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EFFECTS OF EQUATORIAL SCINTILLATION FADING ON SATCOM SIGNALS

Describes the severity and scope of propagation effects that will reduce the reliability of tactical satellite communications

M. R. Paulson and
R. U. F. Hopkins • Research and Development • 8 May 1973

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NAVAL ELECTRONICS LABORATORY CENTER
SAN DIEGO, CALIFORNIA 92152

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PROBLEM

Conduct field investigations and analyses to define the characteristics of equatorial scintillation fading and its effects on satellite communications (SATCOM) systems. Generate a data base for use in evaluating optimum SATCOM techniques.

RESULTS

1. The uhf scintillation near 250 MHz was very intense, exceeding 25 dB peak-to-peak, and faded quite regularly into the system noise. This scintillation was predominantly a nighttime phenomenon.

2. Samples of scintillation data for three successive years suggest that the extent of occurrence of scintillation varies with solar activity.

3. Investigation of latitude dependence of scintillation showed the intensity of the scintillation to be comparable at all three sites when it occurred. The occurrence of scintillation, however, was comparable at the magnetic equator and 7-1/2 degrees north, but was much less at the site 17-1/2 degrees north of the magnetic equator.

4. Investigation of elevation-angle dependence showed the intensity of the scintillation to be comparable at all three elevation angles.

5. Limited tests of frequency diversity and space diversity suggest that frequency differences greater than 100 MHz would be necessary for frequency diversity to overcome the effects of scintillation and that, for space diversity to be effective, separation distances greater than the dimensions of a ship would probably be required.

6. Statistical evaluation of the scintillation records indicates that any system designed to overcome the effects of scintillation must be able to handle signal fadeouts with durations on the order of seconds.

7. No scintillation effects were observed at 7.3 GHz, but during some limited measurements peak-to-peak scintillations of 2 to 5 dB were observed at 2.3 GHz. The intensity of this scintillation was much less than that observed at 250 MHz during the same time period.

RECOMMENDATIONS

1. Measure the occurrence of equatorial scintillation over a period of a full year.

2. Study scintillation in conjunction with other geophysical measurements to try to establish a cause-effect relationship, the objective being the prediction of when scintillation might occur.

3. Evaluate scintillation at frequencies between 250 MHz and 2.3 GHz and determine the reliability improvement possible for SATCOM systems operating at the higher frequencies.

4. Investigate longitudinal variability of scintillation.

5. Make a more complete evaluation of space diversity to determine optimum spacing required.

6. Make a more complete evaluation of frequency diversity to determine what frequency difference would be necessary to overcome the effects of scintillation.

ADMINISTRATIVE INFORMATION

Work was performed under NELC problems M405 and J412 from July 1970 to May 1973 by members of the UHF Technology Division. Sponsorship was provided in part by DCA under MIPRS HC1001-2-00088 and HC1001-3-00031 and in part by NAVELEX (PME-116) under XF48.222.001, Task 2116.6. This report was approved for publication 8 May 1973.

The authors are indebted to numerous people and activities for support in conducting three successful field trips to various Western Pacific equatorial islands, particularly the District Administrators and Communication Center personnel of various districts of the Trust Territory of the Pacific Islands; the U. S. Coast Guard, which provided essential support on the islands of Iwo Jima and Saipan; and personnel of the U. S. Naval Communications Station, Guam. Also much appreciated is the support of the U. S. Air Force Satellite Control Facility (OL-10) on Guam, which provided the 2.3-GHz data, and the Wright-Patterson Air Force Base team, who participated in the 1971 tests.

Assistance from the following NELC personnel who made the collection of field data possible is gratefully acknowledged: J. E. Pohl, R. C. Muelheim, J. E. Hall, E. A. Rettig, and E. D. McClure of the UHF Technology Division; LCDR J. C. Tyner of the Satellite Systems Program Office; and C. R. Hansen of the Design Engineering Division. Also, the help of J. R. Harlowe, who did much of the data reduction and graphic presentation, is appreciated.

CONTENTS

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INTRODUCTION

For many years, signals from radio stars received at a fixed ground station have been observed to scintillate, or fluctuate in amplitude. At first, radio astronomers thought that the fluctuating signal strength was caused by fluctuation in the power of the source (the radio stars). Spaced receiver tests, however, have shown that irregularities in the electron density of the ionosphere were causing the signals to scintillate as the source moved or as the irregularities moved through the propagation path.

With the development of artificial satellites, many new radio sources were available for the study of the scintillation phenomenon. At the same time, it became very important to know what effect these ionospheric irregularities would have on transmissions to and from satellites.

The electron-density irregularities are believed to occur in the F region of the ionosphere. Kent and Koster[1] report measuring irregularities at heights from about 240 km up to about 400 km. The irregularities appear to be elongated regions, with the longer axis parallel to the earth's magnetic field lines. Axial ratios greater than 60 to 1 have been measured[2].

The most frequent and intense scintillation activity occurs in the auroral regions and in a region along the magnetic equator at night[3]. The activity along the equator tends to be greatest around the equinoxes, and is most intense during periods of high sunspot number.

Although it appears that the generation of electron-density irregularities that cause scintillation is dependent on solar activity, no direct cause-effect relationship has as yet been established. Several theories have been proposed for their generation, but none of them are considered completely satisfactory.

Since the refractive index of the ionosphere is a function of radio frequency, irregularities in the ionosphere will have progressively less effect as the transmission frequency is raised. How rapidly the scintillation intensity decreases with increasing radio frequency is not certain. Various authors have estimated that it is inversely proportional to frequency, others inversely proportional to frequency squared,[4] and one has found it inversely proportional to the square root of frequency.[5] It appears that the frequency dependence is not constant, and may vary with ionospheric conditions. One author has measured peak-to-peak scintillation greater than 6 dB at 6 GHz.[6]

Since the Navy has plans for increasing use of satellites in communications and navigation, it is important to know how scintillation activity will affect such systems. While considerable research has already been done, most of this work was done at frequencies below 100 MHz. Additionally, much of the information was presented in terms of scintillation indices which are not very useful for system design purposes. Consequently, the Naval Electronics Laboratory Center was requested to make some measurements in the equatorial region to evaluate the problem in that area. This report summarizes results of measurements made during three equatorial trips to the Pacific in 1970, 1971, and 1972. A more detailed presentation of the 1970 and 1971 results is given in references 7 and 8.

TEST OBJECTIVES

The scintillation measurements reported here were made on various islands in the Pacific near the magnetic equator. Figure 1 identifies the area in which the measurements were performed. Table 1 lists the particular islands involved and gives local time relative to GMT which was used in recording all data. Table 1 also gives approximate latitudes of the various islands in relation to the magnetic equator shown in figure 1.

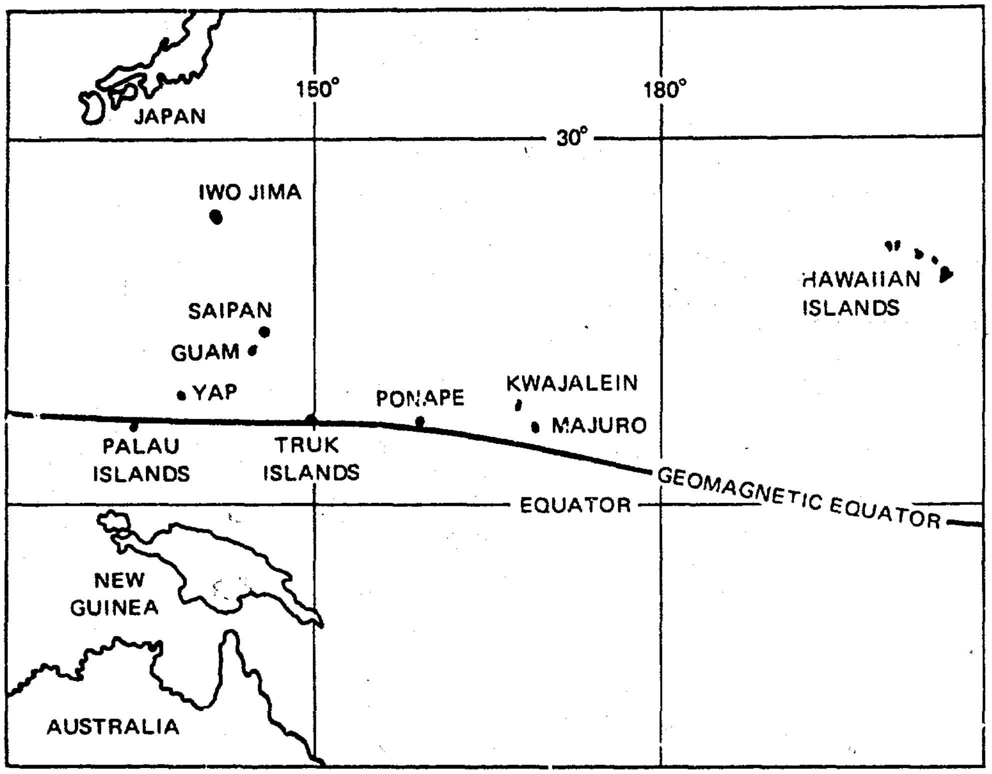


Figure 1. Area of equatorial scintillation test sites.

TABLE 1. SCINTILLATION TEST SITES.

Site	Latitude	Longitude	Local Time	Latitude from Geomagnetic Equator
Palau	7.3°N	134.5°E	GMT +9	0
Ponape	7°N	158°E	GMT +11	0
Majuro	7°N	171°E	GMT +12	2.3°N
Guam	13.5°N	144.8°E	GMT +10	6.0°N
Saipan	15°N	145.7°E	GMT +10	7.5°N
Iwo Jima	25°N	141.3°E	GMT +10	17.5°N

Table 2 gives the dates for each of the field tests, along with the islands involved. The elevation angle to TACSAT I is given for each case since TACSAT I was the satellite used for most of the measurements.

The main objective of the 1970 measurements was to get some information on the statistics of equatorial scintillation at uhf, such as intensity of fading, fading rates, and duration of fades. Secondary objectives were to determine whether space diversity, with spacing on the order of the dimensions of a ship, or frequency diversity might be effective in reducing the effects of scintillation. The uhf beacon near 250 MHz and the uhf communications channel on TACSAT I were used for these tests.

The tests conducted in 1971 were designed to evaluate the dependence of uhf scintillation on latitude and elevation angle. In these measurements, the uhf beacon of TACSAT I was monitored at three sites simultaneously. Some additional spaced-receiver measurements were made to get a measure of the direction and speed of movement of the scintillation pattern over the ground.

Because scintillation has been reported for frequencies as high as 6 GHz, the 1972 tests were designed to evaluate conditions at about 7.3 GHz. Although scintillation intensity at these frequencies would be expected to be quite small, it is possible that ionospherically caused phase disturbances could limit the useful bandwidth of a communications channel. One of the tests was set up to check this possibility using a 20-MHz bandwidth, the maximum allowed by the satellite channel.

TABLE 2. SCINTILLATION TEST DATES.

From	To	Site	Elevation Angle to TACSAT I, deg
8 Sep 70	21 Sep 70	Ponape	6-14
24 Sep 70	5 Oct 70	Majuro	33-36
18 Sep 71	28 Sep 71	Iwo Jima	32
19 Sep 71	29 Sep 71	Saipan	40
23 Sep 71	21 Oct 71	Palau	30
4 Oct 71	21 Oct 71	Majuro	72
7 Oct 71	19 Oct 71	Ponape	56
27 Oct 71	31 Oct 71	Guam	40
13 Sep 72	11 Oct 72	Guam	50-56 Daily

DATA REDUCTION AND RESULTS

OCCURRENCES OF UHF SCINTILLATION

The amplitude of the TACSAT I uhf beacon signal was recorded continuously during all three field tests. The strip charts in figure 2 show an example of scintillation on Majuro Island and compare it to a recording made at San Diego, California, covering the same time period. Since time scales are different, the Majuro record covers only a small portion of the San Diego record.

In the 1970 tests, scintillation conditions were assumed to exist if peak-to-peak amplitude fluctuations exceeded 10 dB. This condition was used because calibration of the receiver was done at an i-f stage. In 1971 and 1972, a calibration source at the beacon frequency was available. For these records, scintillation was considered to exist if the fluctuating amplitude faded more than 6 dB below the undisturbed signal level. An evaluation of the amplitude distributions showed these two conditions to be nearly equivalent.

The times when scintillation started and ended were tabulated for all the records. Scintillation was considered to be continuous if the fading exceeded the limit at least once in 5 minutes. If it did not, scintillation was considered to have ended at the time the limit was last exceeded and to start again the next time the limit was exceeded. In general, fading was rapid enough so that the limits were exceeded many times in a 5-minute period.

