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Variations of Spread-*F* Occurrence Rates at Near-equatorial Stations in the Australasian Zone

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Abstract

The occurrence rates of spread *F* for selected years between 1964 and 1972 are presented for three Australian stations lying between 10° and 25° magnetic latitude. Spreading is mainly of the range-spreading type. Two types of spread *F* are observed: one occurs during the solstices and correlates negatively with sunspot number; the other occurs during the equinoxes and correlates positively with sunspot number and negatively with magnetic activity. The relative importance of the two types is found to vary with latitude.

Introduction

The survey of spread *F* presented here has arisen out of a study of the correlation which exists between equatorial spread *F* and long range v.h.f. radio propagation on transequatorial circuits (McNamara 1973). Regular oblique soundings between Darwin and Yamagawa (in southern Japan) and between Yamagawa and Townsville have shown that the maximum observed frequency is greatly enhanced when bottom-side ionograms recorded at points along the circuits exhibit spread *F*. This phenomenon is known as evening-type transequatorial propagation (TEP). From the point of view of planning a communications system based on TEP, it is necessary to know the diurnal, seasonal and solar cycle variation of its occurrence. It is only then that it is possible to decide whether such a system is either feasible or practicable. This in turn involves knowledge of the variations of the spread-*F* occurrence rates along the circuit. Such information provides an upper limit on the possible rates of TEP occurrence. The occurrence rate of spread *F* also plays an increasingly important part in satellite communications since its presence limits the rate of information transfer.

The geographical distribution of spread-*F* occurrence is characterized by two areas of maxima (Herman 1966). Firstly, there is a belt of high occurrence in the equatorial regions bounded by geomagnetic latitudes of about ±20°. Then there is a second maximum at latitudes greater than about 40°, with little spread *F* being observed between about 20° and 40°. The stations considered here all lie towards the edge of the equatorial belt.

Ionograms for selected years between 1964 and 1972 have been analysed for Vanimo (2·7° S., 141·3° E., magnetic latitude 11° S.), Port Moresby (9·4° S., 147·1° E., magnetic latitude 19° S.) and Cocos Islands (12·2° S., 96·8° E., magnetic latitude 22° S.). The ionograms themselves were examined because it was found that there was very little correlation between the presence of spread *F* (especially range-spreading) on the ionograms and the presence of the descriptive letter F on the scaling sheets.

