEP. Such a characterization ignores the question of whether spread F was present at all times in an evening when TEP was observed. The averaging procedure is really an approximate way of averaging over the period up to 0000 hr, but its validity is confirmed by the general agreement between the results

TABLE 1

CORRELATIONS BETWEEN PRESENCE OF SPREAD F AND TEP

The results show the observed correlations for 1970 between the presence of spread F at either Vanimo or Manila and the presence of TEP on the O–T and Y–T circuits or of v.h.f. propagation on the D–Y circuit. Values have been normalized to 100 events

A (spread F at station)	B (TEP on circuit)		Correlation AUB	$AU\bar{B}$	$\bar{A}UB$	$\bar{A}U\bar{B}$	Number N
Vanimo	O–T		38	21	8	33	196
	Y–T		29	15	6	50	130
	D–Y	48 MHz	49	6	16	29	325
		72 MHz	41	12	9	38	299
		88 MHz	37	20	7	36	330
		102 MHz	25	27	4	44	315
Manila	O–T		36	22	11	31	197
	Y–T		28	32	11	29	113
	D–Y	48 MHz	54	6	16	24	327
		72 MHz	45	18	8	29	273
		88 MHz	37	23	5	35	332
		102 MHz	32	31	1	36	299

derived on this basis and on the basis of the curves of Figure 6. This figure shows that TEP occurred in the absence of spread F on about 7% of days while spread F was present without TEP on about 20% of days, in agreement with the corresponding

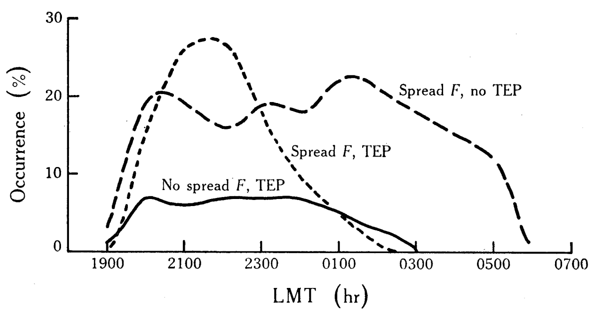

Fig. 6.—Average over 1970 of the diurnal variation of the correlation between the presence of spread F at Vanimo and the reception at Yamagawa of 88 MHz transmission from Darwin.

entries in Table 1. Neglect of breaks in the presence of spread F leads to an over-estimate of the percentage of the time when both spread F and TEP were observed. This should cause no difficulty, however, since we are mainly concerned here with those nights when spread F occurred without TEP.

(a) *Japan–Townsville Circuits*

The main difficulty encountered in the analysis of these data is that of choosing a correct criterion for the presence of TEP on a circuit, since it is not always possible to tell whether the TEP mode in question is present just by examining the MOF's. The afternoon-type mode quite often seems to last for several hours after sunset, independently of the presence of an evening-type mode, and thus the criterion chosen must discriminate to some extent against the afternoon-type mode. The one finally adopted depends on the observation that, when the MOF greatly exceeds the $2F$ MUF, the MOF's in the late evening usually exceed those in the early evening. Identifying this increase with the onset of the evening-type mode, we are led to the criterion that: an evening-type TEP mode is present if the MOF at 2000 hr or later exceeds the MOF at all earlier times during the day, the 1900 hr value being excluded. The times are 135° E. times. The 1900 hr value is mainly excluded in an attempt to separate the two phenomena in time. However, it is possible that yet another type of mode relying on the sunset tilt exists at this time, since the MOF for the Y–T circuit often shows a local maximum at this time.

On the basis of the above criterion, the dependence of the evening-type TEP mode on spread F at Vanimo and Manila is as shown in Table 1. It can be seen that only about 10% of cases contradict the hypothesis that spread F is a necessary (but not sufficient) condition for TEP. As at least some of these cases probably owe their existence to the criterion for TEP, it is not really possible to state that the evening-type mode existed in the absence of spread F. If we consider spread F at either Vanimo or Manila as the necessary condition, there are only about 2% of conflicting cases. There seems to be no point in examining the conflicting cases in more detail, both because of the uncertainties inherent in the criterion and because it may not be necessary to have spread F exactly at either Vanimo or Manila for TEP to occur. The existence of so many cases of spread F without TEP is considered in Section VI.

In order to facilitate the following discussions, we shall adopt from this point onwards the symbolism of set theory in which a letter represents a true statement while the letter with a bar over it represents the negation of that statement. Thus, for example, we can denote the condition "spread F present at Vanimo" by A while "no spread F at Vanimo" is denoted by $\bar{A}$. The letter U denotes the union of any two sets. The statements corresponding to the letters used are indicated in the headings to the appropriate table.