These periods of scintillation have been plotted in figure 3 as a function of GMT time and day for each of the three years. It can be seen from this that equatorial scintillation at this frequency is mainly a nighttime phenomenon. While there were one or two occurrences of significant daytime scintillation lasting about an hour, the scintillation usually started within an hour or two after sundown. The time at which it ended was quite variable, but it didn't continue generally much beyond 1:00 or 2:00 in the morning local time.

In addition to plotting times of occurrence, the total scintillation time has been determined as a percentage of the total recording time for each case, assuming 24 hours a day recording. These values are 11.8, 5.0, and 8.5 percent for each of the years 1970, 1971, and 1972. When a common 11-day period for each of the years is used, these numbers become 11.4, 7.4, and 8.3 percent. When these percentages are compared to the graph of monthly mean relative sunspot numbers in figure 4, a dependence on solar activity is suggested. Considerably longer recording times each year would have been desirable, however, to increase the significance of this correspondence, and it would be useful to get data for additional years.

The occurrences of fading times were used in another way in figure 5. In these graphs (panels A, B, and C), total fading time has been plotted for each GMT day as a percentage of a 24-hour day. In the 1971 and 1972 graphs, occurrence of fading greater than 12 dB below the undisturbed signal has been plotted as well.

Although these graphs give an idea of how much of the time communications in equatorial regions via uhf satellites might encounter problems, they only cover about a month of each year. It would be advisable to evaluate conditions for a complete year to get a more complete understanding of the problem.

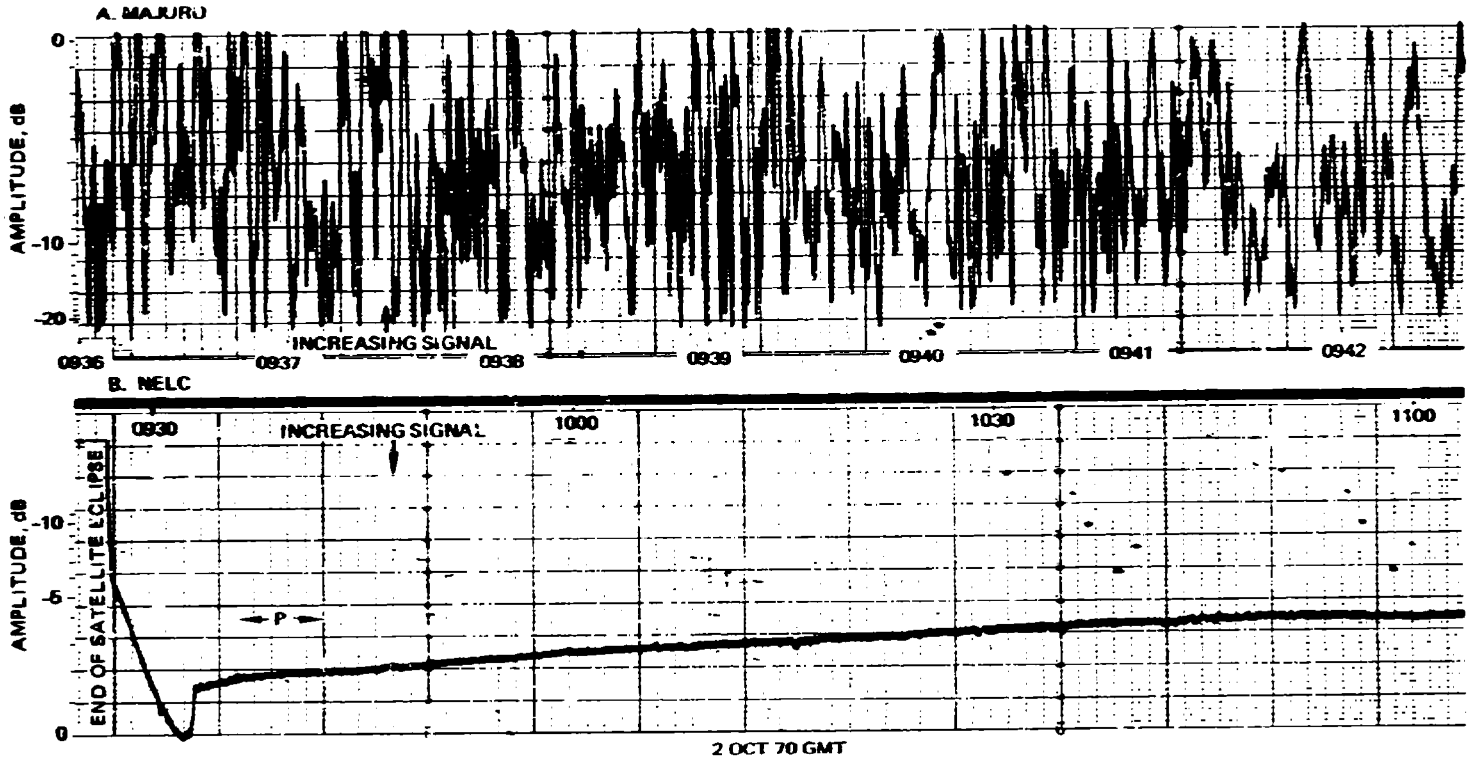


Figure 2. Example of nighttime scintillation (A.) recorded on Majuro (local time is GMT +12). The lower record (B.) was made at NELC at a slower chart speed, and includes the time period (P) shown in the upper record.

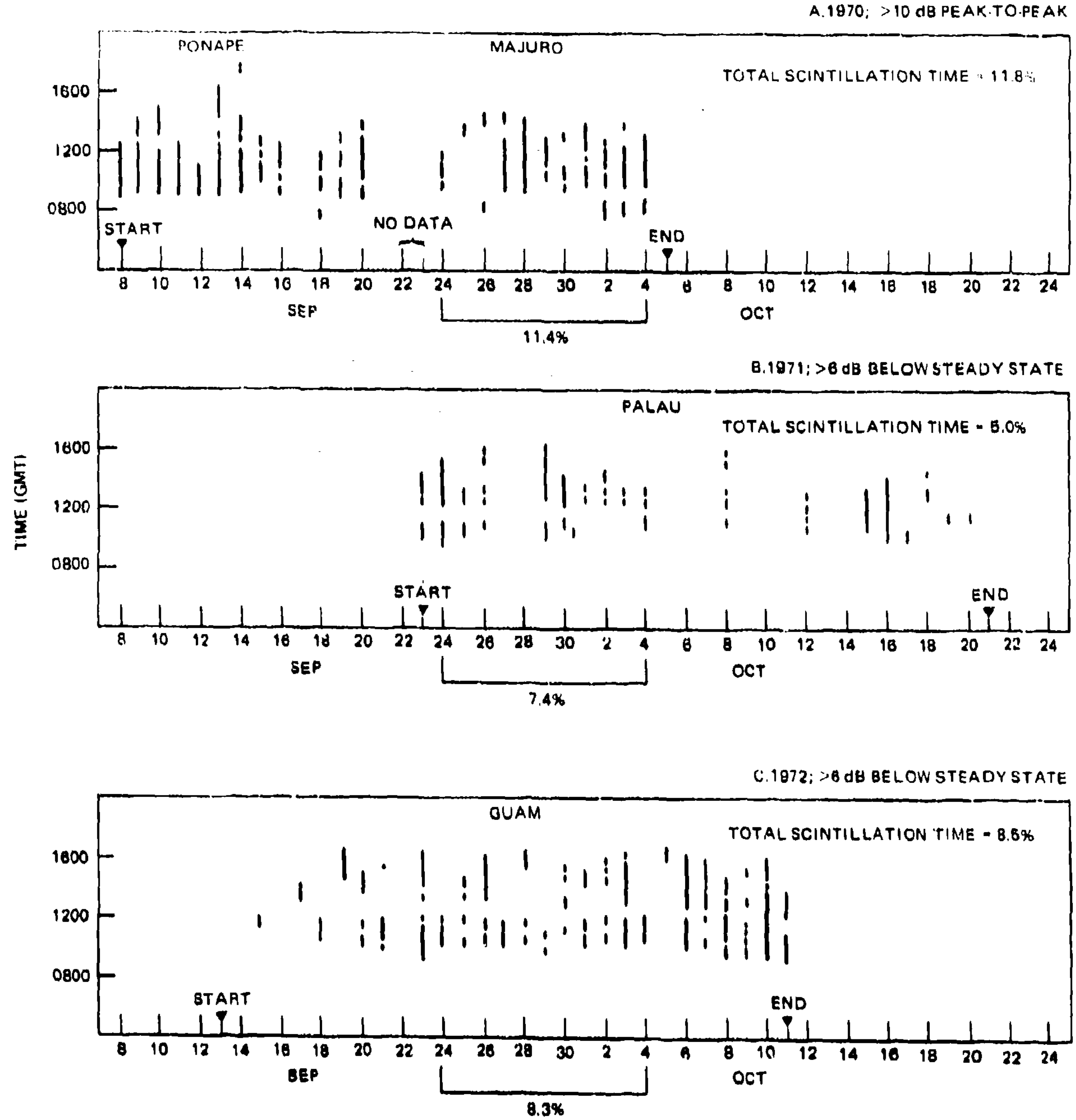


Figure 3. Occurrence of scintillation during each of the three field trips.

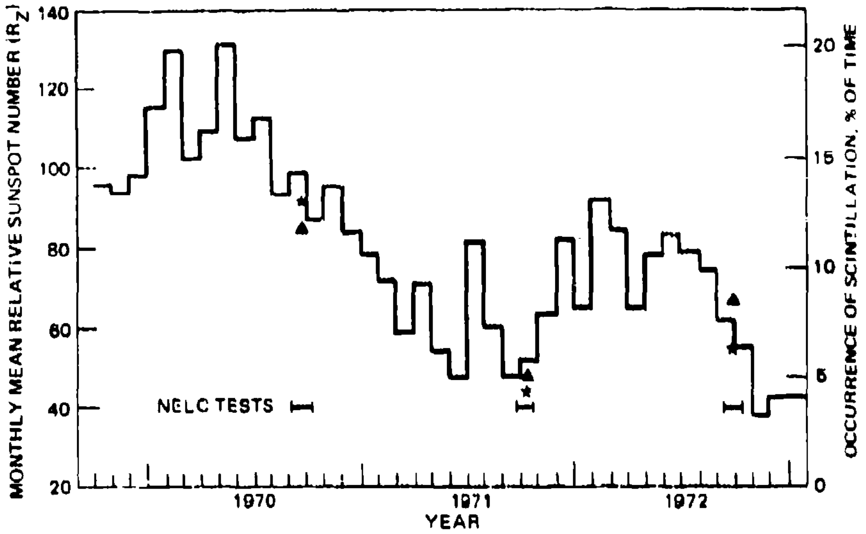


Figure 4. Monthly mean relative sunspot numbers. Δ = the occurrence of scintillation; ★ = the average of the daily relative sunspot numbers for the periods of each of the NELC tests.

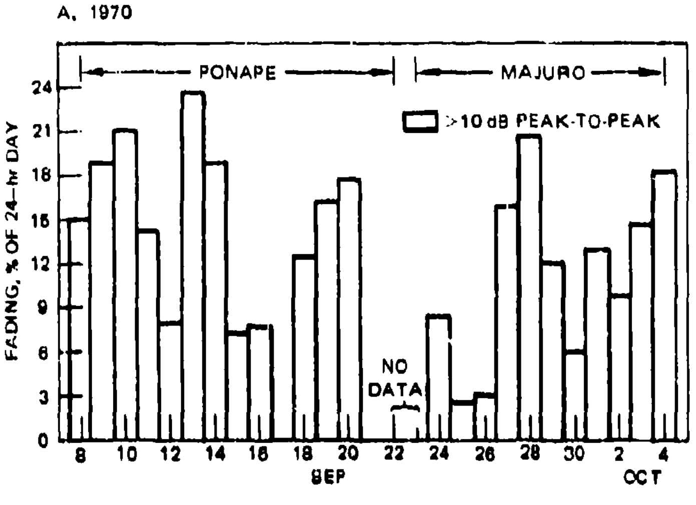
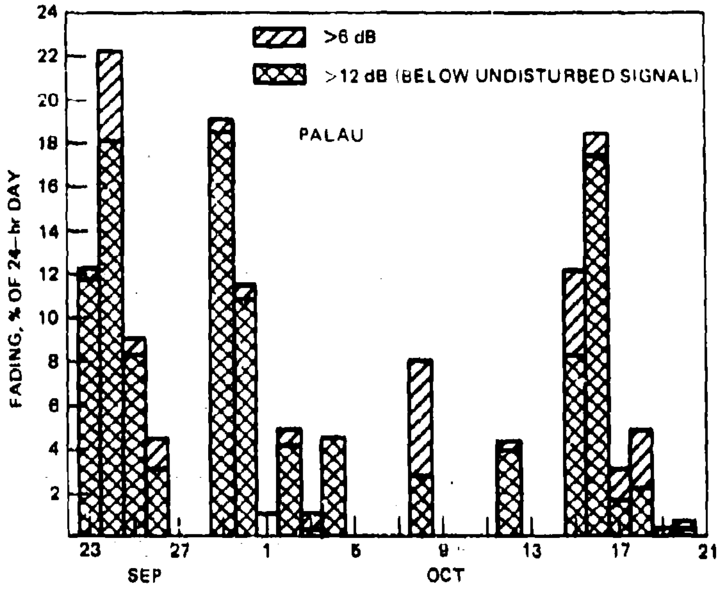


Figure 5. Daily scintillation activity for each of the three test series. Days are GMT.