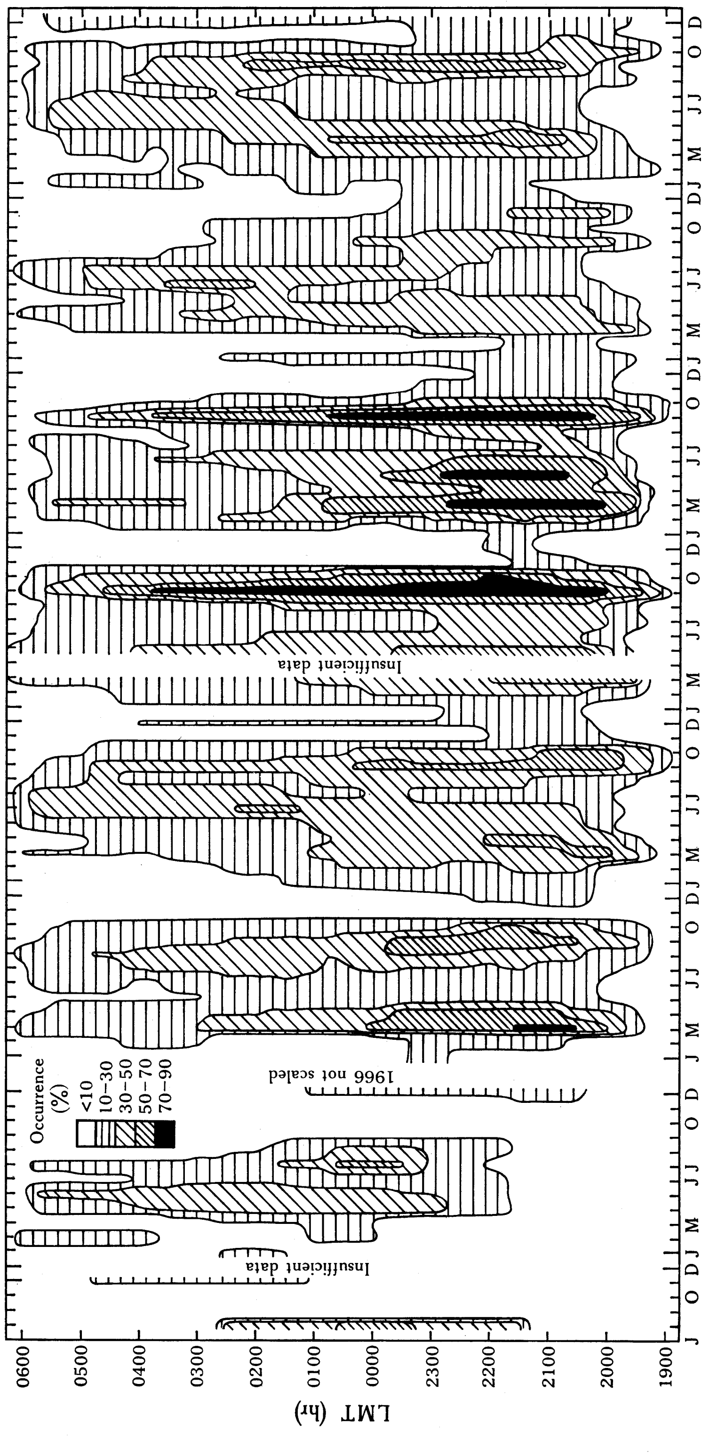

Fig. 1. Contour plot of the monthly percentage occurrence rates of spread *F* at Vanimo as a function of local time and month of the year from August 1964 to December 1972.

Quarter-hourly ionograms have been scaled but only the presence or absence of spread *F* has been recorded, with no attempt to classify the extent of the spreading according to a scheme of indices. Neither has any attempt been made to distinguish between range spreading and frequency spreading since, for the stations considered, spread *F* before midnight, which is of most interest in the studies of TEP, is almost exclusively of the range-spreading type.

Spread *F* in the Equatorial Belt

According to Lyon *et al.* (1960), the equatorial belt of spread *F* extends from about 30° S. to 30° N. in magnetic latitude and has a region of very high incidence, exceeding 90% for the early part of the night, about 20° wide in latitude and centred on the dip equator. The main conclusions reached by various workers on the occurrence pattern of spread *F* in the equatorial zone have been summarized by Skinner and Kelleher (1971), who deduce the following:

Within the equatorial zone, distinction should be made between those stations such as Ibadan, Kodaikanal, Djibouti, Trivandrum and Huancayo which lie within the equatorial electrojet region (5° north and south of the magnetic equator) and stations such as Nairobi, Ahmedabad, Baguio (Manila), Taipei and Singapore which lie between 5° and 20° from the magnetic equator.

In the electrojet region, spread *F* is usually present throughout the night under magnetically quiet conditions, with relatively little nocturnal or seasonal variation. At African and Asian electrojet stations, the solar cycle variation of spread *F* shows a strong positive correlation with sunspot number (Rangaswamy and Kapasi 1963; Chandra and Rastogi 1970). Huancayo, on the other hand, has maximum spread-*F* occurrence in southern solstice months, and an inverse correlation with sunspot number. The occurrence pattern of spread *F* at stations in the 'non-electrojet' equatorial region is rather more complex, and it seems necessary to subdivide the data into groups depending on the time of night, season of year and epoch of solar cycle in order to obtain a consistent picture. The three stations Vanimo, Port Moresby and Cocos Islands are all non-electrojet stations.

Rangaswamy and Kapasi (1963) found that at Ahmedabad the seasonal maximum shifted from the equinoxes in 1958 to the northern solstice in 1962. Marasigan (1960) showed that spread *F* at Manila occurred most often during the northern solstice in periods of low sunspot number but most often during the equinoxes in periods of high sunspot number. Similar conclusions were reached by Skinner and Kelleher (1971) for Nairobi and by Huang and Yeh (1970) for Taipei.

Spread *F* at Vanimo, Port Moresby and Cocos Islands

The solar-cycle, seasonal and diurnal variations of the occurrence rate of spread *F* at Vanimo for the period August 1964 to December 1972 are shown in the contour plot of Fig. 1. The occurrence rates are the monthly percentage occurrence of spread *F* observed at each quarter hour. It can be seen that the distribution exhibits well-defined solar-cycle and seasonal variations which are, however, interlinked. Thus in periods of low sunspot number (1964–66) the occurrence rate is greatest during the northern solstice while in periods of high sunspot number (1967–70) the rate is greatest during the equinoxes. This is shown in more detail in Fig. 2 where the mean duration of spreading per day is given for the different seasons. These results agree with those previously discussed for Manila, Taipei, Nairobi and Ahmedabad.