Because of the averaging procedures carried out, it is not wise to dwell too much on small differences in Table 1 between the spread-F–TEP correlations obtained for two circuits and two vertical incidence stations. Thus the correlation on the O–T circuit is not regarded as being significantly different for Vanimo and Manila spread-F data. However, there does seem to be a significant difference for the Y–T circuit in that while the AUB columns of Table 1 agree fairly well, the $AU\bar{B}$ and $\bar{A}U\bar{B}$ columns do not. The source of this difference lies in the fact that spread F occurred more often at Manila than at Vanimo during the period considered. It would seem that it is necessary to have spread F at points along the circuit other than just at Manila, with Vanimo being a typical necessary point. When spread F is present at both Manila and Vanimo, there is a good chance that irregularities exist along the complete length of the ionospheric part of the circuit. This follows from the positions of Manila and Vanimo on the circuits (near the ends of the ionospheric part of the circuit) and the observed correlation between the presence of spread F at the two stations.

(*b*) *D–Y Circuit*

Except for the 48 MHz reception, which may at times occur by the afternoon-type TEP mode, the reception at Yamagawa of the v.h.f. transmissions from Darwin can always be attributed to a TEP mode. The $2F$ MUF is only about 30 MHz at times when TEP is observed. The spread-F–TEP correlation for this circuit is presented in Table 1. There do not seem to be any significant differences between the correlations obtained with the Vanimo and Manila spread-F data. It can be seen that the validity of the hypothesis that spread F is a necessary (but not sufficient) condition for TEP improves as the frequency increases (i.e. the entries in the $\bar{A}UB$ column decrease). It is also obvious that the percentage of AUB cases decreases while the percentage of $AU\bar{B}$ correspondingly increases.

At least part of the reason for the decrease in the number of AUB cases lies in the higher values of $|\nabla_\perp N_e/N_e|$ necessary to guide the rays around the circuit. Attempts were made to determine whether the 102 MHz reception favoured nights of high critical frequencies at Vanimo and Manila by considering the values of f_0F_2 just before the onset of spread F, but these were inconclusive. It is not possible to scale f_0F_2 accurately when TEP is present since spread F is then also present.

The decrease with frequency of the number of $\bar{A}UB$ cases probably results from the fact that as the frequency increases it approaches the MOF for the circuit. While some deviation from tangency is tolerable at lower frequencies, this tolerance decreases as the frequency increases and it becomes more necessary to have irregularities right in the control regions and along the whole ionospheric path between these regions. The situation is confused by the fact that Vanimo is a little south of the southern control point and so it is probably not always essential to have irregularities above Vanimo itself. However, the decrease of $\bar{A}UB$ cases probably indicates a southward movement of the injection point towards the southern control point as the frequency increases. It seems highly likely that when spread F is observed at this control point it would also be observed at Vanimo.

The decrease of $\bar{A}UB$ cases for the Manila data is more pronounced than for the Vanimo data, probably reflecting the fact that Manila lies between the two control points. The trichroic correlation for 1970 between 88 MHz reception (T) on the D–Y circuit and spread F at Manila (M) and Vanimo (V) is set out below (values normalized to 100 events).

$VUMUT$	$VU\bar{M}UT$	$\bar{V}UMUT$	$\bar{V}U\bar{M}UT$	$VUMU\bar{T}$	$VU\bar{M}U\bar{T}$	$\bar{V}UMU\bar{T}$	$\bar{V}U\bar{M}U\bar{T}$	N
33	5	5	1	12	7	10	27	264

This does not provide significantly more information than before, but it can be seen that TEP occurred on 75% of nights when spread F occurred at both stations and on only 4% of nights when spread F did not occur at either station.

It is of some interest to compare the results for those cases when spread F was observed at only one station. This has been done for 48, 88, and 102 MHz and the results are shown in Table 2. It can be seen that there are fewer conflicting cases for the Manila data but there are also fewer no spread-F with no TEP days. These results mainly arise because spread *F* occurs more often (60% to 40%) at Manila on the days considered. The correlation between spread *F* and TEP is in fact small and positive for the Vanimo data whereas it is negative for the Manila data. Thus spread-*F* data from Vanimo are a better indication than those from Manila of the probability of a TEP mode being present.