B. 1971



C. 1972

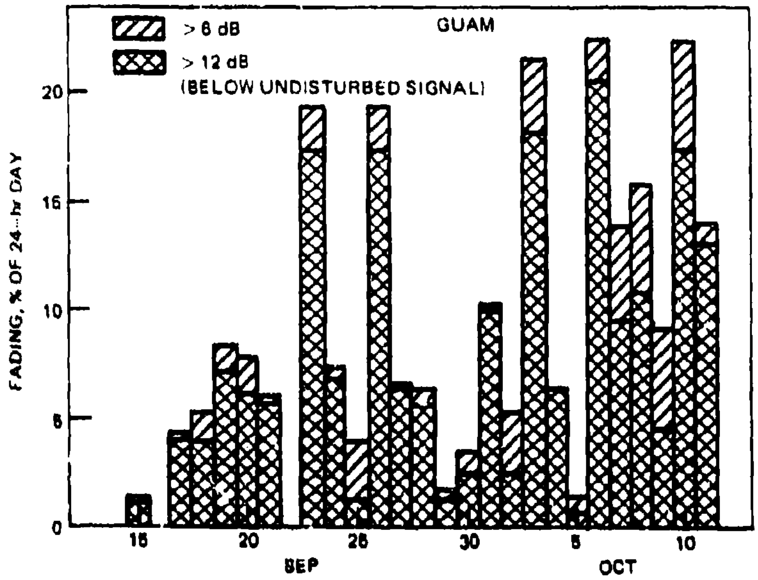


Figure 5. (Continued)

AMPLITUDE DISTRIBUTIONS DURING UHF SCINTILLATION

The 1970 data were recorded on strip charts. Cumulative amplitude distributions were calculated for samples of these charts taken at half-hour intervals during periods of scintillation. Sample lengths were either 3 or 5 minutes, depending on scintillation rate. The samples were digitized at one, two, or four times per second, depending on how rapidly the signal was fading. Four points from these distributions were plotted for relative amplitude in dB as a function of GMT time for each day. These points were the 1-, 10-, and 50-percent points and the maximum signal level. When no scintillation was occurring, the undisturbed signal level was plotted. Figures 6 and 7 show examples of these plots. In figure 6, the undisturbed signal level as recorded at NELC is plotted also. From this, it can be seen that the 50-percent probability points occur near the level of the undisturbed signal.

To facilitate analysis of amplitude records during scintillation, data were recorded on analog magnetic tape as well as on paper strip charts during 1971 and 1972. An electronic distribution analyzer was used to determine cumulative amplitude distributions for these magnetic tape records. This analyzer made it feasible to use 15-minute samples and a sampling rate of 10 per second regardless of the fading rate. Many of these amplitude distributions were plotted on arithmetic normal probability paper, as illustrated in figure 8. Using a linear voltage scale on the amplitude axis, the distributions were found to be very nearly straight-line plots, indicating that the scintillation has a Gaussian distribution.

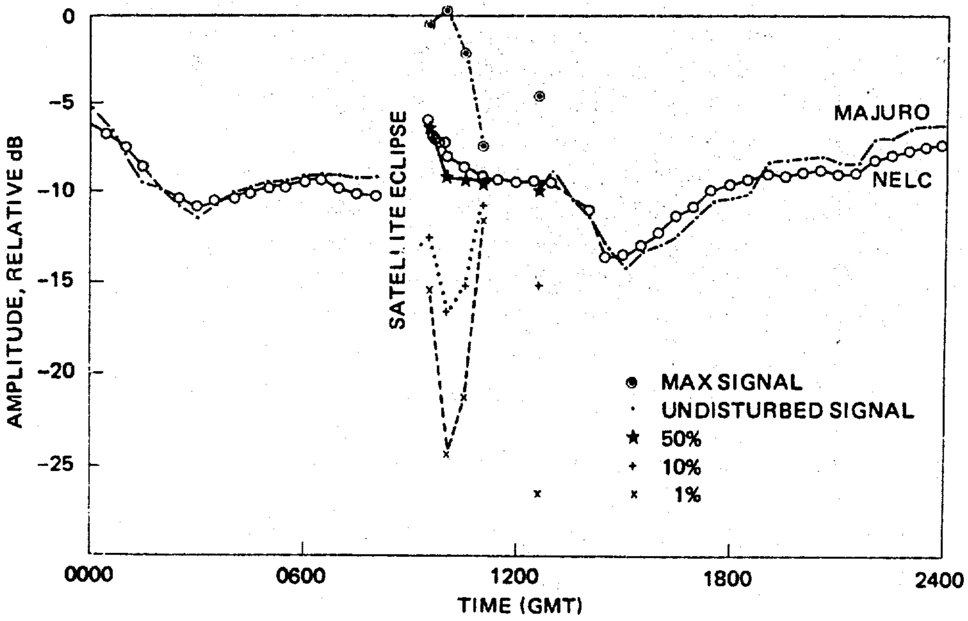


Figure 6. Amplitude of TACSAT I uhf beacon recorded on 30 September 1970 at Majuro compared with that recorded for the same time period at NELC. Four points from the cumulative amplitude distributions are plotted for Majuro during times when scintillation was occurring.

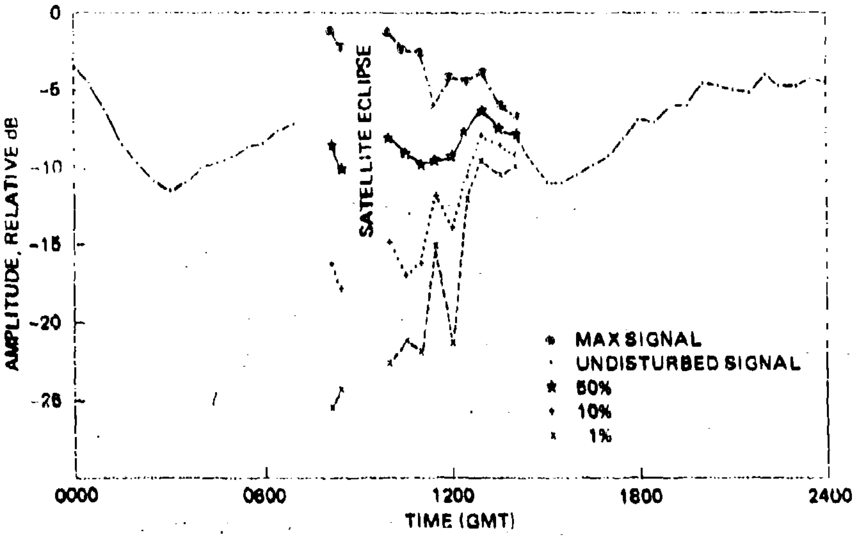


Figure 7. Amplitude of TACSAT I uhf beacon recorded on 4 October 1970 at Majuro. Four points from the cumulative amplitude distributions are plotted for periods when scintillation was occurring.

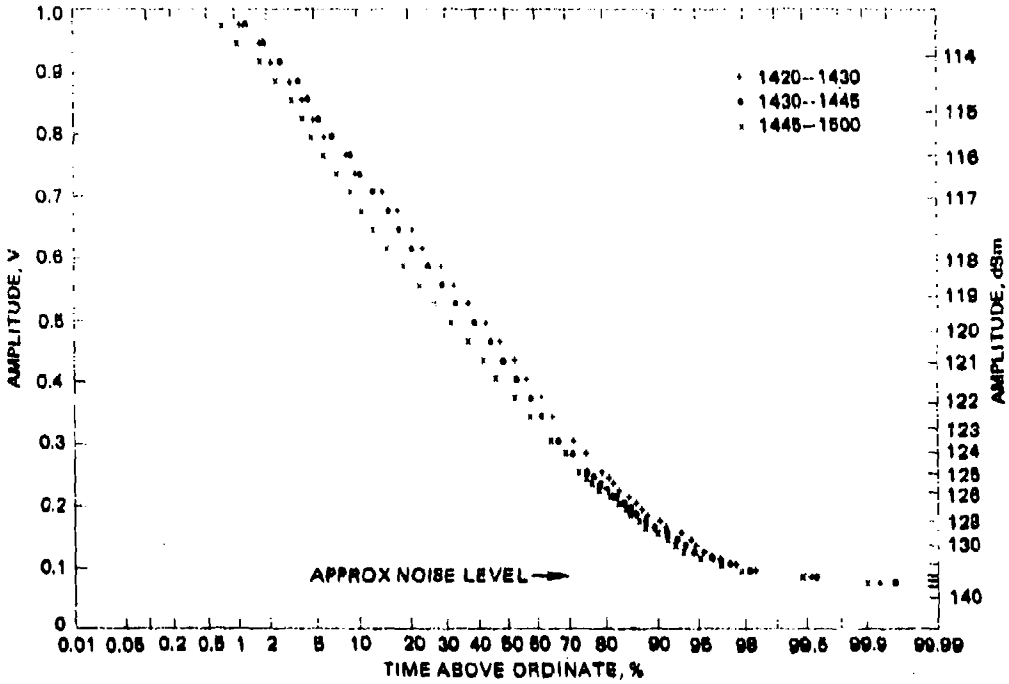


Figure 8. Example showing three cumulative amplitude distributions for records made on the night of 23 September 1972 GMT.

POWER SPECTRA OF UHF SCINTILLATION

Power spectra were calculated for many of the digitized samples to investigate the complexity of the scintillation and to see how the spectrum changed with time. Figure 9 is an example of two of these spectra for samples taken a half-hour apart and sampled twice per second. While the spectra were quite variable from sample to sample and from night to night, in general they were more complex and had higher frequency components early in the evening.

FADE-DURATION DISTRIBUTIONS

Before any method can be devised to overcome the effects of fading due to scintillation, it is necessary to know not only the magnitude but also the duration and frequency of occurrence of deep fades. With this purpose in mind, amplitude levels 6 and 12 dB below the undisturbed signal level were determined for much of the 1970 data and all of the 1971 data.

For the 1970 data, each time the signal amplitude went below the specified level, the time spent below that level was measured and tabulated. These fade times were arranged in order of increasing duration, and plots of the cumulative number of fades as a function of fade duration were made. This resulted

