X-810-72-287
PREPRINT

NASA TM X- 66074

RADIO-WAVE SCINTILLATIONS AT EQUATORIAL REGIONS

A. D. POULARIKAS

(NASA-TM-X-66074) RADIO WAVE SCINTILLATIONS AT EQUATORIAL REGIONS A.D. Poularikas (NASA) Jun. 1972 35 p CSCL 20N
N73-10218
G3/07
Unclas
46430

JUNE 1972

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-810-72-287

RADIO-WAVE SCINTILLATIONS AT EQUATORIAL REGIONS*

A. D. Poularikas**

June 1972

---

*This work was conducted at GSFC under the NASA/ASEE Summer Faculty Fellowship Program.

**Department of Electrical Engineering, University of Rhode Island, Kingston, Rhode Island

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

RADIO-WAVE SCINTILLATIONS AT EQUATORIAL REGIONS

A. D. Poularikas

ABSTRACT

Radio waves, passing through the atmosphere, experience amplitude and phase fluctuations known as scintillations. This document is a review of the character of equatorial scintillation, which has resulted from studies of data recorded primarily in South America and equatorial Africa. Equatorial scintillation phenomena are complex because they appear to vary with time of day (pre- and postmidnight), season (equinoxes), and magnetic activity. A wider and more systematic geographical coverage is needed for both scientific and engineering purposes; therefore, more observations should be made at earth stations (at low-geomagnetic latitudes) to record equatorial scintillation phenomena.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

RADIO-WAVE SCINTILLATIONS AT EQUATORIAL REGIONS

INTRODUCTION

When radio waves pass through the atmosphere, they experience amplitude and phase fluctuations. This phenomenon is called scintillation. These variations are caused by electron density irregularities in the ionosphere and the random spatial change of the index of refraction in the lower atmosphere. Phase variations, caused by ionospheric irregularities, give rise to an amplitude diffraction pattern which is detected at the receiving antennas as scintillation. Scintillations at equatorial regions often become quite severe and interrupt transionospheric communication links.

The magnitude of scintillation, i.e., peak-to-peak amplitude variation, depends on the path through the ionosphere, geomagnetic latitude and longitude, zenith angle, time, frequency of the propagating wave, and ionospheric origin. Some scintillations originate in the E-layer, but most scintillations originate in the F-layer.

To a communication engineer, the magnitude of scintillation is of primary concern. Very high-frequency peak-to-peak amplitude has been known[1, 2] to vary as much as 30 dB. Distribution is believed to be mostly Rayleigh, rather than Gaussian.[3] The ionosphere was believed to have negligible affects for higher frequencies, but this does not appear to be true in the equatorial region. Recent work at L-band (1550 MHz) indicates that peak-to-peak variations of 6 dB often accompany large-magnitude VHF scintillations (20 dB), which appear about the time of the equinoxes. In another study,[4] similar results were found with a 5-dB peak-to-peak variation at L-band. Very high-frequency scintillation fading was present[4] at all times when L-band variations were noted; however, there were times when VHF scintillations occurred without L-band variations. S-band variations were also found;[5] their fluctuations were reported to have unusually large values, sometimes reaching 20 dB.

At UHF, 240 MHz, it was found[6] that daytime fading was usually small in magnitude, ranging from 1 to 4 dB. Sometimes during disturbed conditions, the fading exceeded 20 dB, and signal enhancement was as high as 6 dB above the undisturbed level. Nighttime fading (at 240 MHz, and for 1 month of observation) indicates a pattern similar to that of the VHF fadings. They usually started shortly after local sundown, and quickly increased to maximum fading rates and fading depths. The amplitude distribution curves show normal distributions. Figure 1 indicates the amplitude of the maximum level, the 50-percent level, the 10-percent level, and the 1-percent level for each distribution. The signal recorded at San Diego is included for comparison. Figure 2 shows a typical distribution of fades as a function of fade duration. When space-diversity tests at 200 to 215 meters were conducted in this experiment, a maximum correlation value of 0.85 was obtained. At a distance of 1.6 km, the maximum correlation value dropped to 0.48. Frequency diversity was also tried; a correlation of 0.85 was found for a frequency difference of approximately 5 MHz, and 0.6 for a frequency difference of 50 MHz.

Scintillations were reported[7] at frequencies of 4 and 6 GHz. In this experiment, at least three types of scintillations could be identified. The first type was slow, having relatively large scintillation fading (approximately 6 dB), which was attributed to tropospheric irregularities. This explanation was accepted because the phenomenon usually appeared when the elevation angle was below 10 degrees. The second type of scintillation was fairly rapid and weak (less than 1 dB). Because this type of variation was always accompanied by rain at the station, it was concluded that the rain has a rapid, small effect (but noticeable) on the gain of the antenna. The last type of scintillation was strong and rapid (approximately 6 to 8 dB), and was primarily associated with low-latitude stations. These scintillations occur at essentially any longitude. The effect is enhanced during the equinox period, or local summer conditions. They occur regularly, and shortly after local sunset. The scintillation depth is substantially weaker at 6 GHz than at 4 GHz. Because this behavior is identical to VHF scintillations, some scientists insist that the ionosphere is responsible for these variations.

The irregularities that could produce scintillation were found to be located anywhere from 85 km to 800 km, and to have peaks of occurrence near or below $h_m F2$, and at E_s heights.[8] When records from 34 satellite passes were analyzed, it was observed[9] that the mean thickness of the region containing the irregularities was 174 km, with a standard deviation of a 56-km thickness.

Other equatorial scintillation characteristics are their sudden appearance on any night and their gradual disappearance in the early morning hours.

Figure 3 shows the occurrence of scintillation that was sketched primarily from data collected in South America and East Africa.[10] (The density of hatched area in Figure 3 roughly represents the fading depth.)

DIURNAL OCCURRENCE

The curve representing the pattern of radio scintillation throughout a day has a peak at local midnight. Figure 4 shows a histogram of the number of occurrences of scintillation in each 20-minute interval through the day at Legon Ghana, as produced by the 136-MHz signal radiated by Early Bird in 1965.[3]

Daytime scintillations are less common, and usually have shorter durations. The average duration of daytime scintillations is less than 30 minutes. The average duration of nighttime scintillations is approximately three times as long as that of daytime scintillations. The scintillation index has only moderate values, 20 to 40 percent, during daytime scintillation.

Similar observations were reported in South America.[1,11] Figure 5 shows the average diurnal variation of lost Minitrack passes that were measured for 12 months (from July 1966 through June 1967). Figure 5 also shows that less activity was observed at Quito and Santiago, which are respectively 22°N and 30°S of the equator.

Figure 6 is an approximate probability distribution of the scintillation index taken for each hour of the day in eastern Africa. This recorded frequency was also 136 MHz. Figure 6 shows that the peak of very high values of scintillation index is located between 21 and 22 local mean time (LMT), and the peak for the low values of scintillation index occurs immediately after midnight. Assuming a linear relation between scintillation activity and total electron content, the observed asymmetry may be explained. At premidnight hours, the total electron content is higher, relative to postmidnight. Similar observations are also reported in more recent studies.[12] Note: Spread F appears to be of a different nature before and after midnight;[13] this may have some effect on the nonsymmetrical appearance of the scintillation activities.

Higher frequencies (2278.5 MHz) were used in recent experiments[5] from the Apollo Lunar Surface Experiment Package (ALSEP) that also confirm asymmetry of the scintillation occurrences as observed at VHF. Even at microwave frequencies of 4 and 6 GHz, the diurnal phenomenon is the same.[7] The scintillation activity usually occurs from approximately 40 to 90 minutes after sunset on the ground. The duration of an average active period varies from station to station. For example: Duration is approximately 4 hours at Ascension Island, a period which is small when compared with VHF active periods; but duration is more than 12 hours at Hong Kong,[7] a period which is about equal to VHF activity. Thus, observations at S-band (4 and 6 GHz) indicate duration of scintillation activity to be shorter than VHF durations.

SEASONAL VARIATION

During 4 years of observations at Ghana, experiments at 45-MHz and 108-MHz frequencies have shown that seasons affect scintillation. The autumnal equinox shows a marked enhancement of scintillation. At sunspot minimum, a lesser peak appears after the vernal equinox. During the years near the sunspot maximum, the autumnal enhancement was easily identified although there was no evidence of a clear peak in the spring. This effect was probably caused by saturation, leaving all scintillation so enhanced that lesser seasonal features tended to disappear. The similar seasonal effects shown in Figure 7 were found at 136 MHz, from May 1967 to May 1968.

During 1 year (beginning on July 1, 1966), observations in South America[1, 11] showed similar seasonal trends. Figure 8 shows the percent of total passes missed each month, due to propagation distortion. Lima represents the worst-interference case, and Quito and then Santiago follow in order.

When pulse-code modulated (PCM) telemetry data from OSO 3 (136 MHz) were analyzed, the plots shown in Figure 9 were obtained.[14] The interval of time used for these plots was from 20 to 03 (LMT).

All observations show that scintillation disturbances have a definite seasonal variation.

The 1550-MHz L-band scintillation events[15] appear to follow the diurnal and seasonal character exhibited in previous analyses.[1, 16, 17] In June 1970, an around-the-clock test showed no scintillation effects to occur outside the early evening hours. The nighttime scintillation events were very rare, as was expected during the months around the summer solstice.

FADING RATE

Observations of flux density at 100 MHz (from stars at Kodaikanal, India, near the equator) have shown that scintillation rates depend on many factors (i.e., time of observation, spread-F index, magnetic activity, and zenith angle of the source).[18] The highest rate observed was during the local times of 2000 and 2200 hours. Figure 10 shows 4 years of diurnal scintillation rate. The average scintillation rate increases with spread-F index, as shown in Figure 11. Within 1 day, the maximum scintillation rate occurs several hours before maximum spread F. Similar diurnal trends were also observed in Ghana, Africa.[19]

In general, the relationship between scintillation index and fading rate (at VHF) can be characterized as follows:[17]

- The scintillation rate has a peak value between two fades per minute and four fades per minute for all ranges of scintillation index during the period centered on 0300 hours, local time.

- Results for midnight and 2100 hours show rates progressively larger for ranges of scintillation index up to 80.

- During the interval centered on 2100 hours, the rate increases to greater than nine fades per minute when the scintillation index rises to the 30-percent level.

The premidnight peak of fading rate observed in India is also observed in Africa,[12] as shown in Figure 12. The diurnal variation of a typical mean-fading rate and mean-scintillation index is shown in Figure 13.

Simultaneous observations of scintillations at VHF and L-band were conducted recently.[4] At low-fade depths (2 dB, or less), the duration at both frequencies was approximately the same, but as the depth of fade increased, the VHF fades tended to be considerably longer than the L-band fades were for the same depth. For 10 percent of the time when fades exceeded 2 dB, they lasted for at least 13 seconds at 136 MHz. (Figure 14 shows some interesting results.) At 1550 MHz when the 2-dB fades occurred, they lasted for at least 11.5 seconds for 10 percent of the fades. Therefore, it appears that the fade duration of weak fades was essentially the same at both frequencies. This means that for 90 percent of the time, the duration of fades is the same at both frequencies when the fade has a 2-dB depth.

GEOGRAPHICAL DEPENDENCE

In east Africa,[20] observations at 45 MHz show close correlation between scintillations at Achimota and spread-F echoes at Ibadan. This observation gives a lower limit of 500 km in the longitudinal direction for the irregularities, giving rise to both conditions. Scientists have accepted the belief that the extent is substantially smaller in the east-west direction. From scintillation results taken in Achimota and Cambridge, England, an upper limit of 5000 km was established in the north-south direction.