Table 2

CORRELATIONS BETWEEN PRESENCE OF SPREAD *F* AT ONLY ONE STATION AND TEP

The results show the observed correlations for 1970 between the presence of spread *F* at only Vanimo (V) or Manila (M) and v.h.f. reception (T) on the D–Y circuit. Values have been normalized to 100 events

T (v.h.f. reception on D–Y)	$\overline{M}UT$ VUT	$\overline{M}U\overline{T}$ $VU\overline{T}$	MUT $\overline{V}UT$	$MU\overline{T}$ $\overline{V}U\overline{T}$	N
48 MHz	32	7	45	16	73
88 MHz	15	26	20	39	88
102 MHz	5	33	9	53	74

VI. Correlation of TEP with Duration of Spread *F*

The preceding section was devoted to a discussion of the necessity of spread *F* for TEP to occur and little mention was made of those cases when spread *F* was observed but TEP was not. It will be shown in this section that many of these cases can be attributed to patchiness of the irregularities along the circuit, which is thus not always complete as far as the guiding mechanism is concerned. As described in Section III, the duration of the first period of spread *F* is a measure of the latitudinal

Table 3

CORRELATIONS BETWEEN DURATION OF SPREAD *F* AND TEP

The results show the observed correlations in 1970 between cases of spread *F* with no TEP and the duration d of the first period of spread *F* relative to the monthly average $\bar{d}_m$ of that quantity. Values have been normalized to 100 events

Spread *F* + no TEP on circuit		Vanimo $d > \bar{d}_m$	$d < \bar{d}_m$	N	Manila $d > \bar{d}_m$	$d < \bar{d}_m$	N
O–T		28	72	29	39	61	46
Y–T		37	63	19	41	59	39
D–Y	48 MHz	23	77	18	35	65	20
	72 MHz	33	67	39	27	73	44
	88 MHz	26	74	61	32	68	75
	102 MHz	37	63	84	43	57	93

extent of the spread *F* conditions as monitored at the observing station. A short duration also indicates in general that spread *F* occurs in discrete patches rather than as a continuous distribution over the equatorial belt, and vice versa. With these associations in mind we now consider those nights on which spread *F* occurred without TEP.

As shown in Table 3, cases of spread *F* with no TEP were twice as likely to occur when the spread-*F* duration was less than average. To obtain the results shown in this table, the duration d of the first period of spread F has been compared with the monthly average $\bar{d}_m$ of that quantity. A more definite effect is found if the comparison is made with the yearly average duration, since in general it is the months with short durations which have least TEP. It is difficult to estimate the significance of the small differences between the entries in Table 3. In general it would seem that the effect of the Vanimo duration is slightly more important than the Manila duration. This can be explained in terms of the possible need of a southward extension from Vanimo of spread-F conditions. As seen in Section III(h), such an extension is in general less on nights with short spread-F duration. This effect is in addition to that of the suggested patchiness of the spread-F distribution on nights with short durations.

TABLE 4

CORRELATIONS BETWEEN DURATION OF SPREAD F AND MMOF

The results show the observed correlations in 1970 between the duration d of the first period of spread F (relative to the yearly average $\bar{d}_y$) at Vanimo and Manila and the MMOF during an evening (relative to the monthly median $\overline{\text{MMOF}}$) on the O–T and Y–T circuits. Values have been normalized to 100 events and adjusted to ensure that 50% of the durations are less than average

A ($d > \bar{d}_y$ at station)	B (MMOF > $\overline{\text{MMOF}}$ on circuit)	AUB	$A U\bar{B}$	$\bar{A}UB$	$\bar{A}U\bar{B}$	N
Vanimo	O–T	38	12	10	40	61
	Y–T	33	17	29	21	57
Manila	O–T	28	22	25	25	57
	Y–T	35	15	25	25	27

From Table 3 it would also seem that the effect of short durations is more marked at lower frequencies than at higher frequencies, although the 72 and 88 MHz data tend to nullify this conclusion. However, both Vanimo and Manila data show that the lack of 102 MHz reception is not as readily explained in terms of spread-F duration as is the lack of 48 MHz reception. This suggests that there is another cause of the absence of reception in addition to that of patchiness of the spread-F distribution or insufficient southerly extension from Vanimo of spread-F conditions, since if these were the only causes then the lack of 102 MHz reception should be confined more closely to short duration nights than the lack of 48 MHz reception. The most likely extra cause is the magnitude of $f_0 F_2$ along the circuit. We shall return to this point in Section VII.