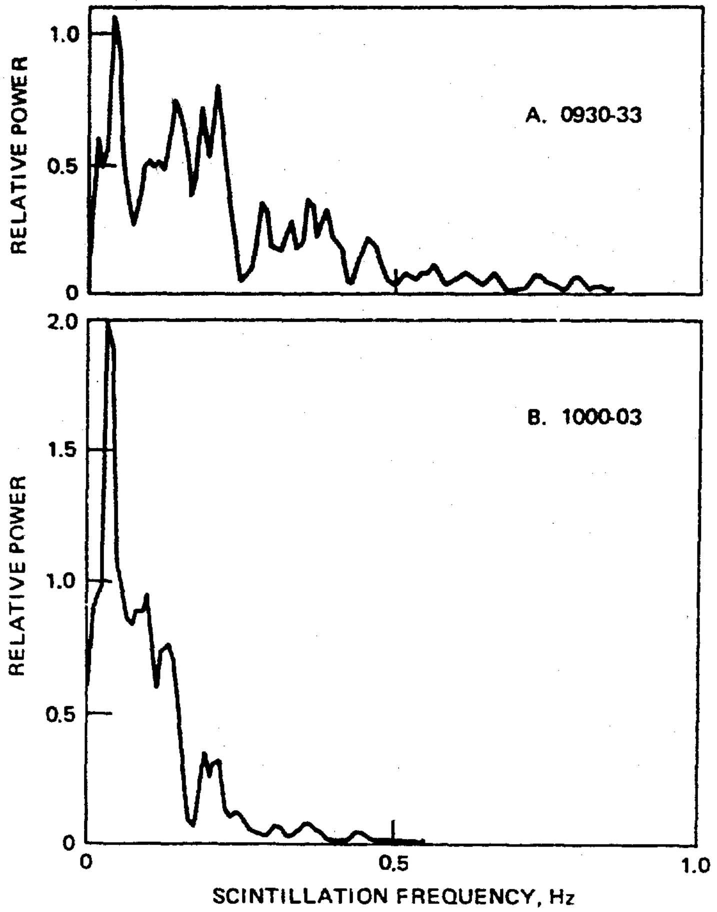
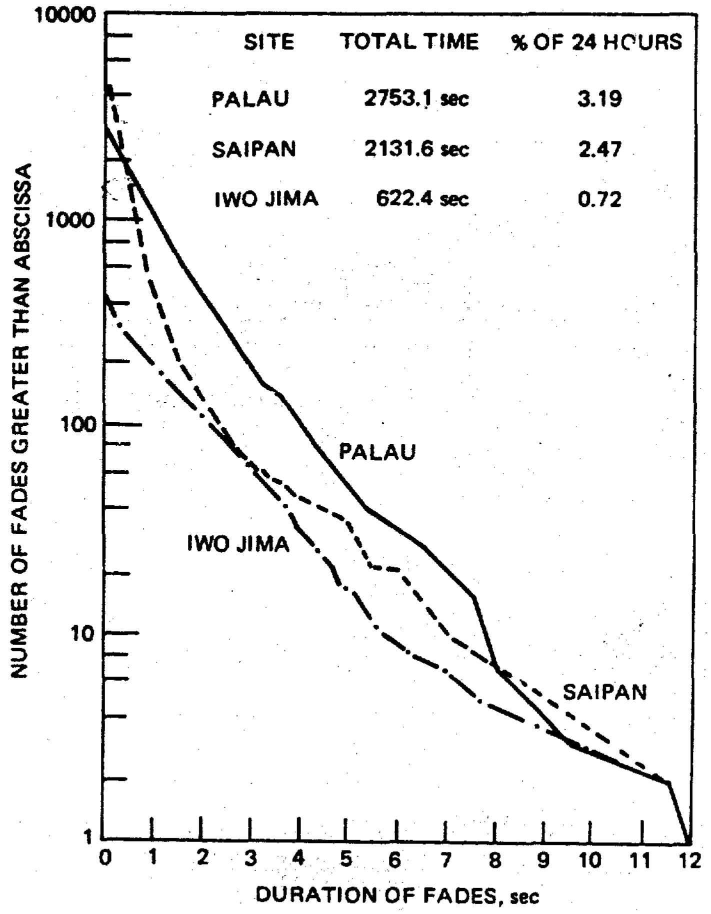


Figure 9. Fourier spectra for two samples of scintillation records taken on Ponape a half-hour apart, 18 September 1970 GMT.

in a graph showing on the vertical axis the number of fades which equaled or exceeded a given fade duration on the horizontal axis.

Essentially the same thing was done for the 1971 data. In this case, however, the distribution analyzer was configured to determine the distributions from the magnetic tape records. A reference voltage 6 or 12 dB below the undisturbed signal was set, and the analyzer measured the time spent below the level each time the signal faded and summed up the number of fades in each time interval. These sums were used to calculate and plot the cumulative number of fades as a function of fade duration. Most of these distributions were determined for sample lengths of a half-hour each, unless the fading did not last that long.

Cumulative fade duration distributions were determined for the complete night of 24 September 1971 at Palau, Iwo Jima, and Saipan. Figures 10 and 11 show these distributions for the 6-dB and 12-dB reference levels, respectively. It can be seen that for any corrective system to be effective it will have to be able to handle fades with durations of several seconds. Even a system with a 12-dB margin would have to handle fades on the order of seconds. The time actually spent below the indicated level has been totaled for each of the sites. When converted to a percentage of a 24-hour period, these total durations represent about 2.5 percent of the day at Saipan, 3.2 percent



SITE	TOTAL TIME	% OF 24 HOURS
PALAU	2753.1 sec	3.19
SAIPAN	2131.6 sec	2.47
IWO JIMA	622.4 sec	0.72

Figure 10. Comparison of uhf fade duration distributions for Palau, Saipan, and Iwo Jima on 24 September 1971 GMT for fades greater than 6 dB.

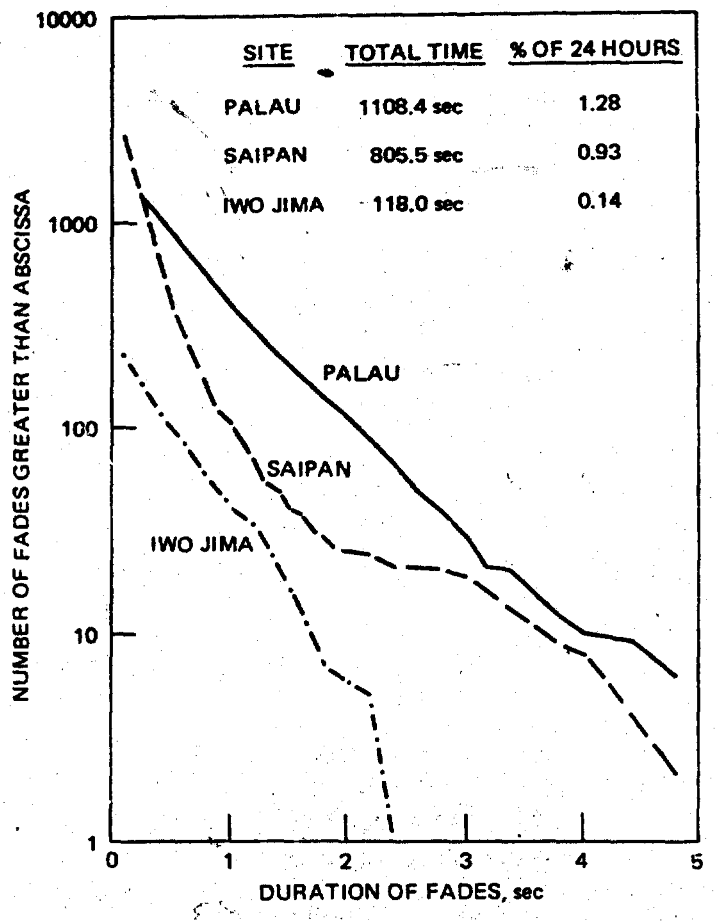


Figure 11. Comparison of uhf fade duration distributions for Palau, Saipan, and Iwo Jima on 24 September 1971 GMT for fades greater than 12 dB.

at Palau, and 0.7 percent at Iwo Jima for the 6-dB level. For the 12-dB level, the values are about 1.0 percent at Palau and Saipan and 0.14 percent at Iwo Jima.

SPACE- AND FREQUENCY-DIVERSITY MEASUREMENTS

SPACE DIVERSITY

Some preliminary measurements were made during the 1970 tests to evaluate the usefulness of space diversity in overcoming the problem of uhf signal fading. On September 30, two receivers were separated about 650 to 700 feet in the east-west direction on Majuro, and simultaneous recordings were made on the TACSAT I beacon from 1020 to 1035 GMT at a chart speed of 12 inches per minute. Station WWVH was monitored at both sites to provide time indications on the records. (There may, however, have been a consistent 1-second error in interpretation of the time signals at the two sites, as explained below.) The records were sampled at 1-second intervals, and a cross-correlation analysis was performed. A maximum correlation value of 0.85 was obtained, with the west recording about a half-second earlier than the east recording. The correlation for zero time difference was 0.8. (A correlation value of 1.0 would indicate that the records were identical.)

Similarly, on October 4 from 0955 to 1010 GMT, the receivers were separated north-south about the same distance, and further recordings were made. In this case, the maximum cross-correlation value was 0.75, with the north recording being about 1-1/2 seconds ahead of the south recording. The zero time difference correlation was 0.4.

The fact that the delay time was greater in the north-south direction than in the east-west was unexpected since other measurements of equatorial scintillation pattern drift have exhibited a velocity in the east-west direction.[2] The most probable explanation is that different interpretations of WWV time signals at the two sites could have caused a consistent 1-second error in the time difference measurements. If this was the case, then there would be a 1-1/2-second delay from west to east, with a zero time difference correlation value of 0.59, and a half-second delay from north to south, with a zero time difference correlation value of 0.72. This would also give a pattern drift velocity of about 130 to 140 meters per second to the east, assuming an east-west direction of movement.

To see what correlation might be expected for larger separations, one of the receivers was taken about 1 mile south and 0.6 mile east of the other one and recordings made for a 15-minute period. (This direction was dictated by Majuro's shape.) The cross correlation is shown in figure 12. The maximum correlation value was 0.48, with the north-west recording about 7-1/2 seconds earlier than the south-east one. At zero time difference, the records were essentially uncorrelated; what little correlation existed was negative. This can be considered proof that the fluctuations in amplitude were caused by the propagation medium and not by any variation in the ERP of the satellite beacon.

If we assume that this 7-1/2-second delay was due only to the east-west component of the separation, we get a drift velocity of about 130 meters per second eastward. This would tend to support the error-in-time explanation proposed above.

Some additional spaced-receiver measurements of scintillation were made on Guam in 1971. In this case, three receiver sites were operated simultaneously in a triangle that was oriented on nearly east-west and north-south lines. (A more complete discussion of these measurements is included in appendix A.) Figure 13 is a typical example of cross correlations obtained for one 5-minute sample of these scintillation records. The drift velocity for this example was 180 meters per second in a direction 100 degrees from north. While the zero-time-delay correlation value for the 750-meter north-south separation was 0.71, it can be seen that if the north-south line had been perpendicular to the drift velocity this value would have been 0.94. Consequently, it appears that any space-diversity system would require a receiver separation in a line parallel to the drift velocity.

If we next consider the cross-correlation curve for the east-west separation of 1100 meters, it is apparent that this separation is optimum for the scintillation conditions in this example, since the zero-time-delay correlation value is at a maximum of 0.42 negative. If we assume that a zero correlation

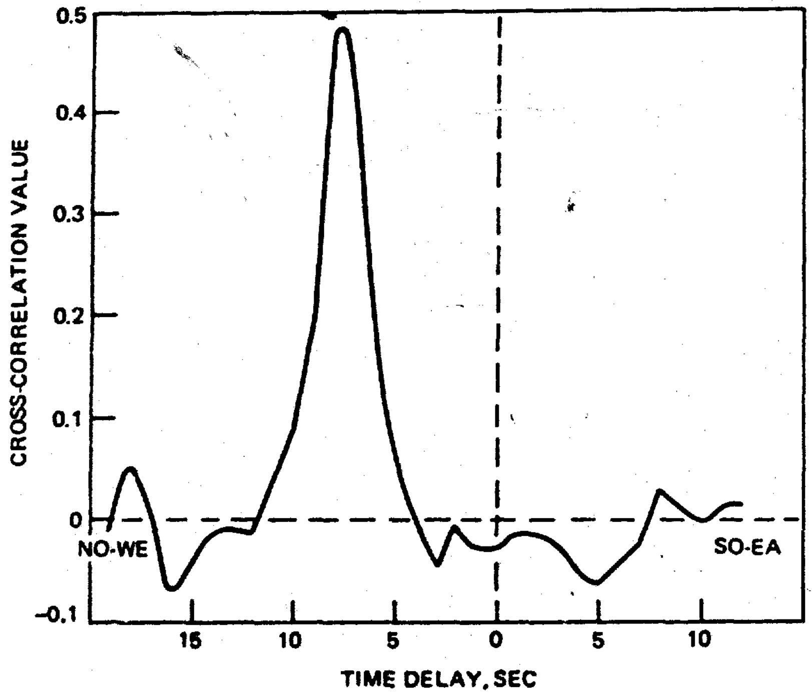


Figure 12. Cross correlation of scintillation records for spaced receivers on Majuro with separation of about 1 mile south and 0.6 mile east; 2 October 1970, 0955 to 1010 GMT.

at zero time delay would be satisfactory, we find that at the 180-meters-per-second drift velocity this would still require an east-west separation of about 550 meters.

These measurements would suggest that space diversity may not be effective in overcoming fading problems for space separations which would be possible on board ships. It should be pointed out, however, that these were very limited measurements, and a more extensive investigation would be necessary to more completely evaluate space diversity.