Similar observations at 40-MHz scintillations[21] substantiate previous observations.[20] Figure 15 shows results of latitudinal dependence of scintillation for different seasons, and the magnetic activity in 1967. At equinoxes and at high-magnetic activity, the scintillation occurrence decreases by one-half at a 20 degree latitude. On quiet days, the width is larger. The phenomenon is more complex at other seasons. Peaks appear at a 20-degree dip latitude during disturbed days.

The same conclusions are reached if the Minitrack passes that were missed due to the propagation distortion are regarded[1] (Figure 8). At Quito (10 degrees geomagnetic north), the number of misses were one-half the number when compared with Lima, Peru (zero-degree geomagnetic latitude). At Santiago, Chile (22 degrees geomagnetic south), the number of misses were one-fourth the number when compared with Lima.

Because there is evidence of positive correlation between spread F and scintillation activity, the geographical distribution of spread F gives a relative picture of the regions where scintillation activity may exist.[22] In the region between plus or minus 15 degrees from the geomagnetic equator, the occurrence of spread F has been known to decrease to one-half of its maximum value. Recently,[23] it was pointed out that in the case of spread F, the width of the equatorial belt is variable. Near the sunspot maximum, it moves beyond 20 degrees north and south of the geomagnetic dip equator; near the sunspot minimum, its width reaches 40 degrees on either side.

Observations at S-band (from the ALSEP experiment on the moon)[5] show that disturbances of the received signal occur simultaneous at the Canary Islands, located east of the Ascension Islands, and the Ascension Islands. Also, scintillation occurs first at the Ascension Islands, and later at the Canary Islands.

Observations at 4 and 6 GHz are summarized in Figure 16 for stations located around the world.[7] The time of observation was between August and November, 1970. Other observers agree that the correlation between geomagnetic latitude and the fraction of the total days of observations (during which some scintillation activity existed) is evident. The stations at low-geomagnetic latitudes were the most active, as anticipated.

FREQUENCY DEPENDENCE

Preliminary observations indicate that there may be differences in frequency dependence of scintillations between equatorial and other high latitude regions.[15, 24] Data on 136 MHz and 1550 MHz[15] show approximately an inverse square-root ($1/\sqrt{f}$) characteristic for equatorial scintillation during the autumnal equinox. The frequency dependence at auroral regions appear to follow an inverse square ($1/f^2$), or an inverse ($1/f$) law. An inverse frequency dependence at the equator is indicated for the relatively rare occurrence of scintillation during the summer solstice.

In another study,[4] the frequency dependence was investigated, and its relation to fading depth was found. The higher fading depths, several dB for from 1 to 5 percent of the time, followed the 1/f rule. Shallow fading (in the order of 2 dB, or less, for from 1 to 5 percent of the time) exhibited a frequency dependence exponent of approximately -0.6 to -0.14. The overall experimental sample of 23 hours indicated a frequency dependence exponent of -0.78. The authors[4] indicate that these results call for further equatorial measurement because of insufficient data.

CORRELATION WITH OTHER PHENOMENA

As early as 1958, the occurrence of scintillations in Africa[20] were reported to have a positive correlation with the presence of spread-F ionospheric echoes. Although the distance between the points of radio-star scintillation and spread-F observation was 450 km apart in the east-west direction, a correlation coefficient of 0.46 was found for 165 pairs of observation during 1 year (1953 and 1954).

In 1960, it was reported[25] thatVHF radio scintillations observed at Ancon, Peru, are strongly correlated with spread F. Similar studies at NASA Minitrack stations in South America show correlation between spread-F echoes and radio scintillation at VHF. The diurnal and seasonal variation of spread F is shown in Figures 17 and 18. The diurnal variation of spread F is similar to the scintillation activity. Seasonal variation has only one cycle as opposed to two cyclic changes shown by the Minitrack data (Figure 8).

Sporadic E may partially contribute to scintillations. Results of an equatorial sporadic E have been reported:[26]

- Equatorial sporadic E occurs within approximately 4 degrees of the dip equator. The width of the belt varies and its position varies slightly.
- Contrary to the current belt, sporadic E does not become stronger and narrower at high-sunspot numbers.
- Equatorial sporadic E is less likely to occur during magnetic activity.
- Equatorial sporadic E is predictable; it appears mostly during the daytime.
- The irregularities that scatter HF waves move westward (daytime) at approximately 60 msec; irregularities that strongly scatter HF waves can be presented by plane waves moving westward at 360 msec.

Scintillations usually occur when spread F is present, but scintillations occassionally occur when spread F is not present. From a survey,[27] it was concluded that the diurnal variation of spread-F occurrence is characteristically maximum in all seasons and locations during the nighttime, and is low (or nonexistent) during the daytime. An example of diurnal variation is shown in Figure 19, as reported at Ibadan.[28] Spread F also occurs most often during equinoxes, or during local summer, at longitudes where the geographical and magnetic equators are far apart (near Huancayo, Peru, for example).[27, 29]

In eastern Africa, it was reported[30] that correlation between scintillations and magnetic disturbances was rather negligible during low-sunspot activity. During the years with high-sunspot activity, a negative correlation existed. At low K_p numbers, correlation does not seem to appear. At higher values of K_p, i.e., $K_p > 4$, scintillations were normally suppressed. In South America, the percentage of occurrence of scintillation indices greater than 40 percent were found [31] approximately the same for all values of K_p. A seasonal effect was also observed.

Correlation between sunspot number and geomagnetic activity for 1 month (from September 29 to October 29, 1970), at 136 MHz and 1550 MHz, showed no significant correlation.[4]

The solar-cycle dependence reported in 1960[30] has been confirmed by observing radio waves from synchronous satellites.[17]

Scintillations were almost twice as frequent in 1967 as they were for small scintillation indices in 1965. This ratio became higher, and reached a value of 17:1 when the scintillation index rose above 90 percent.

IRREGULARITIES

Many methods exist for studying movements of irregularities in the ionosphere; however, all of them have various limitations. An excellent review on ionospheric movements can be found in a recent study.[32] This section presents the results which were found when the morphology of the ionosphere was measured. The method used for measuring is not discussed.

Generally, it is accepted that the behavior in the equatorial zone (within 20 degrees of the geomagnetic equator) is dominated by electromagnetic drift, driven by a current system, which in turn is set up by thermal and gravitational atmospheric tides. The strong diurnal tidal variation is apparent in the diurnal variations of ionospheric parameters, such as ionospheric irregularities detected by radio-wave scintillations. The upward movements that take place after sunset enhance ionospheric irregularities.

From observations, the projected diffraction pattern of the irregularities on the ground have been found to be elongated. In eastern Africa, for example, the mean value of the axial ration was found[19] to be 7.7, and the smallest value was found to be 5.2. Assuming a statistical description for a pattern in a given direction arbitrarily defined when the correlation value 0.5 between the receiving signal of two antennas is achieved, it was found[19] that the mean value of the pattern on the ground in the east-west direction was 442 meters. In addition, the sizes of the irregularities shifted to smaller values toward the evening hours; this may not indicate any absence of larger irregularities. In another study[3], for all practical purposes it was concluded that the pattern on the ground consists of parallel lines lying along the projection of the earth's magnetic field; these lines have a mean size of 232 meters in the east-west direction.

A recent study[8] in Nairobi showed that the sizes of the irregularities change very little with height, throughout the entire range of from 100 to 500 km; there is evidence of some increase at 180 km. No evidence of elongation was noted over Nairobi; east-west and north-south sizes were of the order of 200 meters. In South America,[33] the average sizes were of the order of 200 meters, and not larger than 400 meters. Also, it was hypothesized that the closer the satellite is to the irregularities, the larger the pattern becomes on the ground. When the distance between the satellite and the layer with the irregularities becomes smaller than the Fresnal distance, the rms amplitude of scintillations is significantly reduced.

The irregularities have been known to move in different directions (with different velocities), depending on the time of day. The direction of propagation is from west to east during the night. This trend lasts until morning,[3, 8, 19, 33] and reverses itself during the day. Mean velocities were found to vary anywhere from 30 to 150 msec^{-1}. A definite trend was seen[19] toward the higher velocities as the transit time moved near the early evening hours. A good relation has not been found between ground-pattern velocity and source elevation.

A vertical motion of approximately 5 msec^{-1} is evident for ionospheric irregularities.[8] The F-region moves diurnally, as shown in Figure 20.[34]

DISCUSSION OF OBSERVATIONS

Apparently, scintillation observations at equatorial regions are incomplete. Most of the information is available from east Africa and South America. Effort needs to be directed in a manner that would permit more observation stations (scattered around the earth at low-geomagnetic latitudes) to record scintillation phenomena. Of course, if recordings were without coordination, simultaneous recordings of other ionospheric and exospheric phenomena, and standardization of analysis, would not adequately serve any practical or scientific purpose. Longitudinal observations are considered nonexistent because of the limited data on the subject. Some latitudinal observations have furnished a better picture of the relation between scintillation activities and geomagnetic latitude.

Figure 15 shows why the latitude distribution of scintillation activities cannot be described simply. The phenomena are complex and depend on time (pre- and postmidnight periods), the season (equinoxes), and magnetically quiet or disturbed conditions. Because of these observations, a wider and more systematic geographical coverage is needed.

The diurnal variation is well established. All observations indicate that scintillation activity starts rather abruptly during the early evening hours, continuously increases until midnight, and gradually decreases until morning. The phenomenon for the high strength of scintillations appearing more during premidnight has not yet been fully explained. This characteristic is said to be the result of total electron content asymmetry, but there are other phenomena that behave differently during these two periods. For example, both the nature of spread F and the rate-of-change of total electron content at different heights have different behavior characteristics at pre- and postmidnight periods. Most observations have been made for VHF propagation; very few have been made for other frequencies.

Seasonal variation of only VHF scintillation activities has been reported from just two places, east Africa and South America. A close observation of the results for these two regions shows a displacement of peak occurrences. For example, the peak activity in South America is reached in the middle of November, but the corresponding peak in east Africa is reached in the beginning of September. No explanation is given for this phenomenon; therefore, further study is needed to establish the validity of the apparent discrepancy. Observations at other locations, or frequencies, have not been performed.

Conducted experiments for systematically studying frequency dependence are practically nonexistent. The frequency dependence is determined by scale sizes in the ionosphere, the strength of irregularities, and the distance between irregularity and the ground. Therefore, more experiments are needed to establish frequency dependence of ionospheric scintillations.

The dependence of scintillation with some geophysical phenomena has been established. For example, the positive correlation between spread F and scintillation activity is understood, but no explanation has been given for the scintillation occurrences without the appearances of spread F. No systematic attempt has been made to correlate sporadic-E occurrences with scintillation.

Almost all studies have been reported with regard to amplitude scintillation; therefore, no information is available on phase scintillations.

Because scintillations were recently observed at higher frequencies and in magnitudes much larger than expected, these phenomena could be caused by tropospheric irregularities, rather than by ionospheric disturbances. From observations of the few available experiments, scintillations at higher frequencies

($f > 1$ GHz) are always accompanied by scintillations at VHF. They have the diurnal characteristics of VHF scintillations, and tend to be as short in duration as VHF scintillations with high index. This observation may compel us to accept the belief that scintillations at frequencies higher than 1 GHz are primarily caused by the ionospheric irregularities; this could be partially true if:[35]

- Anomalous behavior of equatorial troposphere does not exist
- Diurnal variations of some of the tropospheric parameters do appear simultaneously with ionospheric variations

A conflict of opinion exists on the source of tropospheric scintillations. It has been suggested,[35] that scintillation activity should increase just after sunset. Although radar returns indicate periods of about one cycle per minute, observed scintillation fades are much faster. Although the trade-wind inversion layer, which may produce scintillations, was not recorded during the observations of scintillations, it is very doubtful that this phenomenon causes the observed scintillations. The observations at L-band (1550 MHz) indicate a high degree of correlation with VHF diurnal and seasonal scintillation patterns. For this reason, the L-band phenomena are thought to be the result of ionospheric rather than tropospheric disturbances. In addition, a negative correlation of the phenomenon with magnetic activity has been observed; this is exactly what happens for VHF. The inverse frequency dependence of scintillations indicates that this phenomenon is positively due to the ionospheric irregularities. Tropospheric scintillations have a negligible frequency dependence, ranging to the L-band frequency range. Furthermore, if any frequency dependence exists, the scintillation index must be proportional to some integral power of frequency. To resolve this question completely, it is suggested that during observations of scintillation activities, the wind activity and any adverse atmospheric conditions should be recorded; this is necessary because scintillations were observed[36] in the order of 1 dB at 7 GHz. In addition, if observations were performed at different elevation angles, it would add to the understanding of the phenomenon and discriminate between ionospheric and tropospheric effects. This is true because the angular dependence for tropospheric scintillations is about 10 times higher than that for ionospheric scintillations.