(a) *Maximum MOF on Japan–Townsville Circuits*

Since a long duration of spread F at Vanimo is taken to indicate a large southward extension of the equatorial spread-F belt and since tangency conditions from Townsville would be much more closely satisfied if this were so, the maximum MOF (MMOF) received during an evening should be greater when the duration of spread F is greater. This is in fact the case, as shown in Table 4. This table compares the MMOF with the monthly median value of that quantity and shows the correlation with spread-F duration. It can be seen that there is a marked tendency for long spread-F durations to be associated with greater than average MMOF's, although the restriction of such MOF's to days with long duration of spread F is not very marked. It can also be seen that the restriction to short durations of nights with lower than median MMOF's is most marked for the Vanimo data and the O–T circuit. There is in fact no restriction for the other three cases. The restriction in the case of the Okinawa circuit is of course readily understood in terms of the failure of the equatorial spread-F belt to extend significantly south of Vanimo.

An obvious way to check the deduction that the correlation of TEP with long durations at Vanimo is due to the southerly spread of the irregularities is to consider spread F at Port Moresby. The correlation of spread F at this station with TEP is in fact very poor. However, it is found that the MOF on the Japan–Townsville circuits is significantly greater on nights when spread F occurred at Port Moresby as well as at Vanimo.

TABLE 5

CORRELATIONS FOR LONG SPREAD-F DURATIONS WITHOUT TEP

The results show the observed correlations in 1970 between cases of long spread-F duration without TEP and the absence ($d = 0$) or duration d of spread F at the other station relative to the yearly average duration $\bar{d}_y$. Values have been normalized to 100 events

$d > \bar{d}_y$ at station	D–Y frequency (MHz)	At other station $d = 0$	$d > \bar{d}_y$	$d < \bar{d}_y$	N
Vanimo	88	27	18	55	11
	102	36	16	48	25
Manila	88	53	16	31	19
	102	44	16	40	25

When the MMOF for a night was compared with the monthly median value of that quantity, it was found that greater than median values were observed on the O–T circuit on 60% of those nights when spread F was present at Port Moresby. The corresponding value for the Y–T circuit was 88%, indicating that the Yamagawa transmissions follow a higher path than the Okinawa transmissions and therefore require in general the presence of irregularities further south from Vanimo than are required by the Okinawa transmissions.

A point which must be explained is the fact that the analysis of the correlation of the Yamagawa MMOF's with the duration of spread F at Vanimo showed no significant restriction of the less than median MMOF's to less than average durations. This seemingly conflicts with the finding that the Yamagawa MMOF's were more closely restricted to nights with spread F at Moresby than were the Okinawa MMOF's. However, this conflict can be resolved if spread F existed to the south of Vanimo at almost all times when the Yamagawa MMOF's were observed. This would then agree with the proposal that the Yamagawa transmissions follow a higher path than the Okinawa transmissions.

(b) *Long Spread-*F *Durations without TEP*

We have seen above that many of the spread-F without TEP cases can be attributed to either patchiness of the spread-F distribution along the circuit or failure of spread F to extend sufficiently far south of Vanimo. We now consider those few cases which cannot be explained in terms of durations at one station. The explanation is in fact similar, except that we are now concerned with the effect of spread F at the other station. The situation is summarized in Table 5. The results show that in over 80% of cases when TEP did not occur, even when the spread-F duration was longer than the 12 month average, there was either no spread F at the other station or at least it was of only short duration. This reinforces the conclusion that most of the spread-F without TEP days can be attributed to lack of continuity of irregularities along the circuit.

VII. Effects of $f_0 F_2$ Values along Circuit

We have seen in Section IV(*b*) that the condition for guidance by field-aligned irregularities is easier to achieve under conditions of high plasma frequencies. Since the magnitude of the monthly median values of $f_0 F_2$ has solstitial minima at both Vanimo and Manila, it is quite likely that at least some of the cases of spread F without TEP during the solstices can be attributed to the lower values of $f_0 F_2$ along the circuit at these times.

Any attempts to show that the values of $f_0 F_2$ along the circuit have an effect on the occurrence of TEP must of necessity be indirect, since no data are available over the magnetic equator, where the values of $f_0 F_2$ are least and thus most important. Even at Vanimo and Manila $f_0 F_2$ values cannot usually be scaled accurately because of the presence of spread F and only fairly general statements concerning their size are possible. However, there are two features which can be explained most readily in terms of the values of $f_0 F_2$ along the circuit, namely the disappearance of TEP after about midnight and the seasonal variation of the association between short spread-F durations and the spread-F without TEP cases.