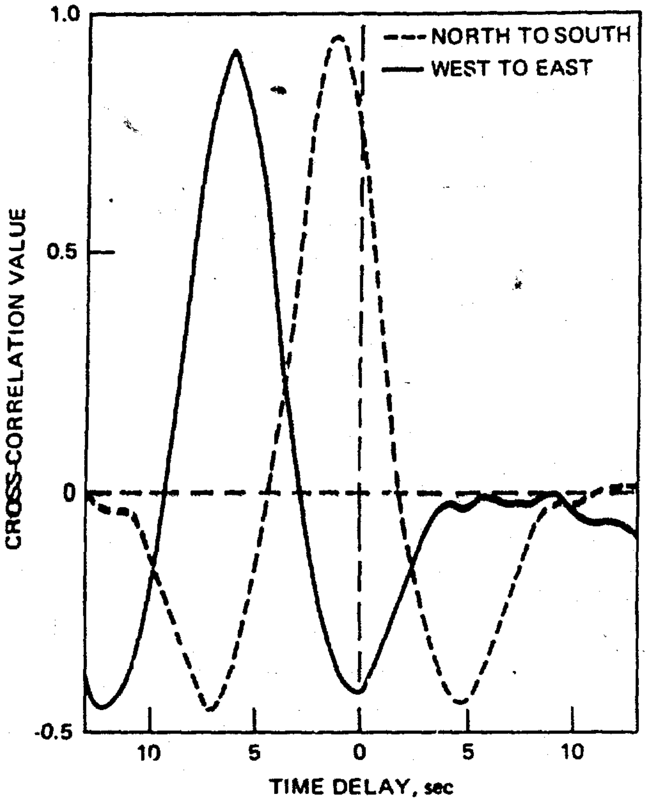


Figure 13. Cross-correlation values calculated for spaced-receiver triangle on Guam for records from 1255 to 1300 GMT, 28 October 1971. West-to-east spacing was 1100 meters, and north-to-south spacing was 750 meters.

FREQUENCY DIVERSITY

During the 1970 tests, measurements were also made to get some idea of the usefulness of frequency diversity in overcoming the effects of fading. On several occasions, NELC transmitted a signal from San Diego over the satellite uhf communications channel, and this signal was recorded simultaneously with the beacon on Majuro. A cross correlation between two of these records obtained from 1030 to 1045 GMT on September 24 gave a correlation value of 0.85 using signals differing in frequency by about 5 MHz.

To get a larger frequency separation, a signal was transmitted from Majuro via the satellite and recorded at NELC. A cross correlation between one of these records and the beacon recorded on Majuro from 1015 to 1030 GMT on October 1 gave a correlation of 0.6 employing a frequency difference of about 50 MHz. These two values of correlation coefficient are plotted as a function of frequency separation using log-log scales in figure 14. If the assumption is made that the cross-correlation value is near 1.0 for a frequency separation of 0.1 MHz, a projection of this curve would suggest that the cross-correlation value would still be around 0.5 for a frequency difference of 100 MHz. Consequently, it appears that a frequency separation considerably greater than this would be necessary for frequency diversity to be effective in overcoming the effects of fading.

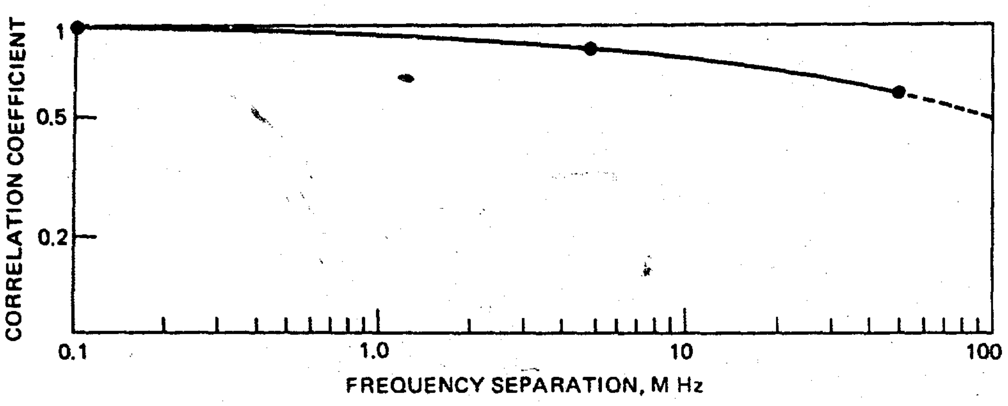


Figure 14. Correlation coefficient as a function of frequency separation (i.e. frequency diversity) at uhf.

DEPENDENCE OF UHF SCINTILLATION ON LATITUDE AND ELEVATION ANGLE

LATITUDE DEPENDENCE

One of the objectives of the 1971 tests was to get a measure of the dependence of uhf scintillation on latitude. Receivers were set up on Palau, Saipan, and Iwo Jima, and the amplitude of the TACSAT uhf beacon signal was recorded for almost two weeks. As shown in table 1, Palau is on the magnetic equator, while Saipan and Iwo Jima are about 7-1/2 and 17-1/2 degrees north of this equatorial line.

When cumulative amplitude distributions were calculated for these three sites, no significant differences were found. The intensity of the scintillation was comparable for all three sites. Figure 15 provides a comparison of three of these distributions. Observe that the example for Palau was taken three nights after the other two. At this time, the ERP of the satellite beacon was about 3 dB higher than it was for the other two examples.

Since it appeared that when it occurred scintillation was just as intense at all three sites, latitude dependence was investigated on the basis of occurrence. The total time that scintillation was greater than 6 dB and greater than 12 dB was calculated for each site as a percentage of the total time recordings were made. These results are plotted in figure 16 as a function of latitude. The same computations were performed for the time that any two sites were recording signals, and these values are also plotted. The results show that occurrence of scintillation at Palau and Saipan was comparable, but there was a pronounced decrease in the occurrence of scintillation at Iwo Jima.

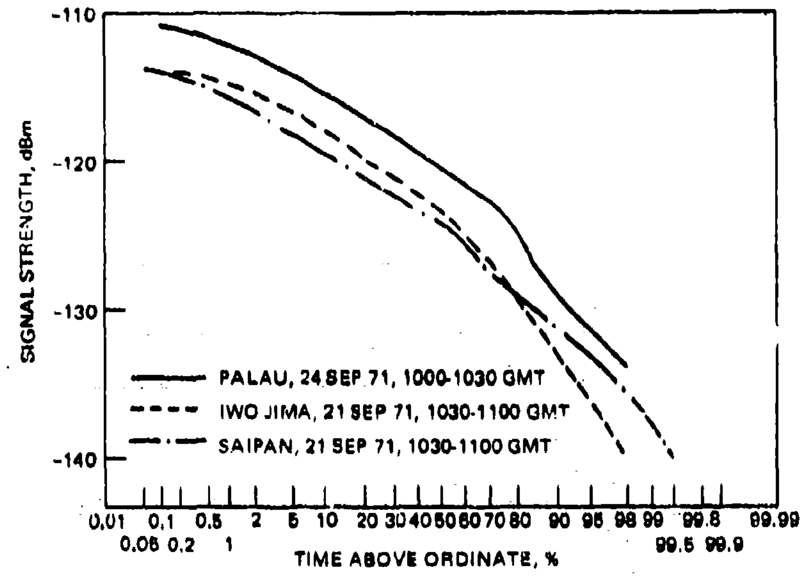


Figure 15. Comparison of cumulative amplitude distributions for records made at Palau, Saipan, and Iwo Jima.

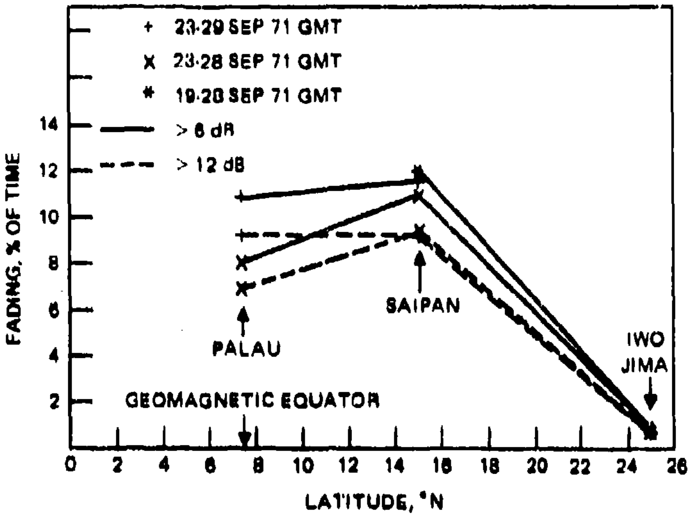


Figure 16. Latitude dependence of the occurrence of scintillation.

ELEVATION-ANGLE DEPENDENCE

The second objective of the 1971 tests was to evaluate dependence of uhf scintillation on angle of elevation. To this end, receivers were installed on Ponape and Majuro, while the third receiver remained on Palau. This provided three locations near the magnetic equator with elevation angles to the satellite of 30, 56, and 72 degrees. Signals from the TACSAT I beacon were recorded at these sites for about two weeks.

Several cumulative amplitude distributions were calculated from these records. Figure 17 shows a comparison of three of these. While the distribution for Palau is lower than the others, this Palau recording was made on a different night, when the ERP of the beacon was lower. Thus, there appears to be no significant difference in these curves.

These records were also evaluated on the basis of occurrence of scintillation. Total times for fading greater than 6 dB and 12 dB, respectively, were determined for each site as a percentage of total time that all three sites were recording. These values are plotted in figure 18 as a function of elevation angle. The same thing was done for just the Palau and Majuro sites, since they were in operation several days longer than the Ponape site. These results are also plotted in figure 18. These curves suggest that occurrence of scintillation is slightly greater at lower elevation angles than at high angles. Because of the limited time covered by these measurements, however, the difference is probably not significant. A longer period of measurements would be needed to increase the significance of the results.

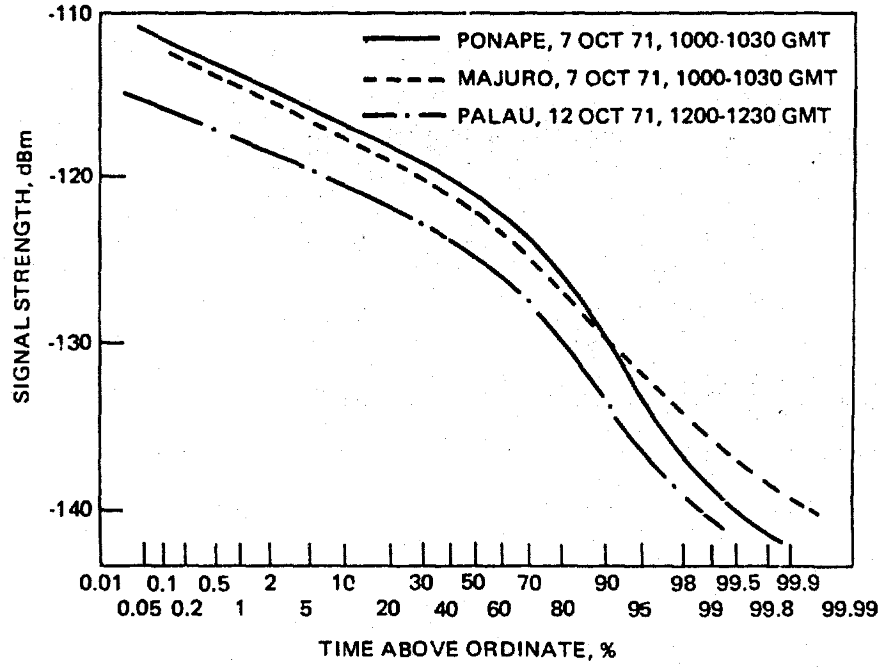


Figure 17. Comparison of cumulative amplitude distributions for Majuro, Ponape, and Palau.

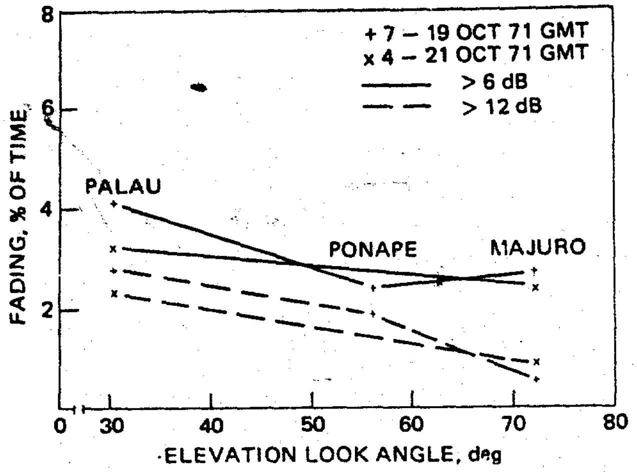


Figure 18. Elevation-angle dependence of the occurrence of scintillation.

UHF DIFFRACTION-PATTERN DRIFT MEASUREMENTS

On completion of the elevation-angle dependence measurements, the three receivers were installed in a triangular configuration at the Naval Communications Station on Guam. The object of this experiment was to get a measurement of movement of or changes in the scintillation diffraction pattern. While signals from the TACSAT I uhf beacon were recorded for five successive nights, scintillation was observed only on the night of 28 October 1971. Results of a cross-correlation analysis indicate that the observed scintillation was caused by movement of the diffraction pattern rather than by time changes in its structure.