Throughout the solar cycle, the occurrence rate during the northern solstice far exceeds that during the southern solstice (Fig. 2). There does not seem to be any consistent variation with sunspot number of the rate during the northern solstice, possibly because of the overlapping effect of the equinoctial peaks during periods of high sunspot number. The rate during the southern solstice is too low to give any significant trend. In general the diurnal variation of the occurrence rate during the equinoxes in years of high sunspot number agrees with that at Nairobi and Taipei, with a maximum before midnight. However, the post-midnight maximum observed at these stations during the northern solstice months near sunspot minimum is not evident at Vanimo. The start times are earliest in the years of maximum occurrence rate.

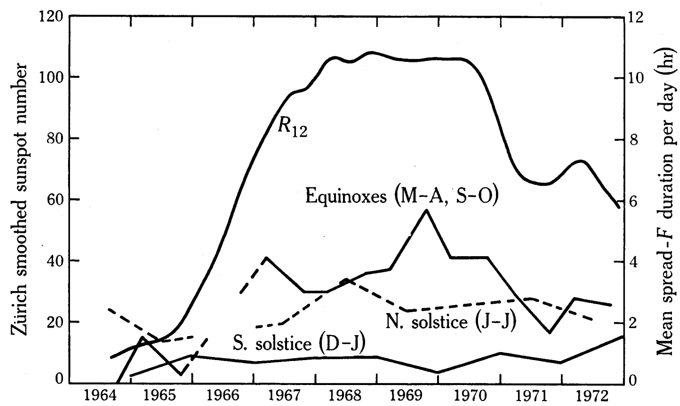

Fig. 2. Variation of spread-*F* occurrence at Vanimo with solar activity. Plots of the mean daily duration of spread *F* during the southern solstice, northern solstice and equinox from 1964 to 1972 (1966 omitted) are compared with the solar activity over these years as described by the smoothed sunspot curve.

As can be seen from Figs 3 and 4, the spread-*F* occurrence rates at Cocos Islands and Port Moresby are very similar, with northern solstice maxima and southern solstice submaxima, both of which correlate inversely with sunspot number (Fig. 4). During the years of low solar activity the northern solstice occurrence of spread *F* increases over a number of months, making it difficult to resolve the equinoctial occurrence. However, during the periods of high sunspot number the equinoctial maxima can be distinguished, especially for Port Moresby (Fig. 3*a*), but these are not as strong as the northern solstice maxima during the years of low solar activity. The occurrence rates are greatest at Cocos Islands between 2200 and 0100 hr LMT while at Port Moresby they are greatest between 2300 and 0500 hr.

The presence of northern solstice maxima at these stations and Vanimo agrees with predictions on the basis of the spread-*F* equator described by Reber (1956) and Singleton (1963). Stations lying to the south of this equator, which passes through Japan, exhibit seasonal maxima in June–July while stations to the north exhibit maxima in