(*a*) *Disappearance of TEP after Midnight*

An obvious feature of the diurnal variation of TEP occurrence is that, with the exception of the 48 MHz D–Y transmissions, TEP is not observed after about 0100 or 0200 hr, even though spread F is often observed until much later than this. There are several possible explanations of this feature and so several factors may be operating simultaneously.

In view of our success in explaining days of spread F without TEP in terms of lack of continuity of irregularities along the circuit, it is highly probable that this effect was present, especially since the disappearance and reappearance of spread F was very pronounced after about midnight. Another possible effect would be the general change of the spread F to frequency-spreading in the early hours of the morning. As we have seen, spread F before that time is always of the range-spreading type. However, the change in the morphology of the spread F seen by the ionosonde does not necessarily bear any relation to changes in the field-aligned irregularities and this point will not be pursued.

The disappearance of TEP after midnight can in fact be explained quite simply in terms of the rather rapid post-midnight decrease in critical frequencies. This would lead to the need for high values of $\nabla_{\perp} N_e$ to ensure that guidance could still take place. Thus once the critical frequencies dropped below a certain value set by the available gradients, the guiding mechanism would cease to operate. As would be expected on the basis of this suggestion, the lower the frequency the later should it continue to be propagated. In fact 48 MHz reception often occurs all night. This is not surprising because night-time values of $f_0 F_2$ rarely fall below half of the value they attain when the 102 MHz signals are being propagated.

The conclusion that the post-midnight dropout of TEP is due to the decrease in values of $f_0 F_2$ is not possible to support in detail because of the impossibility of scaling this parameter reliably in the presence of spread F. However, it is at least a far more likely cause than the breakdown of the continuity of irregularities. If this were in fact the prime cause, it would be expected that TEP should exhibit the same stop-start behaviour as spread F. Although the 102 MHz often exhibits such behaviour, none of the 72, 88, and 102 MHz transmissions are ever received after about 0200 hr.

(*b*) *Seasonal Variation of Effect of Short Spread-*F *Durations*

The spread-F without TEP cases have already been analysed in terms of short spread-F durations for each of the six sets of data. To investigate the seasonal variation of the effect of spread-F durations, all six sets have been grouped together and the seasonal variation investigated in terms of either solstitial or equinoctial data. The Vanimo data show that the no-TEP cases are more closely confined to short-duration nights during equinoctial months (three out of four) than during solstitial months (two out of three). This effect is very marked at 48, 72, and 88 MHz on the D–Y circuit, but not at 102 MHz. The final values are of course heavily weighted by the 102 MHz data. A total of only 10% of equinoctial no-TEP cases for the lowest three frequencies occurred on nights with longer than average spread-F durations. The corresponding value for the solstices was over 40%.

The seasonal variation at Vanimo can be explained in terms of $f_0 F_2$ variations. During the equinoxes, when the values of $f_0 F_2$ are greatest, the condition for guidance is more readily satisfied and propagation would be mainly controlled by breaks in the distribution of irregularities along the circuit. However, during the solstices the lower values of $f_0 F_2$ which occur may not be sufficiently high to allow guidance at high frequencies even though the distribution of irregularities along the circuit is complete. Thus spread-F without TEP cases during solstices would not be expected to show a high correlation with short spread-F durations, the correlation at 102 MHz being expected to be lowest of all the four frequencies.

The Manila data do not show any significant seasonal variation of the effect of short spread-F durations. However, if the February data are ignored, the situation is similar to that obtained with the Vanimo data, although the seasonal difference is not as great. Most of the conflicting February cases can be explained in terms of either complete absence or only short duration of spread F at Vanimo.

VIII. Conclusions

The correlation between the existence of evening-type TEP on transequatorial circuits and the presence of spread F at stations along or near the circuits has been found to be highly significant, and it is concluded that spread F is a necessary but not sufficient condition for the existence of TEP. From an examination of the correlation in terms of a type of field-guided propagation mode which is closely associated with the presence of small-scale irregularities aligned along the Earth's magnetic field, evidence for the correctness of this model has been provided both by experiment and by the self-consistent interpretations that have been made here.

Two causes have been proposed for the lack of TEP on many occasions when spread F was present along the circuit. Before about midnight, most of these cases can be attributed to the lack of continuity of irregularities along the circuit or failure of the belt of irregularities to approach sufficiently closely the latitudes of the transmitter or receiver. Some of the cases can also be attributed to the fact that the values of the electron density along the circuit were not sufficiently high to support the guided mode. The failure of TEP to extend later than about 0200 hr LMT is attributed to the normal post-midnight decrease of electron densities.

IX. Acknowledgments

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