The results of a cross-spectrum analysis show good agreement with the cross-correlation results. In general, all the frequencies in the scintillation spectrum appear to move in the same direction with about the same speed. Both types of analysis show a drift velocity which varied from about 130 to 180 meters per second in a direction which varied from east to slightly south of east. A more detailed discussion is included in appendix A.

FREQUENCY DEPENDENCE OF SCINTILLATION

SHF MEASUREMENTS

In these measurements, the amplitudes of the uhf and shf beacons of TACSAT I were monitored continuously on Guam. The receiver used for recording the 7.3-GHz beacon signals was borrowed from a Marine Corps MSC-57 jeep SATCOM terminal. This receiving installation included a 3-foot dish, parametric amplifier, and phase-lock detection. The receiver maintained phase lock to approximately 12 dB below the level of the received beacon signal. The equipment was calibrated using an rf attenuator between the parametric amplifier and the main receiver.

Figure 19 provides a typical example of the amplitude record of the TACSAT I shf beacon at a time when the signals from the uhf beacon were scintillating. Note that the amplitude of the shf signal is quite steady, while the uhf signal fluctuates violently.

In conjunction with these tests, equipment built by Teledyne Micronetics was borrowed from the Air Force and used with the MSC-46 terminal at the Naval Communications Station to evaluate differential phase variations within a 20-MHz bandwidth centered at 7.3 GHz. This equipment generated three lines of nearly equal amplitude with a 10-MHz frequency separation. These lines were transmitted through a DSCS Phase I satellite and received back on the ground by the MSC-46 terminal. Among other things, the Micronetics equipment provided outputs giving the amplitudes of each of the three lines along with an output of phase differences between the upper and the lower lines. In these tests, only the amplitude of one of the lines and the phase differences were recorded. Approximately 70 hours of nighttime data were obtained using this system.

Figure 20 is a typical example of records taken with this system. The upper record gives the amplitude of the 7.3-GHz signal, and the middle record shows the phase difference between the upper and lower frequency lines. In this case, the signals passed through the ionosphere twice. The bottom record shows amplitude variations of the TACSAT I uhf beacon signal for the same period. Although the ionosphere caused no noticeable effect on amplitude or delta phase at shf, intense rain did affect the amplitude of the received signal. Figure 21 illustrates this effect during a heavy rain shower.

When scintillation occurs, the angle of signal arrival is expected to fluctuate. Consequently, during all the tests using the MSC-46 terminal, the azimuth and elevation servo error signals (ΔAZ and ΔEL) were also recorded. Full-scale sensitivity was about ±0.1 degree with peak-to-peak tracking noise of about 0.05 degree under good signal conditions. No variations in the angle of arrival of shf signals were observed while operating the MSC-46 terminal, except during rainy periods.

While the tests on Guam in the fall of 1972 showed little evidence of scintillation around 7.3 GHz, considerable scintillation activity was observed around 6 GHz by the COMSAT Corporation at Hong Kong in 1969. In private correspondence, COMSAT personnel have offered the following observations on this question:

> "Based on our measurements, Guam has apparently less scintillation activity than Hong Kong even though the geomagnetic latitude of Guam is lower than that of Hong Kong. Data taken during the fall equinox of 1972 at Hong Kong show a substantial decrease in scintillation, both in occurrences and amplitudes. Therefore, I would think the same phenomena are occurring at Guam and if during the year of the solar maximum (1969) the peak-to-peak fluctuation (at Guam) is generally less than 2 dB scintillation at 6 GHz should become almost negligible during Fall of 1972."

At 7.3 GHz, the scintillation would be expected to be even less.

The smoothed sunspot numbers during the 1969 peak (when COMSAT 6-GHz data were taken) reached a value of about 110. During the 1972 tests on Guam, this value had decreased to about 70. The current sunspot cycle is considered quite typical or average, and it is a matter of conjecture what the

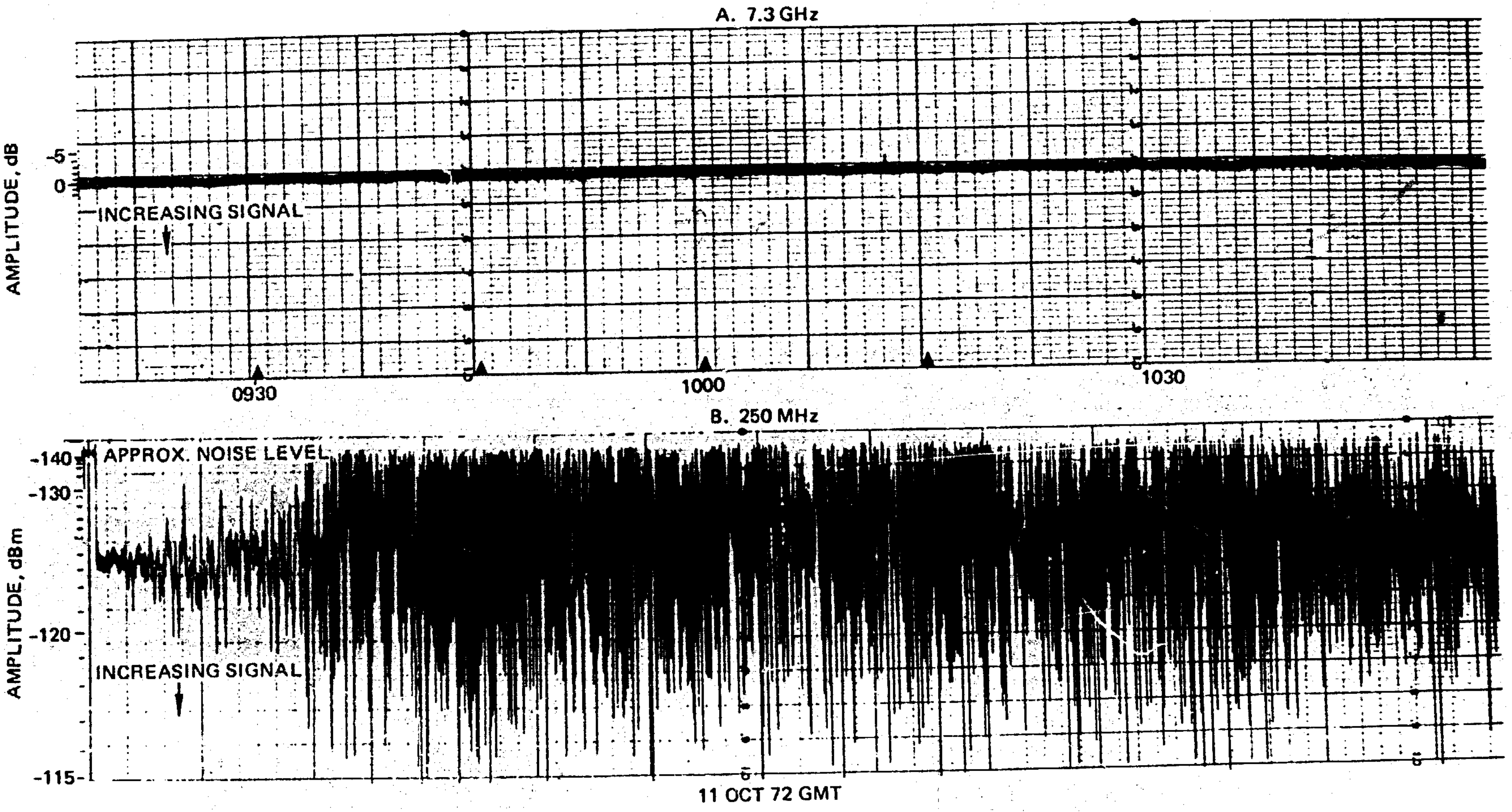


Figure 19. Example of signals recorded on Guam from TACSAT I shf and uhf beacons during scintillation of the uhf signals.

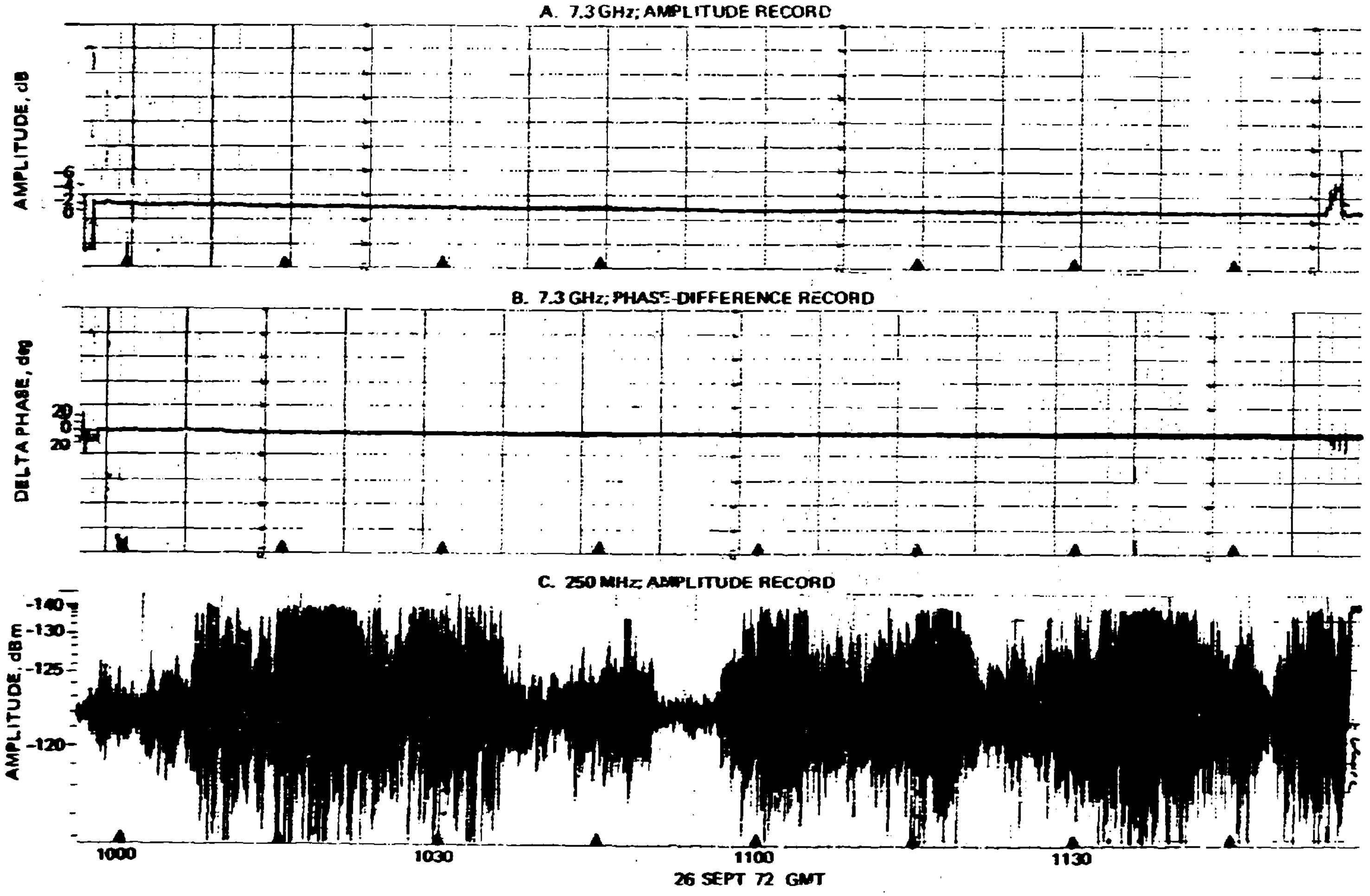


Figure 20. Example of shf amplitude and phase difference for a 20-MHz frequency difference at about 7.3 GHz during periods of uhf scintillation.

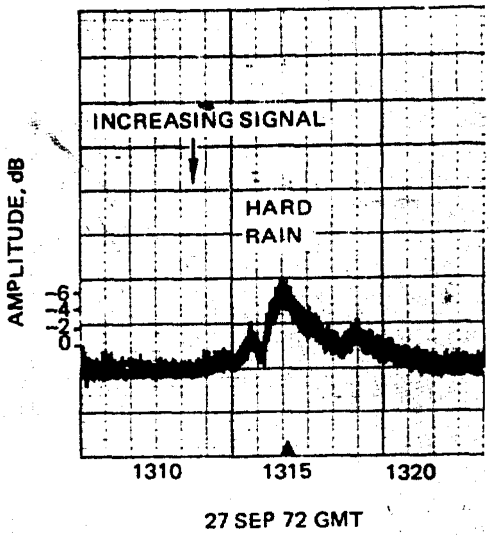


Figure 21. Example of 7.3-GHz attenuation during an intense rain shower.

scintillation activity might have been during the last cycle which had a peak of slightly over 200. Only observation of scintillation during periods of high sunspot activity will answer this question.