Daytime scintillation has not been fully investigated. Daytime scintillations in east Africa[12] have been reported to be rather rare, to have mean drift-velocity patterns on the ground ($13.7\ \mathrm{msec}^{-1}$), to drift from east to west, and that the scintillation index has moderate values. No attempt has been made to locate the source of these scintillations, or no study seems to have been conducted to establish the degree with which the sporadic E (with its peak values at midday) influences the magnitude of these scintillations.

REFERENCES

1. T. S. Golden. "Ionospheric Distortion of Minitrack Signals in South America." GSFC X-525-68-56. February 1968.

2. George K. Kuegler. "Equatorial Scintillations Experienced During Apollo 13 Support, March 30 to April 18, 1970." GSFC X-460-70-240. August 1970.

3. J. R. Koster. "Ionospheric Studies on the 'Early Bird' Synchronous Satellite." Annales de Géoph. 22, No. 3. 1966. p.435.

4. E. E. Crampton, Jr. and W. B. Sessions. "Experimental Results of Simultaneous Measurement of Ionospheric Amplitude Variations of 136 MHz and 1550 MHz Signals at the Geomagnetic Equator." GSFC X-490-71-54. January 1971.

5. R. M. Christiansen. "Preliminary Report of S-Band Propagating Disturbances During ALSEP Mission Support (November 19, 1969 - June 30, 1970)." GSFC X-861-71-239. June 1971.

6. M. R. Paulson and J. C. Tyner. "An Investigation of Equatorial Fading of TACSAT I UHF Signals." Rep. TN 1837, Naval Electronics Laboratory Center, San Diego, Calif. April 14, 1971.

7. H. D. Craft, Jr. "Investigation of Satellite Link Propagation Anomalies at 4 and 6 GHz." Preliminary Report, Tech. Memo. CL-9-71. Communications Satellite Corporation, COMSAT Laboratories. February 9, 1971.

8. R. F. Kelleher and J. Sinclair. "Some Properties of Ionospheric Irregularities as Deduced from Recordings of the San Marco II and BE-B Satellite." J. Atm. Terrst. Phys., 32. 1970. p. 1259.

9. J. R. Koster. "Studies of the Equatorial Ionosphere Using Transmissions from Active Satellites." Rep. AFCRL-68-0020. September 1967.

10. J. Aarons, H. E. Whitney, and R. S. Allen. "Global Morphology of Ionospheric Scintillations." Proc. IEEE, 39. 1971. p. 159.

11. R. J. Coates and T. S. Golden. "Ionospheric Effects on Telemetry and Tracking Signals from Orbiting Spacecraft." GSFC X-520-68-76. March 1968.

12. J. R. Koster. "Equatorial Studies of the VHF Signal Radiated by INTELSAT II, F-3, I. Ionospheric Scintillation." Report AD 681462. September 1968.

13. B. V. K. Murthy and B. R. Rao. "Variation of Spread-F Index with Frequency in Pre- and Post-midnight Periods of Waltair." J. Atmosph. Terr. Phys. 26. 1964. p. 783.

14. Bernard G. Narrow. "Relationship Between Time of Acquisition and Telemetry Data Recovery Based on OSO-3 and OSO-4 Data." GSFC X-564-68-411. November 1968.

15. T. S. Golden. "A Note on Equatorial Ionospheric Scintillations at 136 MHz and 1550 MHz." GSFC X-520-70-397. October 1970.

16. Jules Aarons. "Special Problems in Scintillation" from "A Survey of Scintillation Data and its Relationship to Satellite Communications." Agardograph Rept. 571. August 1969.

17. John R. Koster. "Equatorial Scintillations" from "Summaries of Papers." Symposium on the Applications of Atmospheric Studies of Satellite Transmissions. Boston, Massachusetts. September 3-5, 1969. p. 68.

18. B. N. Bhargava. "Radio-Star Scintillations in Equatorial Region." J. Inst. Telecom., 10, No. 8. 1964. p. 404.

19. J. R. Koster. "Some Measurements of the Irregularities Giving Rise to Radio-Star Scintillations at the Equator." J. Geophys. Res., 68, No. 9. 1963. p. 2579.

20. J. R. Koster. "Radio-Star Scintillation at an Equatorial Station." J. Atm. Terr. Phys., 12. 1958. p. 100.

21. J. Sinclair and R. F. Kelleher. "The F Region Equatorial Irregularity Belt." J. Atm. Terr. Phys., 31. 1969. p. 201.

22. W. Calvert and C. W. Schmid. "Spread-F Observations by the Alouette Topside Sounder Satellite." J. Geophys. Res., 69. 1964. p. 1839.

23. D. G. Singleton. "The Morphology of Spread-F Occurrence over Half a Sunspot Cycle." J. Geophys. Res., 73. 1968. p. 295.

24. J. H. Pope and R. B. Fritz. "High Latitude Scintillation Effects on VHF and S-Band Satellite Transmissions." NOAA TR ERL 207-OD 6, Environmental Research Lab., Boulder, Colorado. November 1970.

25. Ronald F. Woodman. "Irregular Refraction of Satellite Signals Observed at Ancon, Peru" presented at the Symposium of Space Research, Buenos Aires, Argentina. December 3, 1960.

26. J. D. Whitehead. "Production and Prediction of Sporadic E." Reviews of Geophys. and Space Phys., 8, No. 1. 1970. p. 65.

27. John R. Herman. "Spread F and Ionospheric F-Region Irregularities." Reviews of Geophys., 4. 1966. p. 255.

28. A. J. Lyon, N. J. Skinner, and R. W. Wright. "Some Ionospheric Results Obtained During the I. G. Y." Elsevier Publishing Company, Amsterdam. 1960. p. 633.

29. W. Calvert. "Equatorial Spread F." NBS Tech. Note 145. August 5, 1962.

30. J. R. Koster and R. W. Wright. "Scintillation, Spread F, and Transequatorial Scatter." J. Geophys. Res., 65. 1960. p. 2303.

31. P. Bandyopadhyay and J. Aarons. "The Equatorial F-Layer Irregularity Extent as Observed from Huancayo, Peru." Radio. Sci., 5. 1970. p. 931.

32. G. S. Kent. "Measurements of Ionospheric Movements." Reviews of Geophys. and Space Phys., 8, No. 2. 1970. p. 229.

33. José Pomalaza, Ronald F. Woodman, Gilberto Tisnado, Jaime Sandoval, and Alberto Guillén. "A Progress Report on Scintillation Observations at Ancón and Jicamarca Observatories." GSFC X-520-70-398. October 1970.

34. H. Carru, M. Petit, G. Vasseur, and P. Waldteufel. "Resultats Ionospheriques Obtenus par Diffusion de Thomson 1966-1967." Ann. Geophys., 23. 1967. p. 455.

35. J. H. Pope. Private Communications. NOAA, Boulder, Colorado. July 1971.

36. J. W. B. Day and K. S. McCormick. "Propagation Measurements at 7 GHz on a Satellite to Earth Path" in "Tropospheric Wave Propagation." Conf. Proceedings, No. 48. September 30 to October 2, 1968. The Institution of Electrical Engineers, Savoy Place, London, W. C. 2.

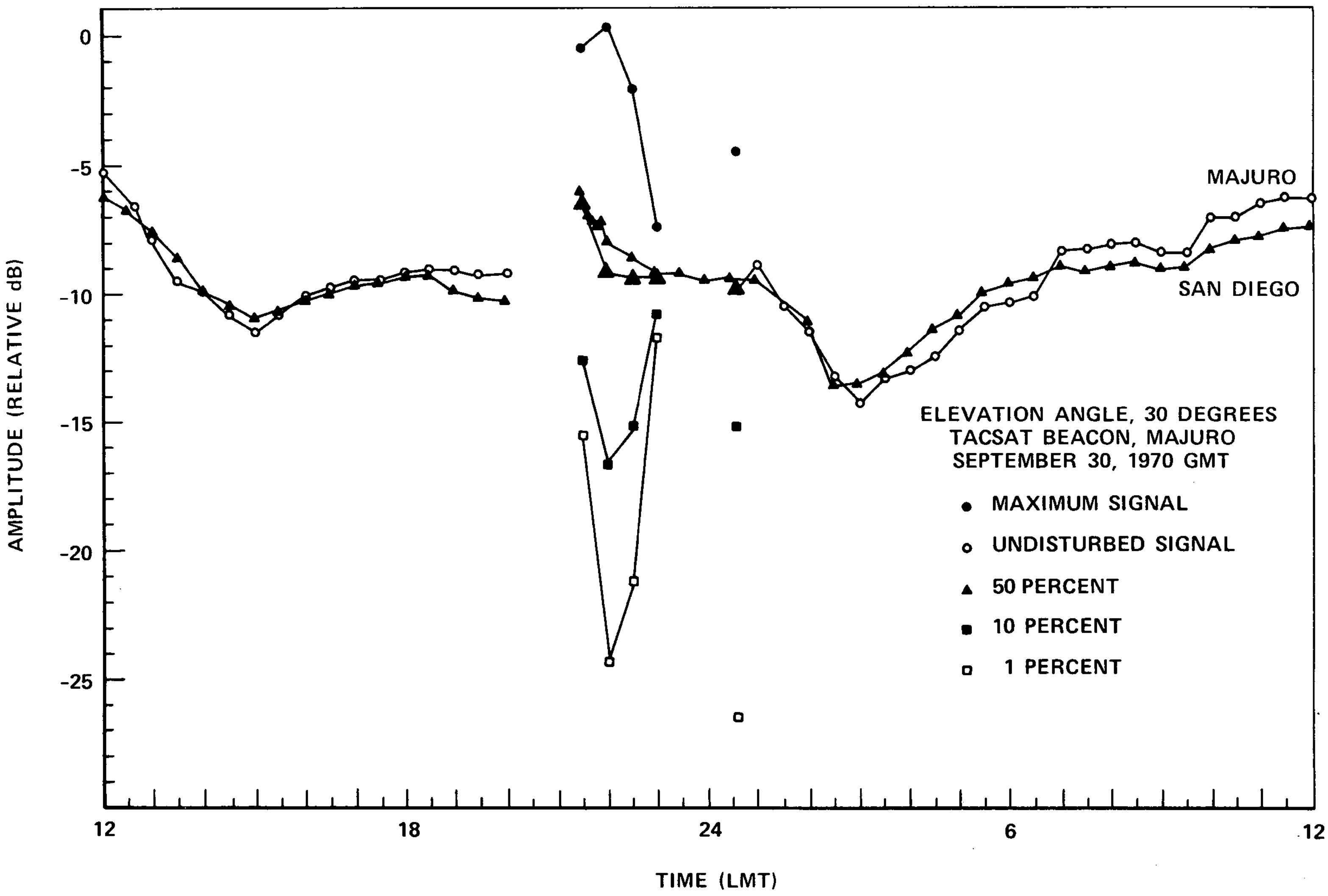


Figure 1. Amplitude Plots with Selected Levels from Amplitude Distribution Plots (After Paulson and Tyner, Ref. 6)