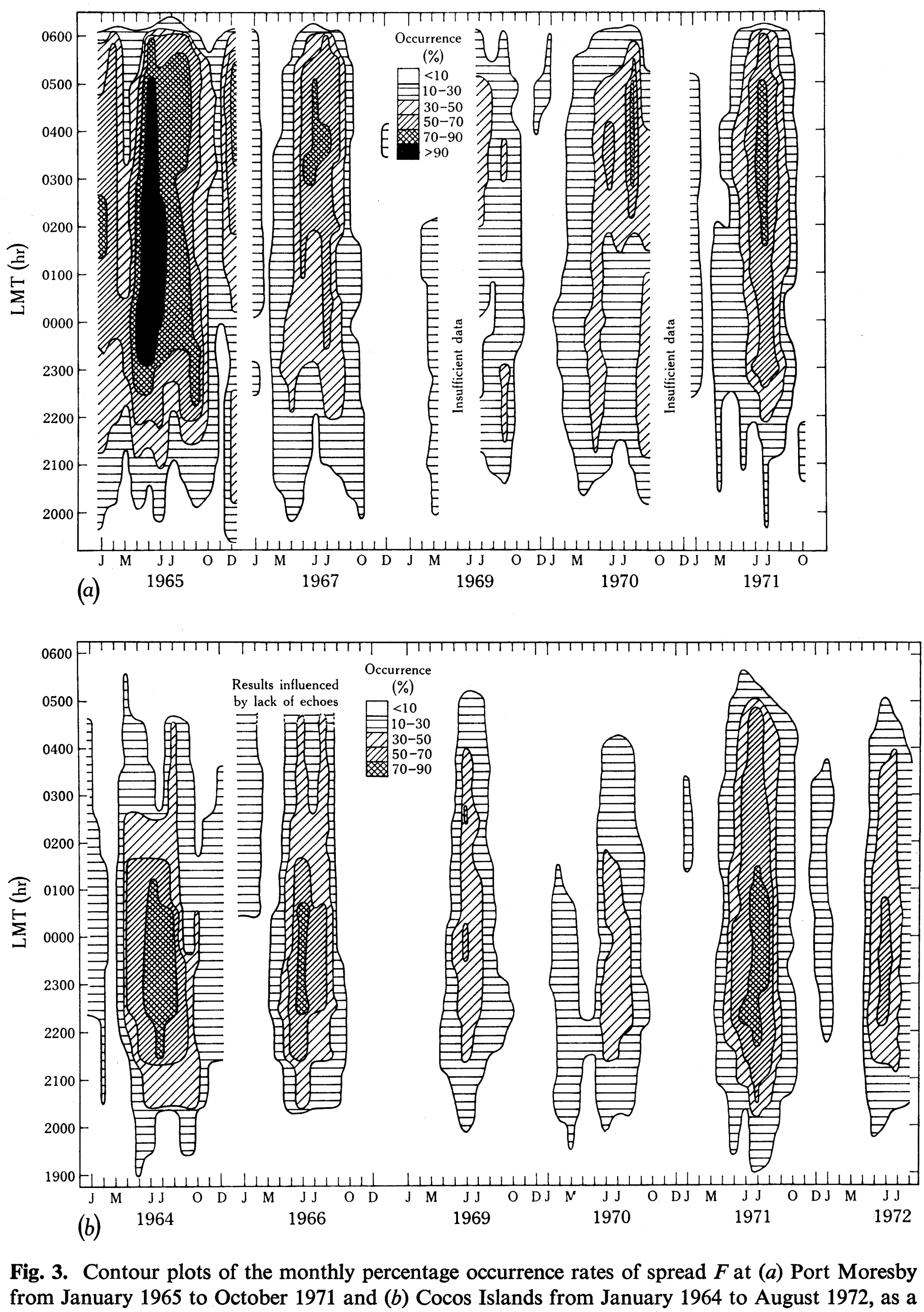

Fig. 3. Contour plots of the monthly percentage occurrence rates of spread F at (*a*) Port Moresby from January 1965 to October 1971 and (*b*) Cocos Islands from January 1964 to August 1972, as a function of local time and month of the year.

December–January; the months of the solstitial submaxima are reversed. The other stations mentioned, Manila, Ahmedabad, Taipei and Nairobi, also lie south of the spread-*F* equator.

Effect of Magnetic Activity

Several broad conclusions have been well established concerning the effect of magnetic activity on occurrence rate. Firstly, there is a general negative correlation which exists for stations at high latitudes (Shimazaki 1959; Lyon *et al.* 1960). In most cases and especially at the equinoxes, the changeover occurs at magnetic latitudes of about ±30° in all longitude zones. Consequently the belt of inverse correlation coincides closely with the total width of the quiet day spread-*F* belt (Lyon *et al.* 1960).

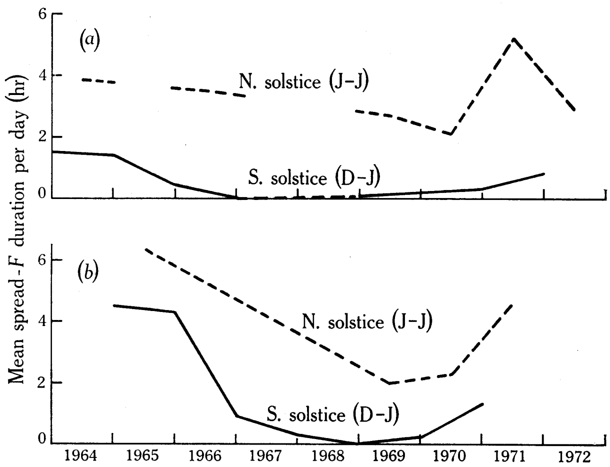

Fig. 4. Variation of spread-*F* occurrence at (*a*) Cocos Islands and (*b*) Port Moresby during the solstices.