S-BAND MEASUREMENTS

In addition to the foregoing shf measurements, the Air Force Satellite Control Facility (OL-10) on Guam recorded a limited amount of amplitude data on the 2.3-GHz TACSAT I telemetry signal when this did not interfere with other duties. These data were recorded for about a half-hour per night from 7 to 10 October 1972 and for an hour during the night of 11 October. During approximately 75% of this time, periods of high uhf scintillation activity with measurable effects at 2.3 GHz were experienced. Figure 22 shows an example of S-band data (upper graph) along with the uhf beacon data for the same time period (lower graph). In the upper record, amplitude increases upward; in the lower record, it increases downward.

These S-band records were digitized at a rate of twice per second, and cumulative amplitude distributions were calculated for each 5-minute sample. The same analysis was made for corresponding time periods of the uhf beacon records. Figure 23 shows a comparison of these distributions for one of these 5-minute periods.

The amplitude difference between the 1- and 99-percent points was determined at each frequency for each of the 5-minute samples. These values are plotted in figure 24 as dB difference for S-band as a function of dB difference for uhf. Amplitude differences were also obtained for the 5- and 95-percent points and for the 10- and 90-percent points. A least-squares fit to a straight line was calculated for each of the three cases. These lines are shown in figure 25. The straight line for the 1-and-99-percent case is indicated in figure 24 as well. The data show a correlation with the straight

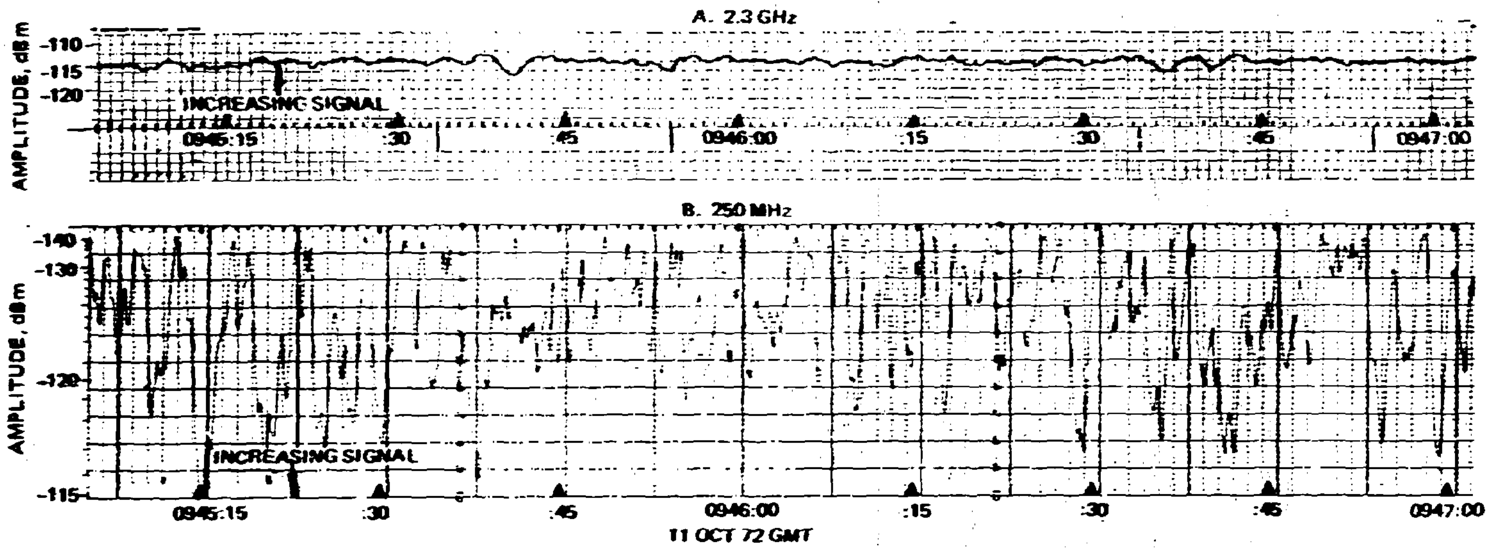


Figure 22. Example of equatorial scintillation of 250-MHz and 2.3-GHz signals from TACSAT I recorded on Guam.

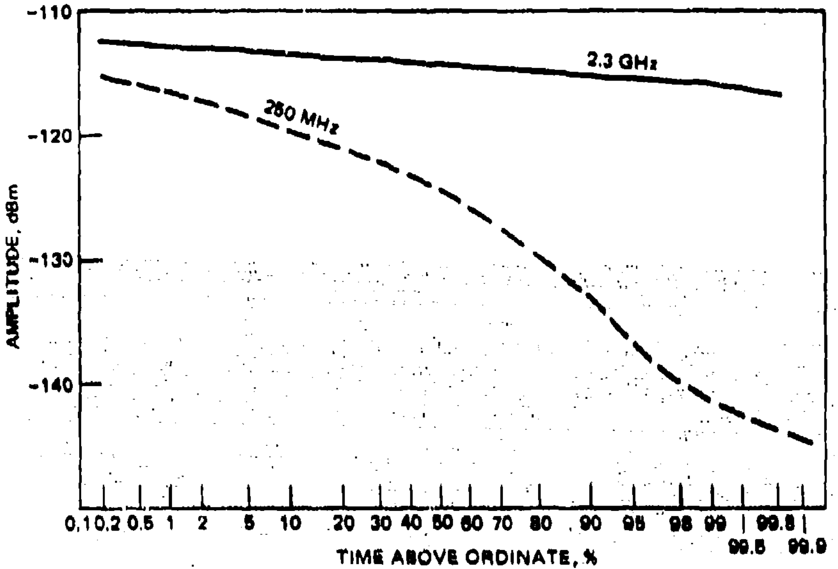


Figure 23. Comparison of cumulative amplitude distributions for TACSAT I uhf and S-band signals; Guam, 11 October 1972, 0945 to 0950 GMT.

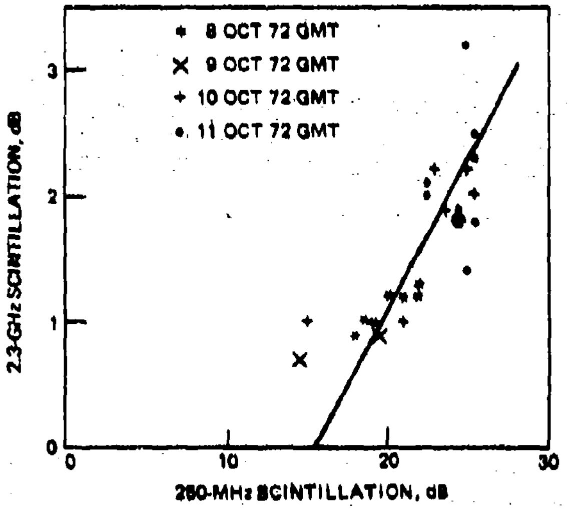


Figure 24. Variation between the 1- and 99-percent points on cumulative amplitude distributions at 2.3 GHz compared to those at 250 MHz. The line is a least-squares fit of the data to a straight line.

line of 0.6 for the 10-and-90-percent case, 0.7 for the 5-and-95-percent case, and 0.8 for the 1-and-99-percent case. (A correlation of 1.0 would mean that all the points fell on the given line in each case.)

The NASA Tracking Station on Guam has observed as much as 8-dB peak-to-peak S-band scintillation at times. If the straight-line dependence of

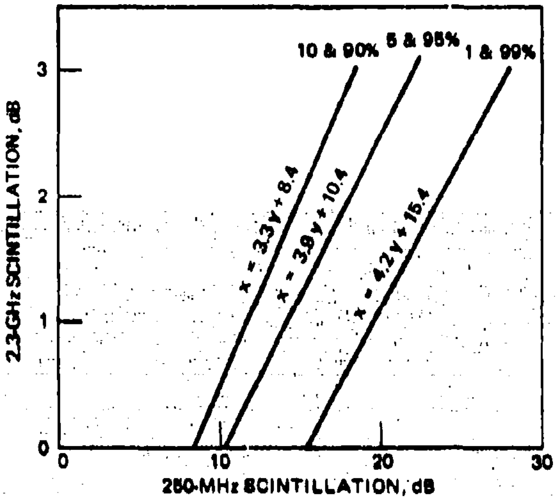


Figure 25. Comparison of least-square fits to a straight line for data similar to those shown in figure 25 except that the 10- and 90-percent points and the 5- and 95-percent points were used. The 1-and-99-percent line is indicated as well.

figure 24 is valid over this range, it suggests that as much as 50-dB peak-to-peak scintillation may be experienced at 250 MHz at certain times.

COMPARISON OF FADING SPECTRA

A frequency spectrum of the scintillation was calculated for each of the records giving the cumulative amplitude distributions in figure 23. Figure 26 is a comparison of these spectra. The scintillation at uhf, in addition to being much more intense than at S-band, appears to have many components at higher frequencies. A more extensive study of scintillation at the two frequencies would be necessary, however, before any conclusions could be made.

SIGNIFICANCE OF FREQUENCY-DEPENDENCE RESULTS

It is quite clear that space-to-earth channels (NAVSAT, TACSAT, etc.) operating in the lower uhf band will be substantially degraded by equatorial scintillation effects. The results above show that considerable improvement in channel reliability can be achieved by using higher carrier frequencies. When one considers other substantial improvements possible using higher frequencies, such as reduced rfi and radar interference and more optimum receiving conditions in the low-noise window above 1.0 GHz, it is evident that some consideration should be given to evaluation of this possibility for future space-to-earth systems.

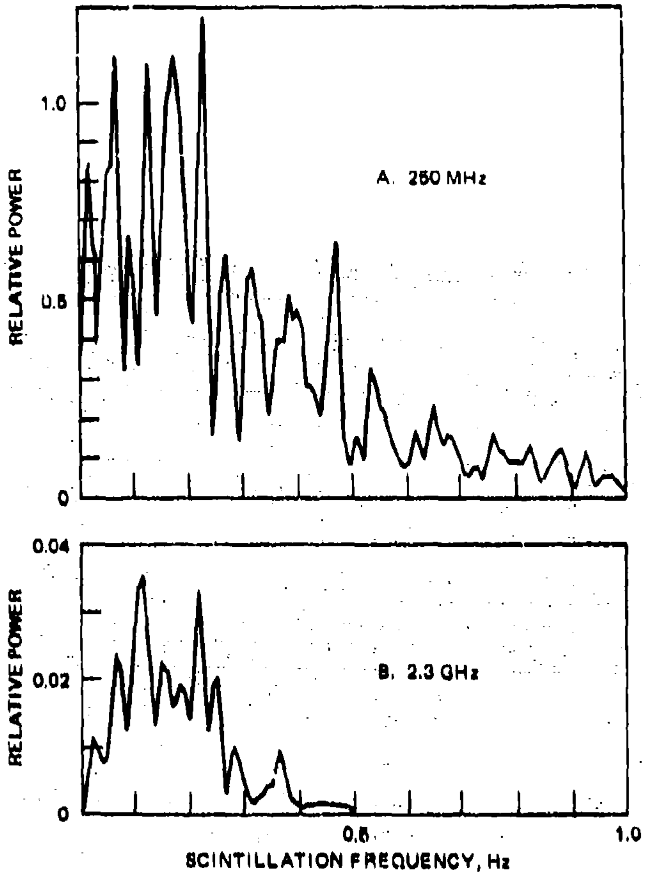


Figure 26. Comparison of Fourier spectra of scintillation of signals at 250 MHz and 2.3 GHz received at Guam for the same time period (0945 to 50 GMT, 11 October 1972).

SUMMARY

1. The uhf scintillation near 250 MHz was very intense, exceeding 25 dB peak-to-peak, and faded quite regularly into the system noise. This scintillation was predominantly a nighttime phenomenon, usually starting within an hour or two after ground sunset and often occurring until 1:00 or 2:00 in the morning local time. On one or two occasions, scintillation occurred until 4:00 or 5:00 in the morning.

2. Samples of scintillation data for three successive years suggest that the extent of occurrence of scintillation varies with solar activity.

3. Investigation of latitude dependence of scintillation showed the intensity of the scintillation to be comparable at all three sites when it occurred. The occurrence of scintillation, however, was comparable at the magnetic equator and 7½ degrees north, but was much less at the site 17½ degrees north of the magnetic equator.

4. Investigation of elevation-angle dependence showed the intensity of the scintillation to be comparable at all three elevation angles. The occurrence of scintillation, however, was slightly less at the 72-degree elevation angle than it was at the 30-degree angle. Because of the short time covered in these measurements, however, this difference may not be significant.

5. Limited tests of frequency diversity and space diversity suggest that frequency differences greater than 100 MHz would be necessary for frequency diversity to overcome the effects of scintillation and that, for space diversity to be effective, separation distances greater than the dimensions of a ship would probably be required.