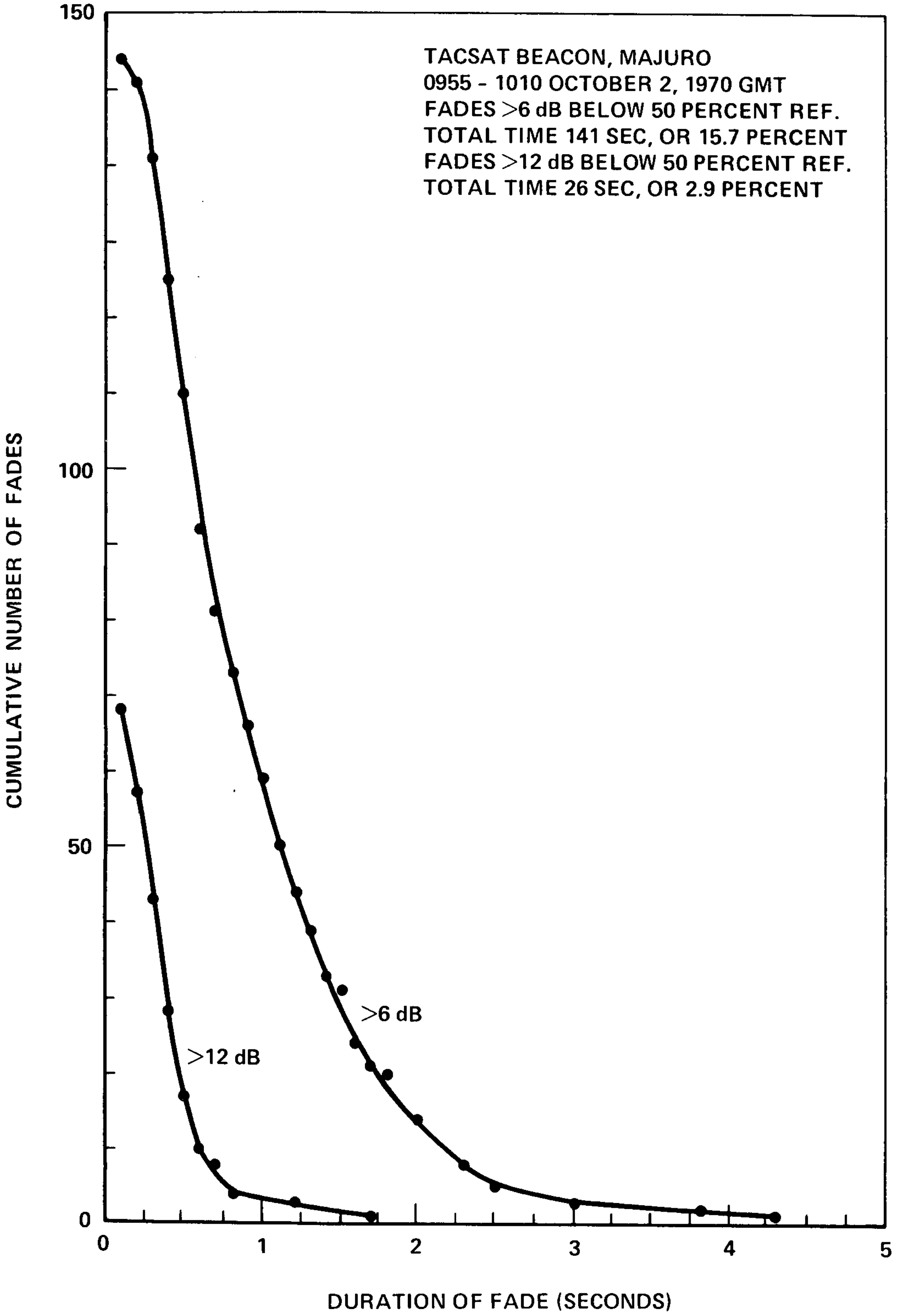


Figure 2. Distribution of Fades Versus Fade Duration
(After Paulson and Tyner, Ref. 6)

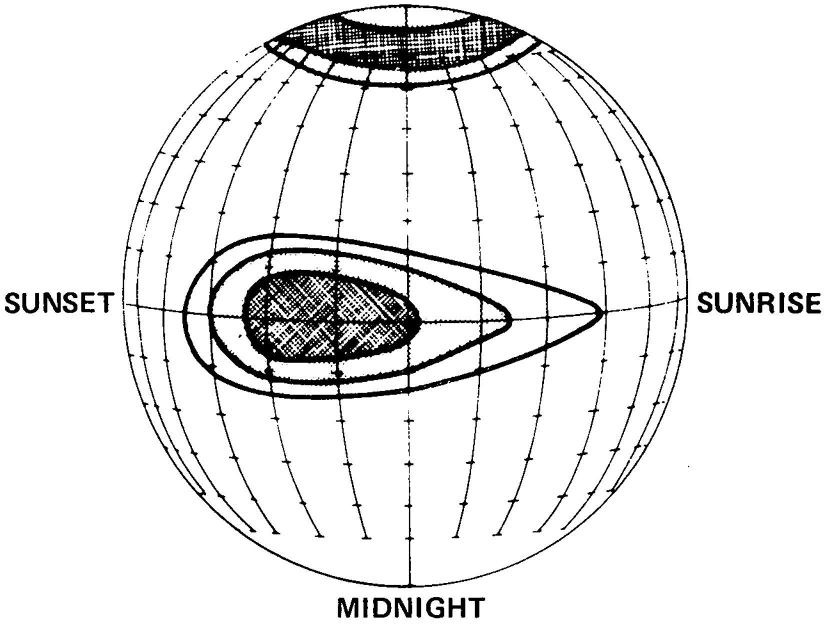


Figure 3. Occurrence of Scintillation Diagram
(After Aarons, et al., Ref. 10)

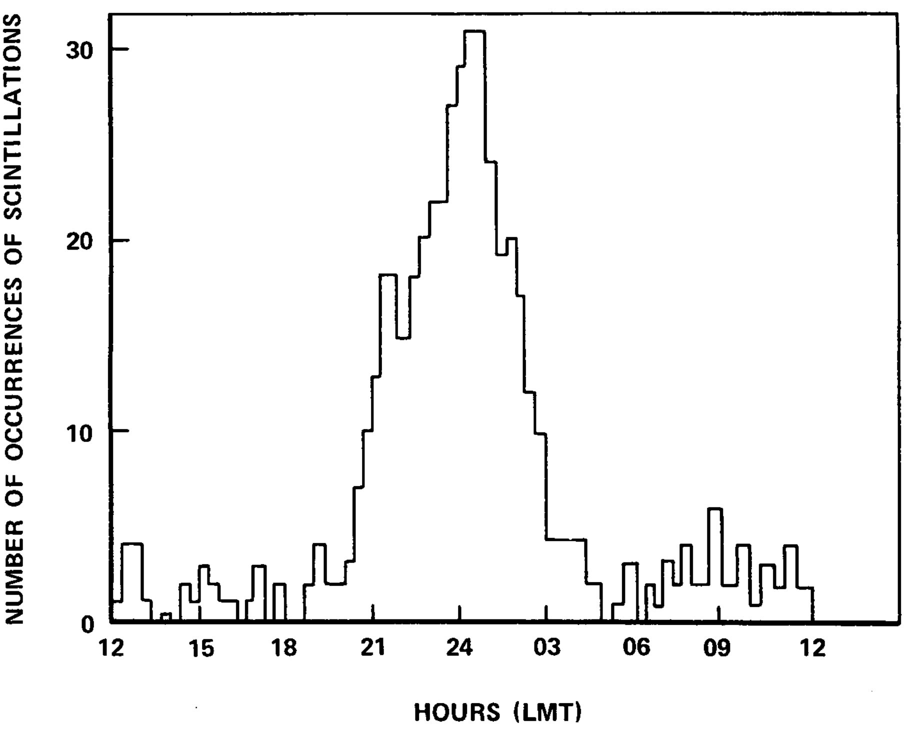


Figure 4. Diurnal Variation of Occurrence of Scintillation
(After Koster, Ref. 3)

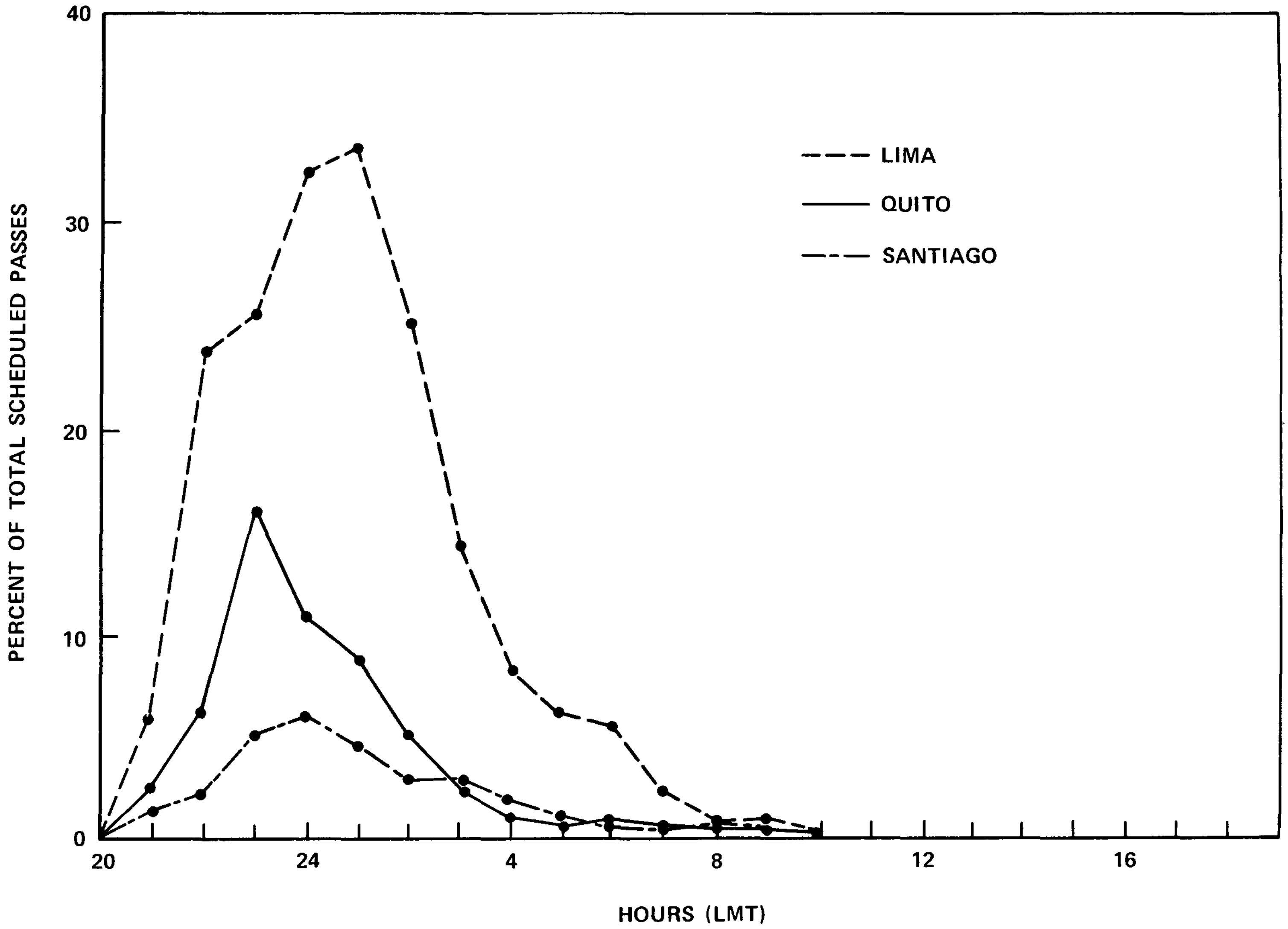


Figure 5. Scheduled Minitrack Passes that were Missed
(After Golden, Ref. 1)