The second conclusion is that the correlation for the equatorial spread-*F* belt tends to be more definite at sunspot maximum than at sunspot minimum (Marasigan 1960; Clemesha and Wright 1966; Huang and Yeh 1970; Skinner and Kelleher 1971). Northern summer in the American zone presents an exception to the general picture for equatorial spread *F* in that there is no marked reduction of the spread-*F* index under magnetically disturbed conditions (Lyon *et al.* 1960). Skinner and Kelleher have drawn the same conclusion but only for sunspot minimum. The extent of the correlation is found to be most marked during the equinoxes and least during the northern solstice (Rao and Rao 1961; Rangaswamy and Kapasi 1963; Chandra and Rastogi 1972). Rangaswamy and Kapasi also report a positive correlation during the southern solstice in years of sunspot minimum.

The effect of magnetic activity on the presence of spread *F* at Vanimo, Port Moresby and Cocos Islands has been analysed in terms of the spread-*F* durations on the five International Quiet Days and five International Disturbed Days (Fig. 5). Pre-midnight (1800–0000 hr LMT) and post-midnight (0100–0400 hr) spread *F* have been considered separately since the behaviour for the two periods is not necessarily the same (Skinner and Kelleher 1971).

The correlation at Vanimo was found to be predominantly negative during the equinoxes, as expected from the results of other workers. There was no consistent trend during the northern solstices and virtually no spread *F* during southern solstices. No obvious differences between pre-midnight and post-midnight data were seen. The Port Moresby data were heavily affected by equipment failures and it is difficult to draw reliable conclusions. However, there was a tendency for the correlation to be positive after midnight and also in years of solar minimum. It is also difficult to draw conclusions for Cocos Islands but most sizable correlations were negative, both before and after midnight.

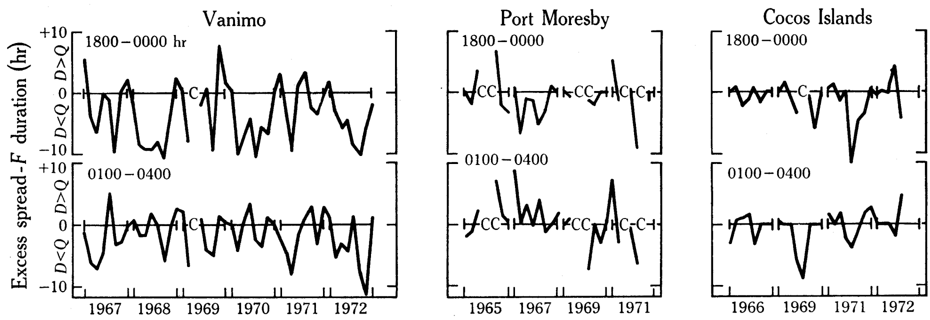

Fig. 5. Excess duration of spread-*F* occurrence on the five International Disturbed Days compared with the five International Quiet Days. A positive value indicates a longer duration on a disturbed day ($D > Q$). Each year has been divided into seasons: January; March, April; June, July; September, October; December. The data for premidnight (1800–0000 hr) and postmidnight (0000–0400 hr) periods have been considered separately. The letter C indicates unreliable data.

Correlation between Occurrence of Spread *F* and Height Changes in the *F* Region

Previous work on the correlation between the onset of spread *F* and the rise and fall of the *F* layer has been summarized by Skinner and Kelleher (1971). Equatorial spread *F* has been observed to coincide with the descent of the layer after the post-sunset rise, with the probability of occurrence correlating positively with the size of the rise in $h'F$. In order to make the present study more complete and to bring it into line with other spread-*F* investigations, the correlation between $h'F$ and the occurrence of spread *F* has been studied for Vanimo, Port Moresby and Cocos Islands at both low and high solar activities.

Since the *E* region has a low density over the night-time hours, we can consider the values of $h'F$ to be close to the real base height of the *F* layer. The change of the height of the base of the layer has been found to coincide with a corresponding change in the height of the layer maximum (Lyon *et al.* 1961). Thus the variation of $h'F$ indicates the movement of the layer as a whole.