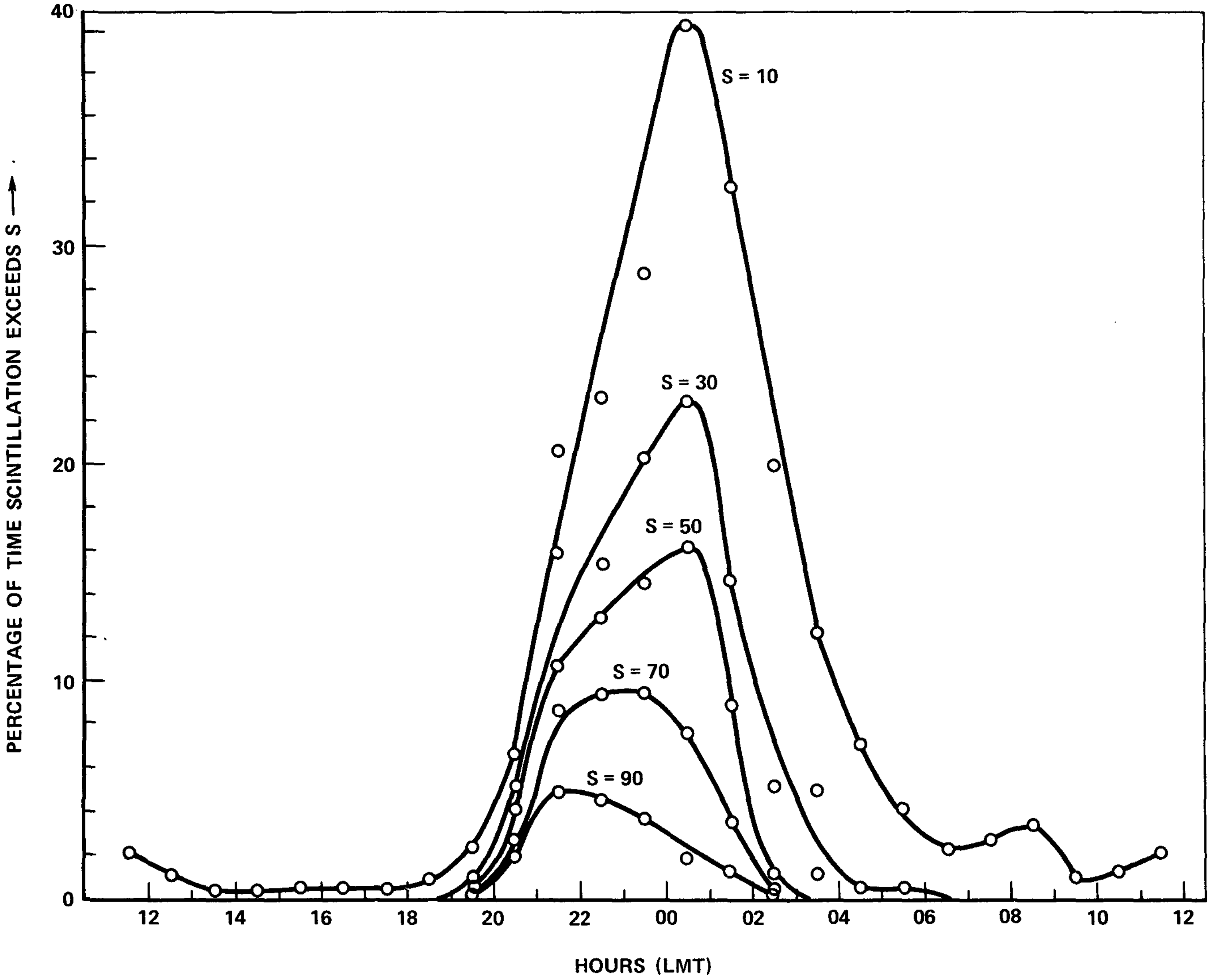


Figure 6. Probability Distribution of Scintillation Index S Versus Time
(After Koster, Ref. 9)

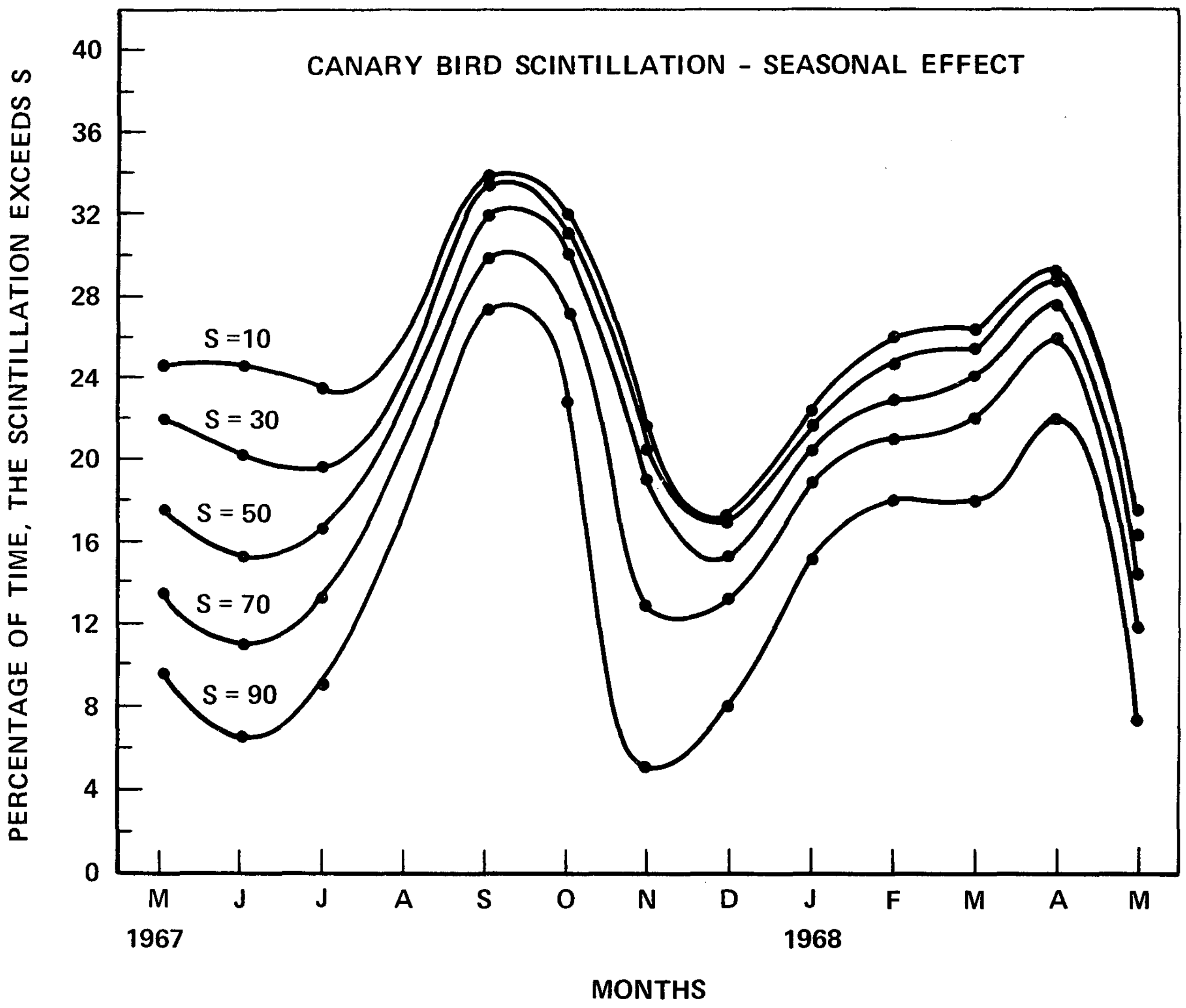


Figure 7. Seasonal Dependence of Scintillation
(After Koster, Ref. 12)

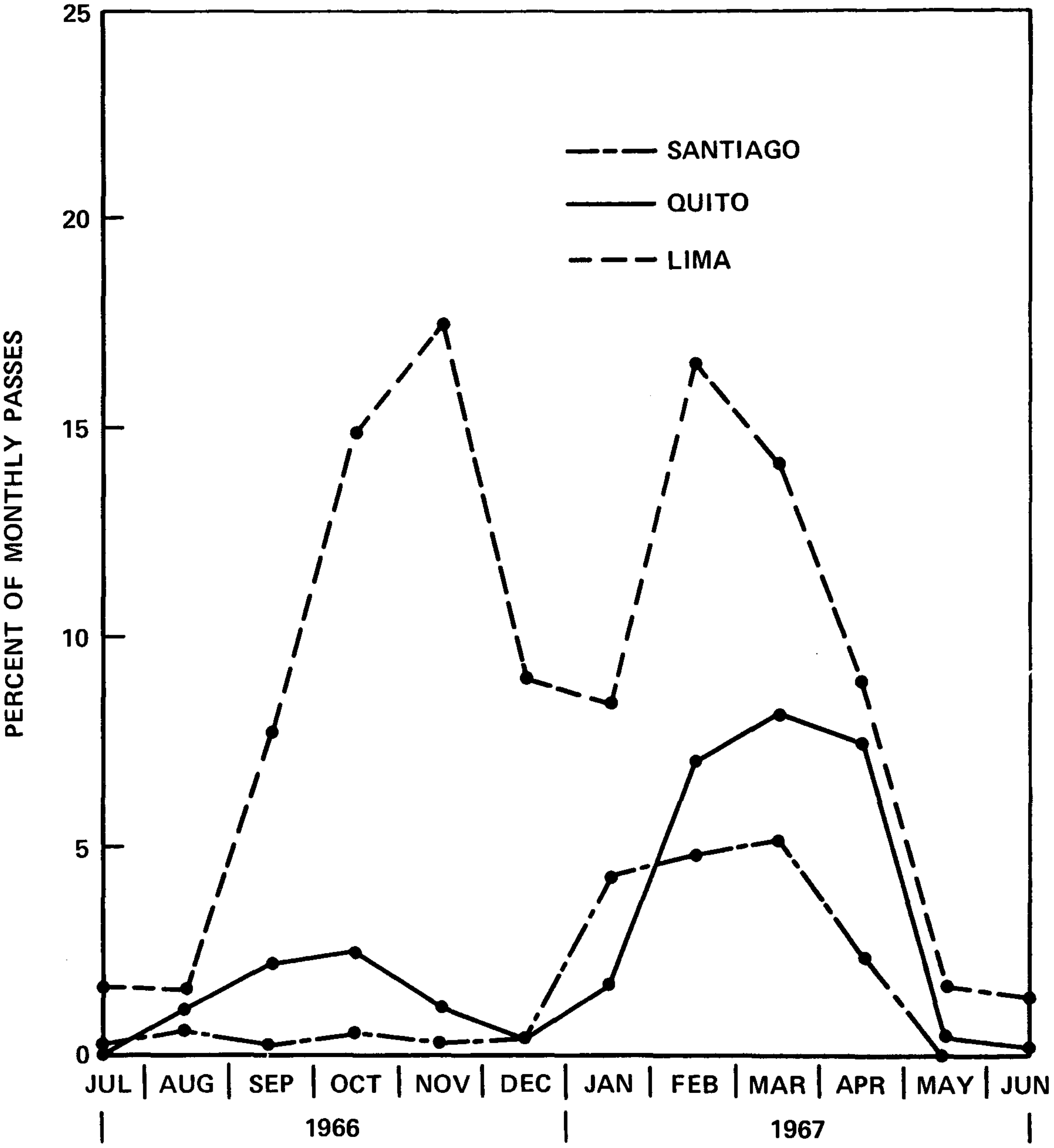


Figure 8. Scheduled Minitrack Passes Missed by Month
(After Golden, Ref. 1)

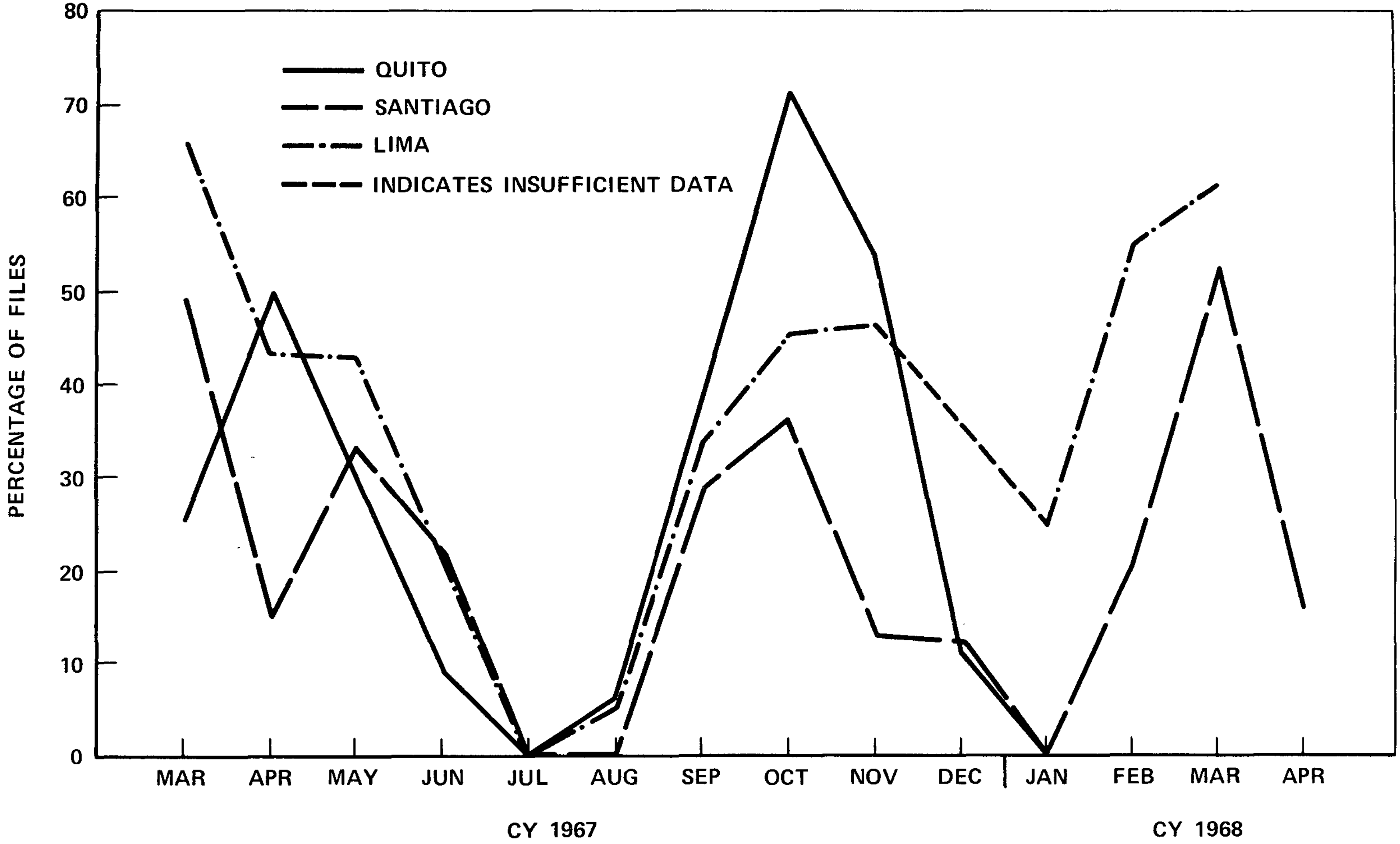


Figure 9. Percentage of Files Acquired (Below Breakpoint)
(After Narrow, Ref. 14)

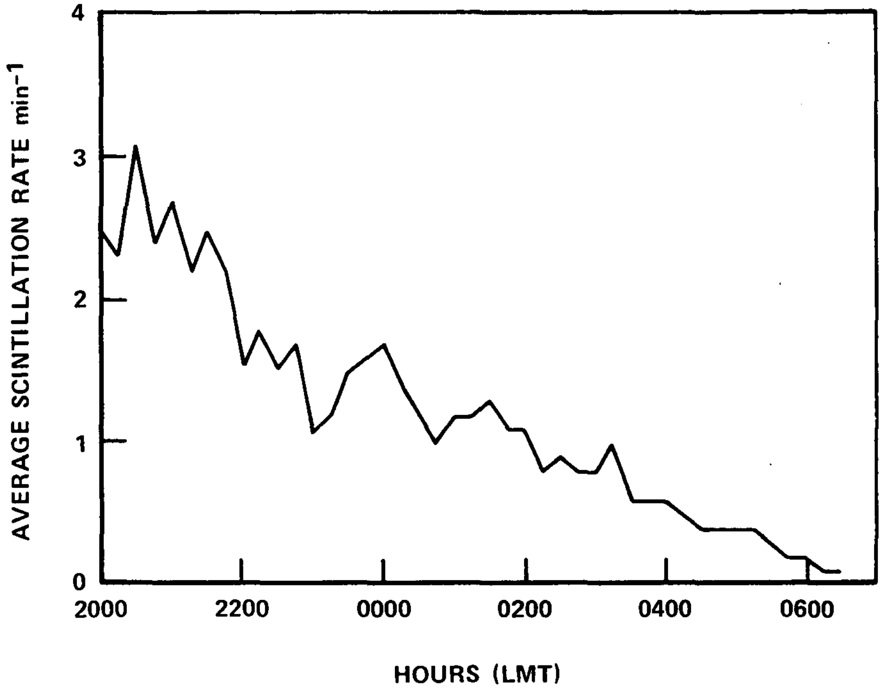


Figure 10. Scintillation Rate Versus Time (After Bhargava, Ref. 18)

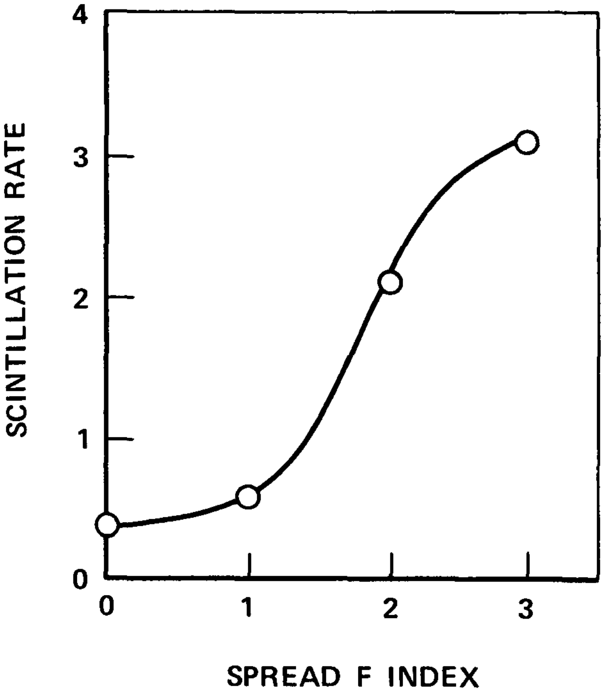


Figure 11. Scintillation Rate Versus Spread-F Index (After Bhargava, Ref. 18)

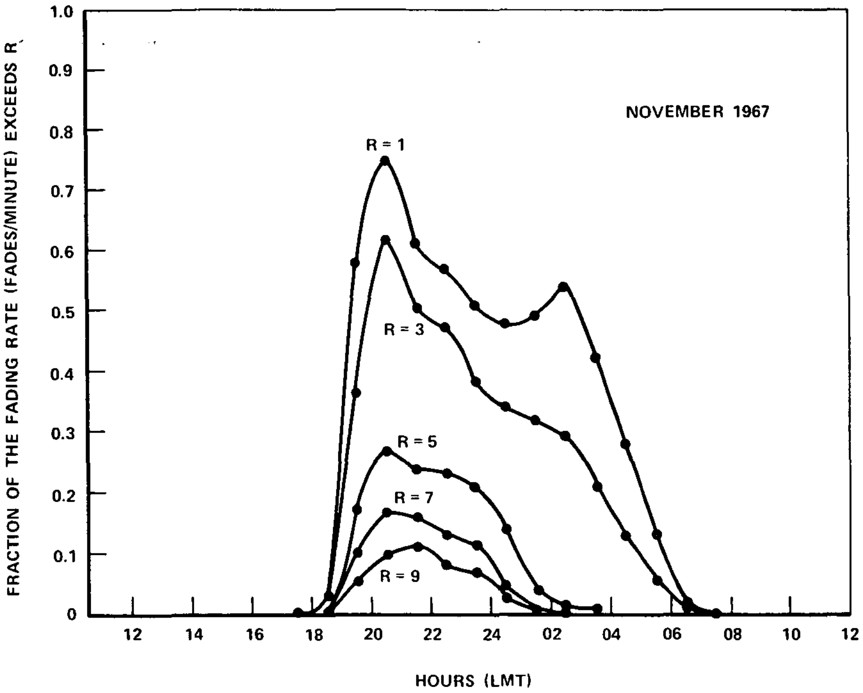


Figure 12. Fraction of Time-Fading Rate Exceeding R
(After Koster, Ref. 12)