Fig. 6*a* illustrates the variation of $h'F$ at Vanimo during minimum solar activity (1964–65). Median heights have been averaged over four-monthly periods for northern solstice, southern solstice and equinoxes. Comparing these with the distribution of the start times of spread *F*, which is also shown in Fig. 6*a*, it can be seen that the distributions correspond closely except during equinoxes. In this case, the post-sunset rise and fall is over before the spread *F* starts. At Cocos Islands and Port Moresby, the two distributions correspond closely in all seasons.

During sunspot maximum the pattern of the rise and fall of the F layer remains much the same as during the minimum, although there are differences in the maximum heights reached. The greatest rate of onset of spread F again coincides with the greatest height reached in the post-sunset rise. As shown in Fig. 6*b*, the correspondence between the two distributions during equinoxes is much closer during sunspot maximum than during sunspot minimum. There is little spread F during the southern solstice and consequently the numbers are too small at that time to be significant.

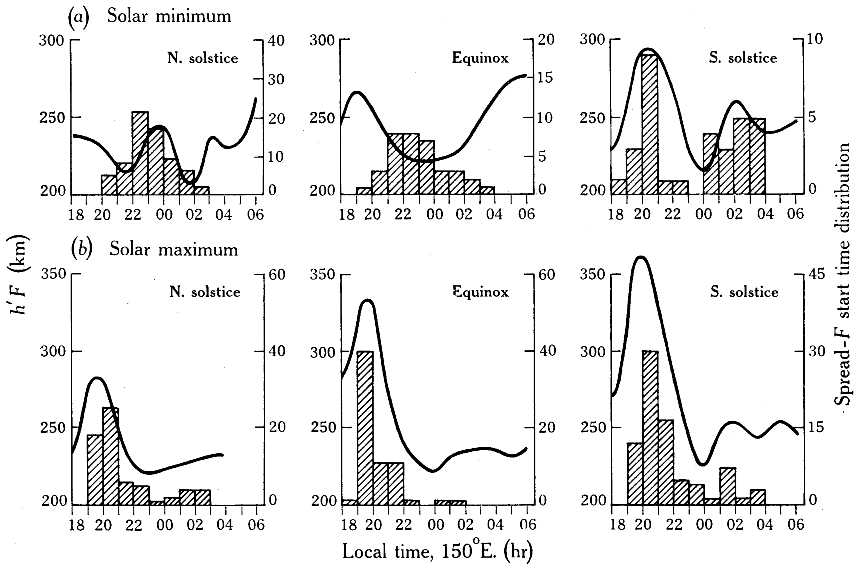

Fig. 6. Comparisons between variation of $h'F$ (curves) and distribution of spread-F start times (histograms) at Vanimo for periods of minimum solar activity (1964–65) and maximum solar activity (1969–70).

Narasinga Rao (1966) found that at Kodaikanal and Huancayo a critical height has to be exceeded before spread F can occur. However, this effect is not obvious for the stations considered here. The distribution of $h'F$ values at the times when spread F commences does show that there is a height with a maximum occurrence of spread F, but the distribution about that height is generally too wide for there to be a threshold effect.

Discussion

The results presented above show that spread-F occurrence at near-equatorial stations in the Australasian zone has a seasonal variation which depends on the epoch of the solar cycle. During the sunspot minimum there is a northern solstice maximum and a southern solstice submaximum at Port Moresby, Cocos Islands and Vanimo. During the sunspot maximum all three stations show equinoctial peaks, although Port Moresby and Cocos Islands still exhibit significant northern solstice occurrence rates. During the solstices, the spread-F occurrence rates correlate negatively with sunspot number while during the equinoxes they correlate positively with sunspot number. The correlation with magnetic activity is predominantly negative especially during the equinoxes. The solstices show no clear correlations.

It appears that at the latitude of Vanimo, Port Moresby and Cocos Islands there are two types of spread *F* with different occurrence properties, namely temperate latitude and equatorial types with maximum occurrence at the solstices and equinoxes respectively. These stations are well south of the spread-*F* equator (Singleton 1963) and the occurrence rate is much greater during the northern solstice than during the southern solstice. They also lie near the magnetic equator and exhibit equinoctial peaks. The equinoctial occurrence rates are less at Port Moresby and Cocos Islands than at Vanimo, which is closest to the magnetic equator.

It is suggested that a similar situation will exist for other stations, which will in general exhibit spread *F* of both types with seasonal peaks during the northern solstice, the southern solstice and the equinoxes. The relative sizes of the peaks will depend on the position of the station relative to the magnetic and spread-*F* equators and one or two peaks may in fact be negligible.

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