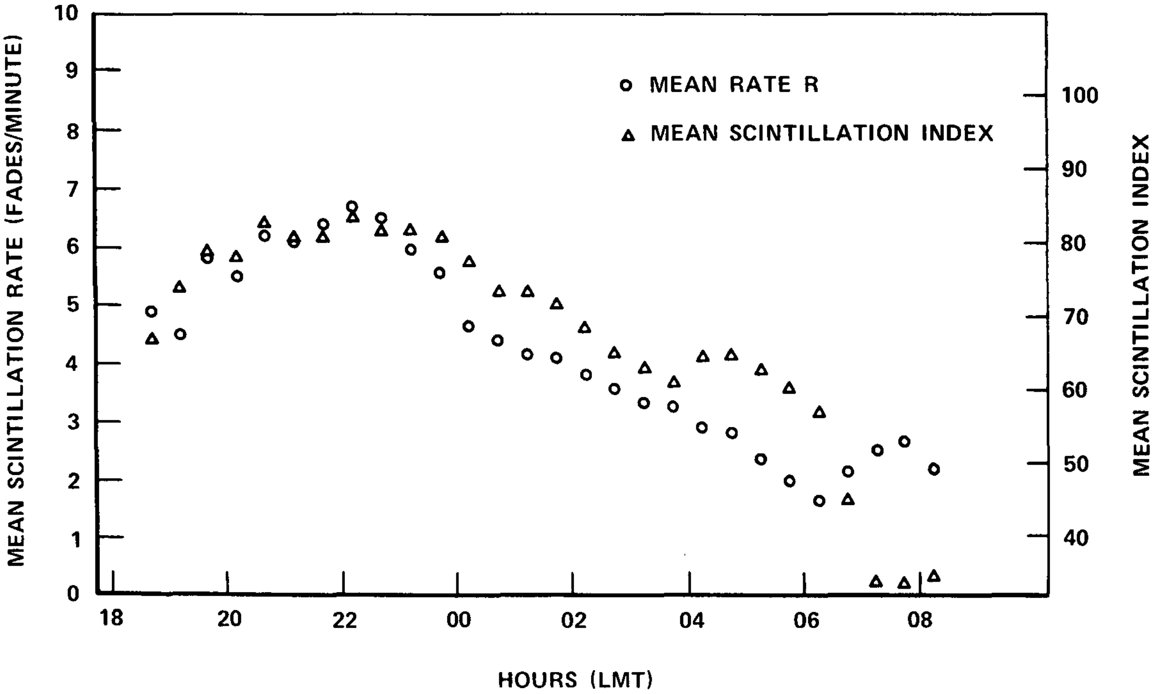
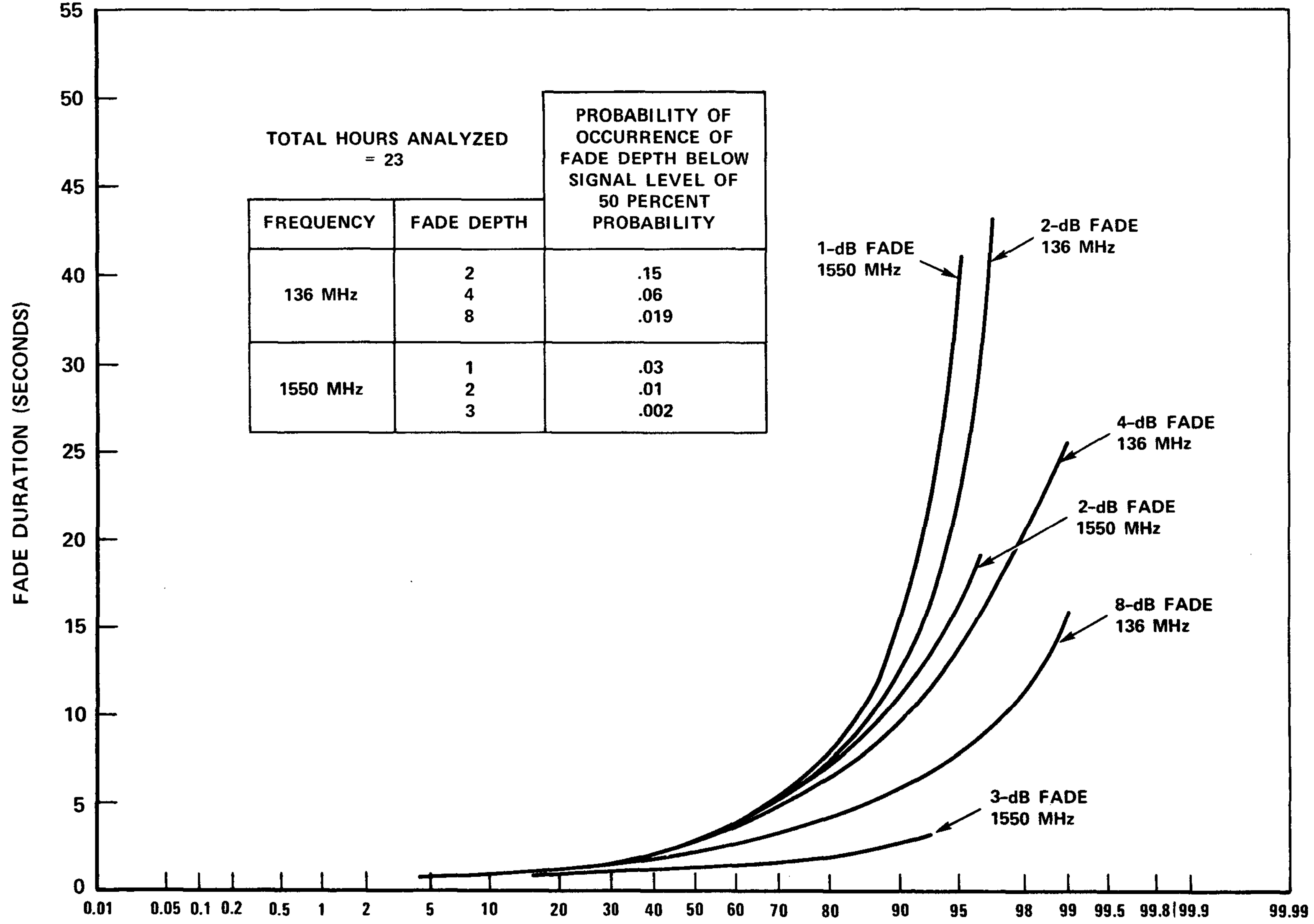


Figure 13. Diurnal Variation of Mean R and Mean S
(After Koster, Ref. 12)



TOTAL HOURS ANALYZED = 23

FREQUENCY	FADE DEPTH	PROBABILITY OF OCCURRENCE OF FADE DEPTH BELOW SIGNAL LEVEL OF 50 PERCENT PROBABILITY
136 MHz	2	.15
	4	.06
	8	.019
1550 MHz	1	.03
	2	.01
	3	.002

Figure 14. Probability that the Duration of a given Fade Depth will not Exceed the Ordinate Value (After Crampton and Sessions, Ref. 4)

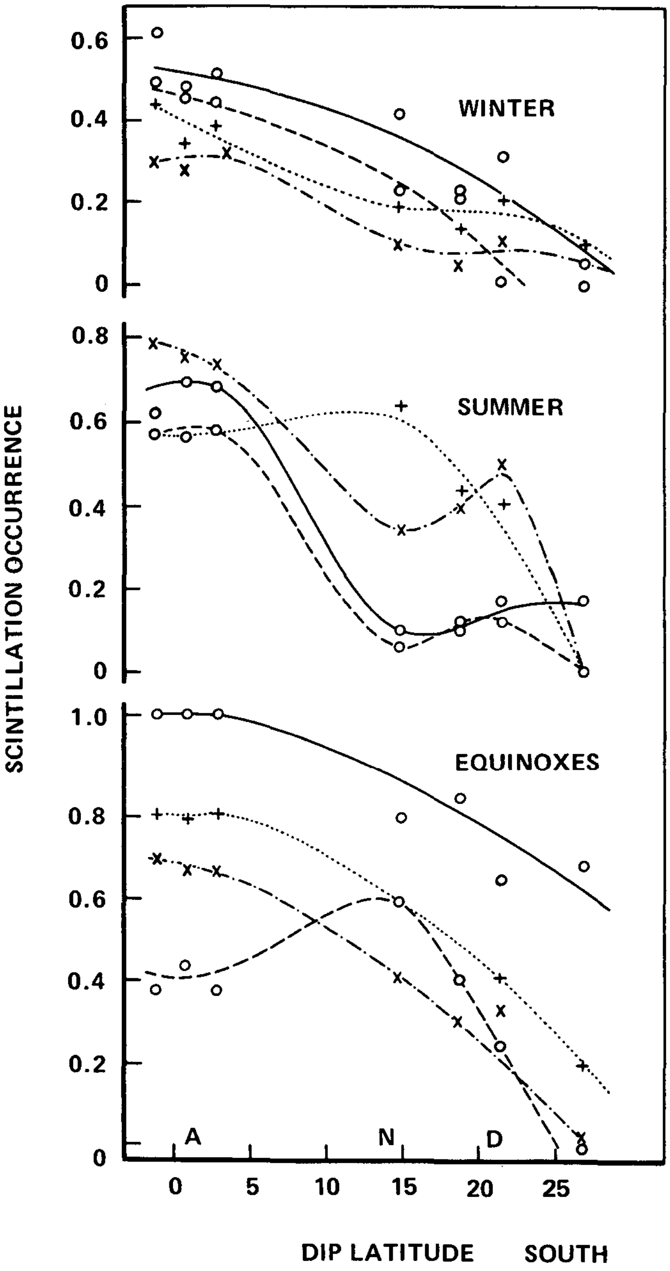


Figure 15. Scintillation Occurrence for Magnetically Quiet and Disturbed Conditions for Each Season, (Pre- and Postmidnight) —continuous line 0 premidnight, disturbed; dotted line + postmidnight, quiet; dashed-dotted line x postmidnight, disturbed (After Sinclair and Kelleher, Ref. 21)

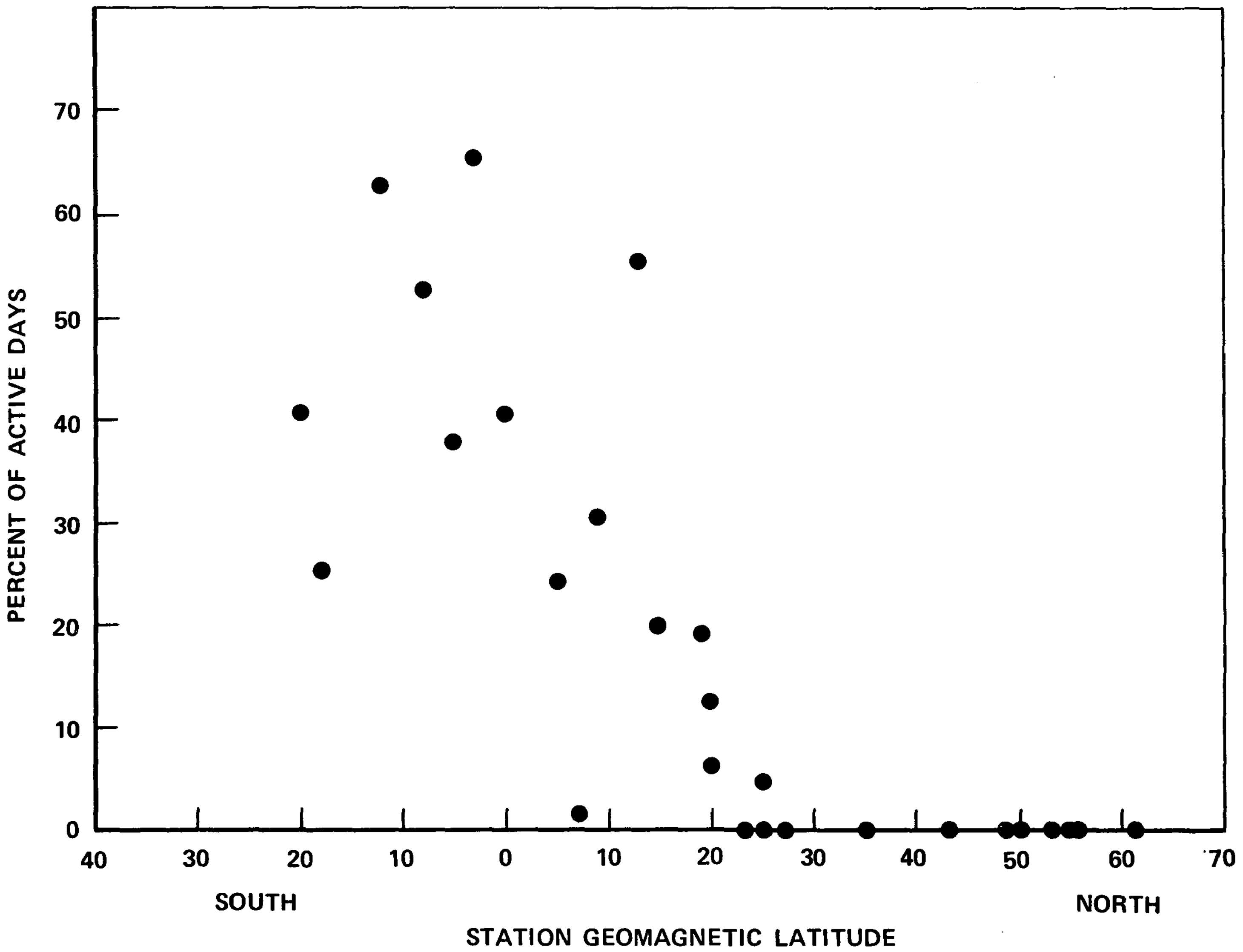


Figure 16. Percent of Total Days Containing Some Scintillation Activity (After Craft, Ref. 7)

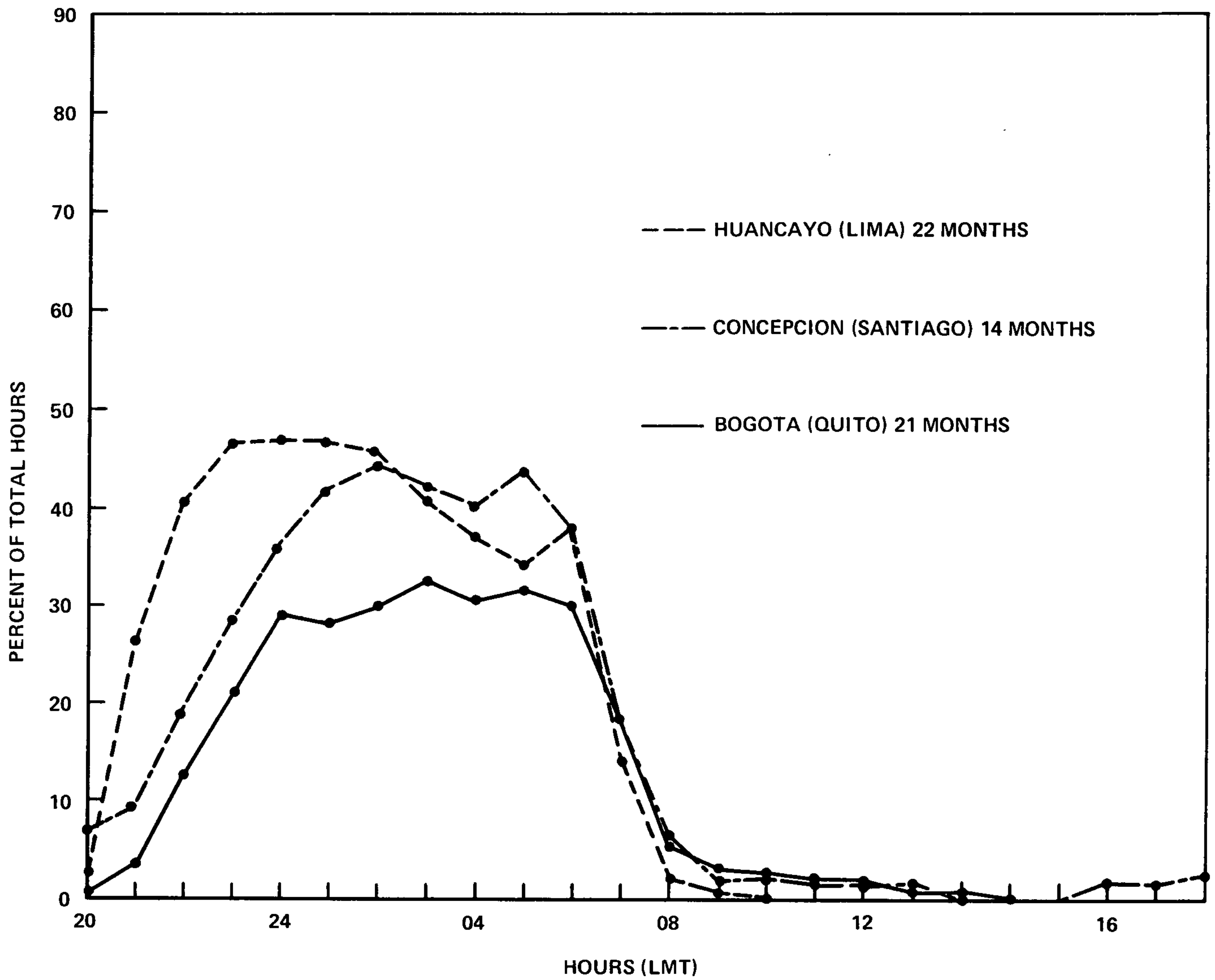


Figure 17. Percent of Total Hours (by Hour) in Which Spread Echoes were Reported (After Golden, Ref. 1)

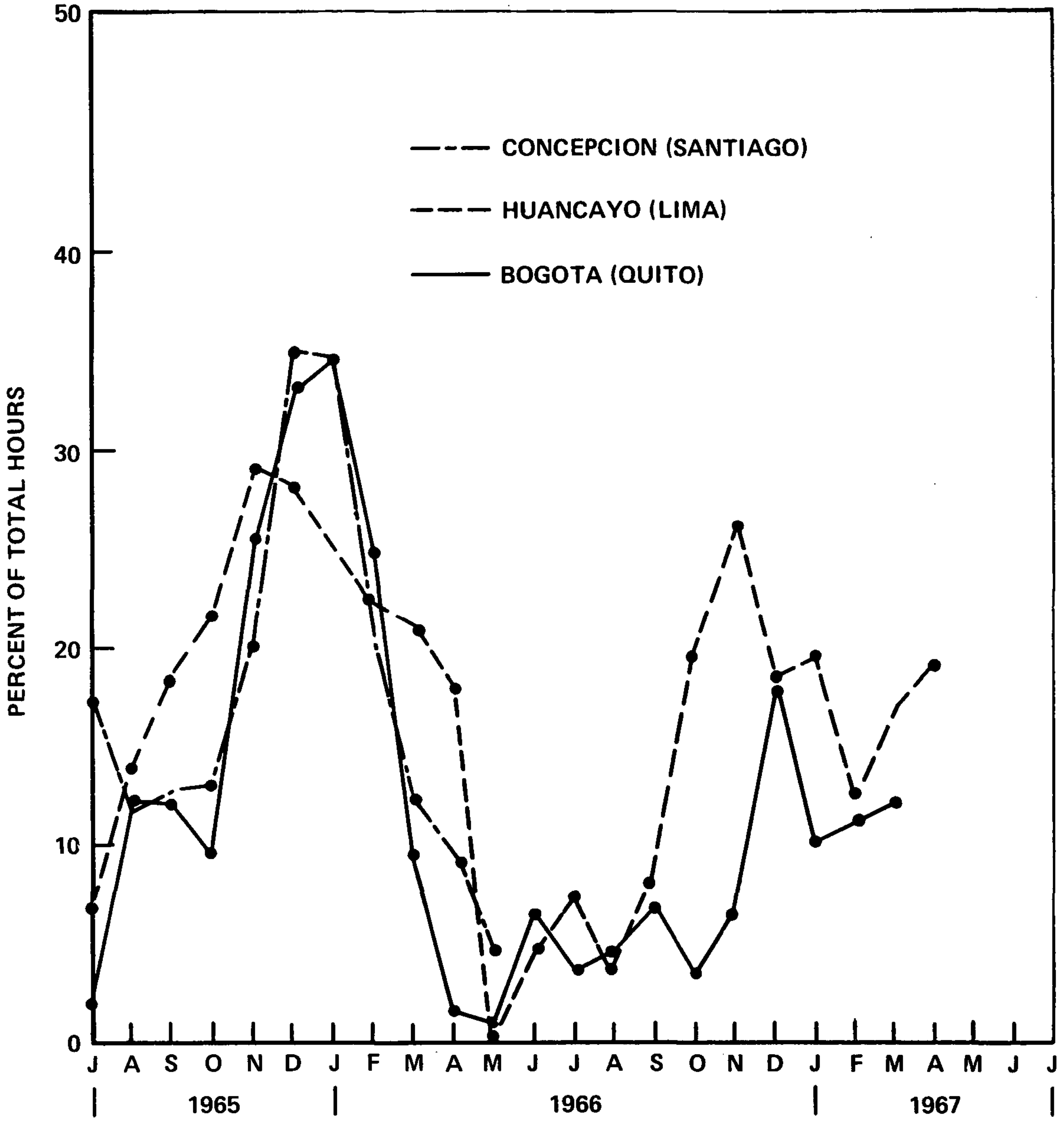


Figure 18. Percent of Total Hours (by Month) in Which Spread Echoes were Reported (After Golden, Ref. 1)

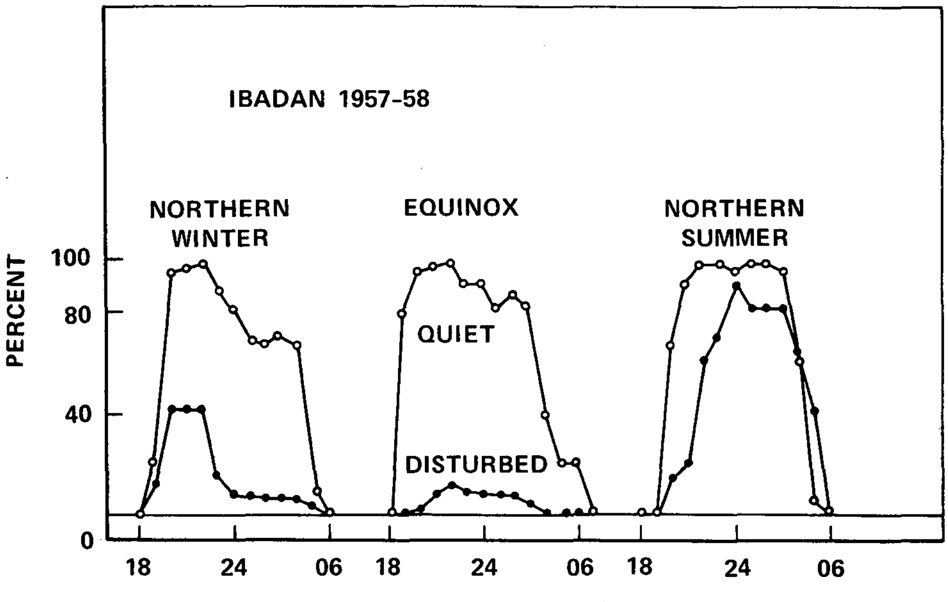


Figure 19. Percentage Occurrence of Spread F
(After Lyon, et al., Ref. 28)

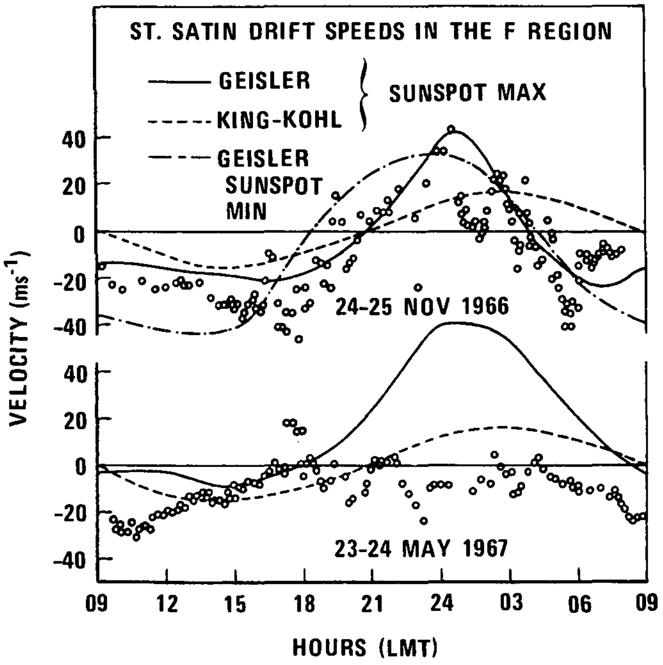


Figure 20. Vertical Drift in the F-Region at St. Santin
(After Carru, et. al., Ref. 34)