6. Statistical evaluation of the scintillation records indicates that any system designed to overcome the effects of scintillation must be able to handle signal fadeouts with durations on the order of seconds.

7. No scintillation effects were observed at 7.3 GHz, but during some limited measurements peak-to-peak scintillations of 2 to 5 dB were observed at 2.3 GHz. The intensity of this scintillation was much less than that observed at 250 MHz during the same time period.

RECOMMENDATIONS

1. Measure the occurrence of equatorial scintillation over a period of a full year.

2. Study scintillation in conjunction with other geophysical measurements to try to establish a cause-effect relationship, the objective being the prediction of when scintillation might occur.

3. Evaluate scintillation at frequencies between 250 MHz and 2.3 GHz and determine the reliability improvement possible for SATCOM systems operating at the higher frequencies.

4. Investigate longitudinal variability of scintillation.

5. Make a more complete evaluation of space diversity to determine optimum spacing required.

6. Make a more complete evaluation of frequency diversity to determine what frequency difference would be necessary to overcome the effects of scintillation.

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APPENDIX A: THREE-SPACED-RECEIVER MEASUREMENTS

INTRODUCTION

The irregularities in the electron density of the equatorial ionosphere at night (see above) produce a diffraction pattern at the ground when radio signals pass through the ionosphere. When this pattern changes with time or has a coherent drift, such as that for a wind, scintillation occurs.

The usual method used to study such a diffraction pattern is to set up three receivers in a triangle and record signals from a common radio source above the ionosphere. The fading records at the three sites are then compared.

This appendix covers a brief study made on Guam during October 1971 using uhf signals from the TACSAT 1 beacon and this three-spaced-receiver technique. The study was part of a larger project to study scintillation of satellite signals in the equatorial region.

THEORY OF TRIANGLE MEASUREMENTS

If an unchanging diffraction pattern moves with a velocity, V, the fading records for two receivers separated in the direction of movement would be identical, but there would be a time lag between them. V could be determined from the distance of separation and the time lag. When the receivers are separated in a direction perpendicular to V, there is no time lag between the records. With small separation distances, the records are similar, but as the distance is increased they become progressively less similar until at some separation there no longer is any recognizable similarity. The separation necessary for this condition is dependent on the transverse size of the structure in the diffraction pattern.

In practice, a triangle of receivers can have any orientation. The time delays between pairs of records can be found by shifting the two records in time to achieve the best fit and measuring the time offset or, as is more commonly done, by performing a cross correlation between the two records and getting the time delay for maximum correlation. The delay times between pairs of records along with the separation of recording sites can be used to get a phase velocity along each side of the triangle. These three phase velocities can then be used in pairs to get three values for the velocity of movement of the diffraction pattern. Ideally, the three values should be the same.

When the diffraction pattern changes with time as it drifts, the preceding method no longer gives the true velocity of drift. Briggs, Phillips, and Shinn[9] have shown that the velocities measured along the sides of the triangle are higher than they would be for an unchanging diffraction pattern moving at the same speed. They define a term which has the dimensions of a velocity, which they call the characteristic velocity, V_c. This characteristic velocity gives a quantitative measure of the random changes taking place. The relationship between this characteristic velocity and the velocity along any side of the receiver triangle is shown to be

$$VV' = V_c^2 + V^2 \qquad (A1)$$

Where V' is the "apparent velocity" along any side of the triangle, and is just the receiver separation divided by the delay time. (For a constant diffraction pattern, $V_c = 0$ and $V' = V$, and the problem reduces to the simple case discussed in the preceding paragraph.)

To determine the true drift velocity of the diffraction pattern, it is necessary to calculate V for each side of the triangle. While V' is readily obtained from the cross correlations of the fading records and the spacing of the receivers, it is necessary to know V_c in order to get V. Kent and Koster[10] have shown a method for getting the approximate ratio V/V_c using the cross correlation between two records and the mean autocorrelation for the two records. They show that if these two curves have an appearance such as that in figure A1, then

$$V/V_c = PR/QR \qquad (A2)$$

gives a minimum estimate of the true value of V/V_c.

If we let $PR/QR = a$, solve for V_c, and substitute this into equation A1, we get

$$V = (a^2/(1+a^2))\, V' \qquad (A3)$$

or

$$V = kV' \qquad (A4)$$

It is seen that as PR/QR gets large the constant approaches unity and V' approaches V.

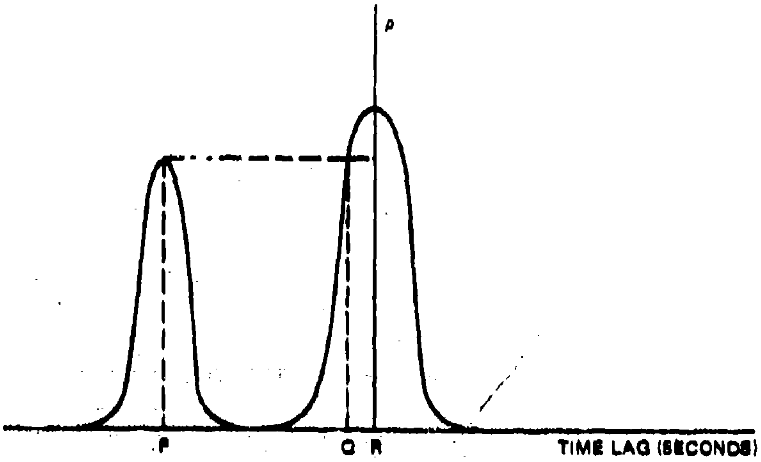


Figure A1. Approximate method of getting V/V_c using cross correlation and autocorrelation.

Another way of analyzing spaced-receiver fading data is a cross-spectrum technique.[11] In this method, Fourier transformations are made of the cross covariances between pairs of records for the receiver triangle. If the cross-covariance function is asymmetrical, both even and odd terms will be present and the cross spectrum will be complex. The co-spectrum, or real part, corresponds to the in-phase components, and the quad-spectrum, or imaginary part, corresponds to the components which are out of phase.

The co-spectrum and quad-spectrum components can be used to find an apparent velocity, similar to V′ in the cross-correlation method, along each side of the receiver triangle for each frequency in the fading spectrum. These velocities can then be used to get a speed and direction of movement for each frequency in the fading spectrum. In regions of the fading spectrum where there is no energy, the velocities calculated would not be significant. A calculation of coherence between records should show this, since coherence would be low for that portion of the spectrum. For a detailed discussion of this technique, see Gossard et al.[11]

MEASUREMENT TECHNIQUE

Three receivers were set up at the Naval Communications Station on Guam in a triangle with the dimensions and orientation shown in figure A2.

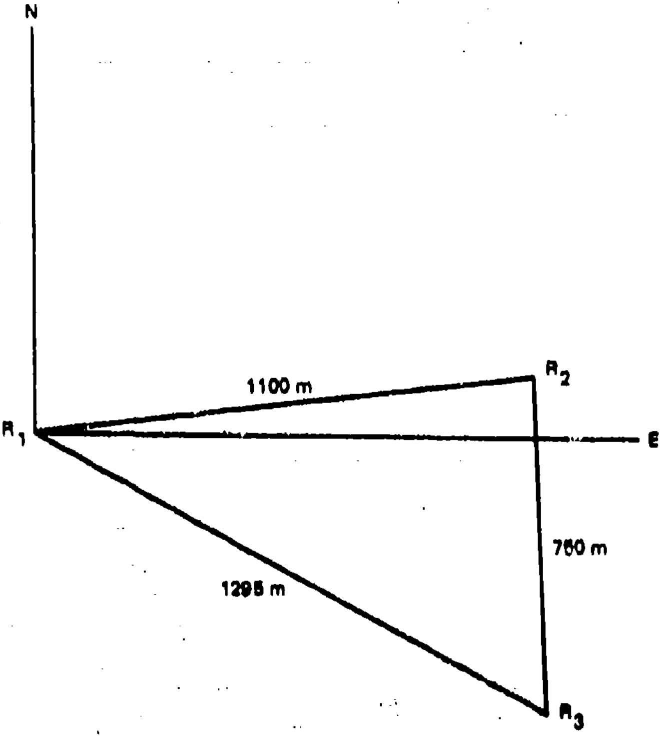


Figure A2. Dimensions and orientation of receiver triangle used at Naval Communications Station, Guam.

Signals from the TACSAT I uhf beacon were recorded with a linear output on strip charts and on magnetic tape. WWV was used to put accurate time marks on the records at all three sites.

This system was operated at night from 27 October through 31 October 1971 GMT. During this time, fading was observed only on the night of 28 October.

DATA ANALYSIS

Only the strip charts were used in this analysis. The amplitude on each chart was read at 1-second intervals and punched on IBM cards for all the time when fading was occurring. The data were then processed for 5-minute sample periods using a combined cross-correlation- and cross-spectrum-analysis computer program that has been used successfully at NELC for a number of years to study movement in the D region of the ionosphere.

In the cross-correlation analysis, equation (A4) was used to get V in each case before determining the drift velocity. In all cases, however, k was so close to unity that it caused very little change in the velocity. The speed and direction of these velocities are plotted as a function of GMT time in Figure A3. Local time was GMT + 10.

The computer also calculates and plots the power spectrum of the fading and determines a speed and direction of drift for each line in the power spectrum. This is done for combinations of velocities along the sides of the triangle taken two at a time, resulting in three determinations for each velocity.

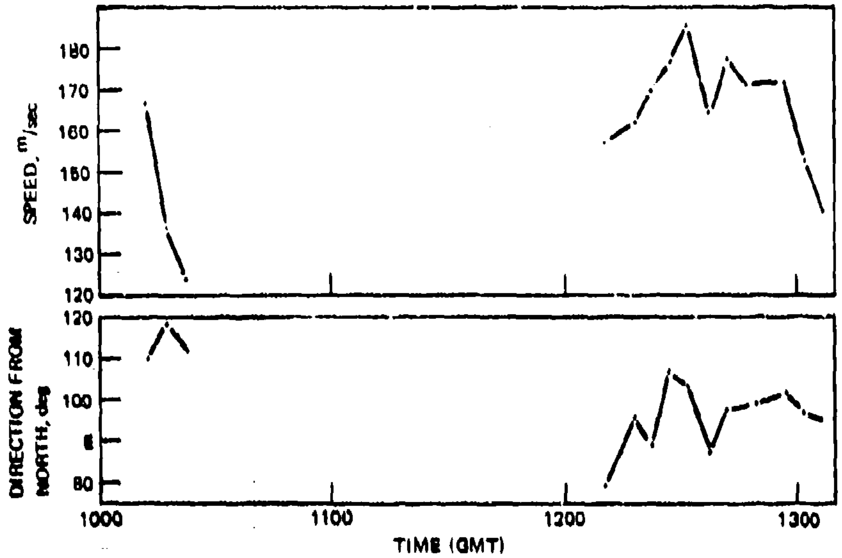


Figure A3. Speed and direction of movement of diffraction pattern for night of 28 October 1971 GMT at Guam.

Plots of power spectra and speed and direction of movement for each line in the spectrum are shown for each 5-minute sample in figure A4. As already mentioned, there are three velocity calculations for each line. The amount of spread in these three points gives some idea of the accuracy and/or significance of the value.

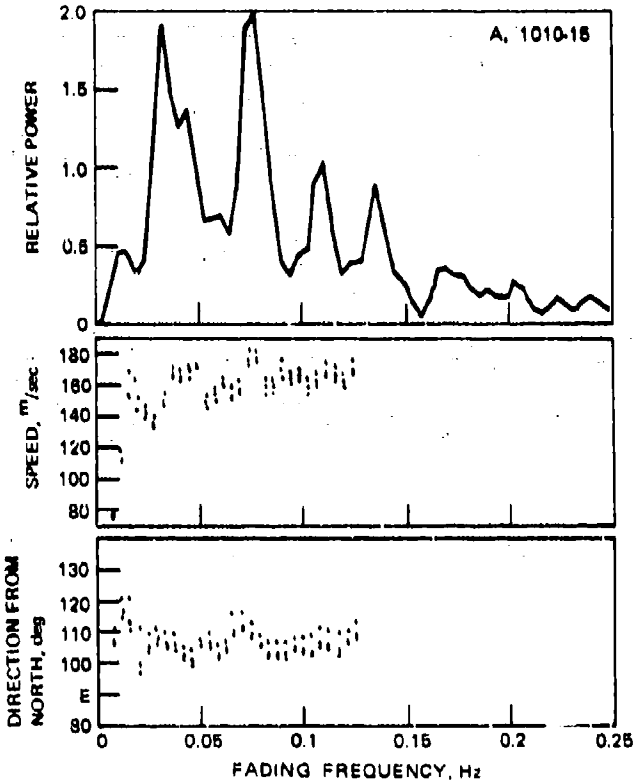
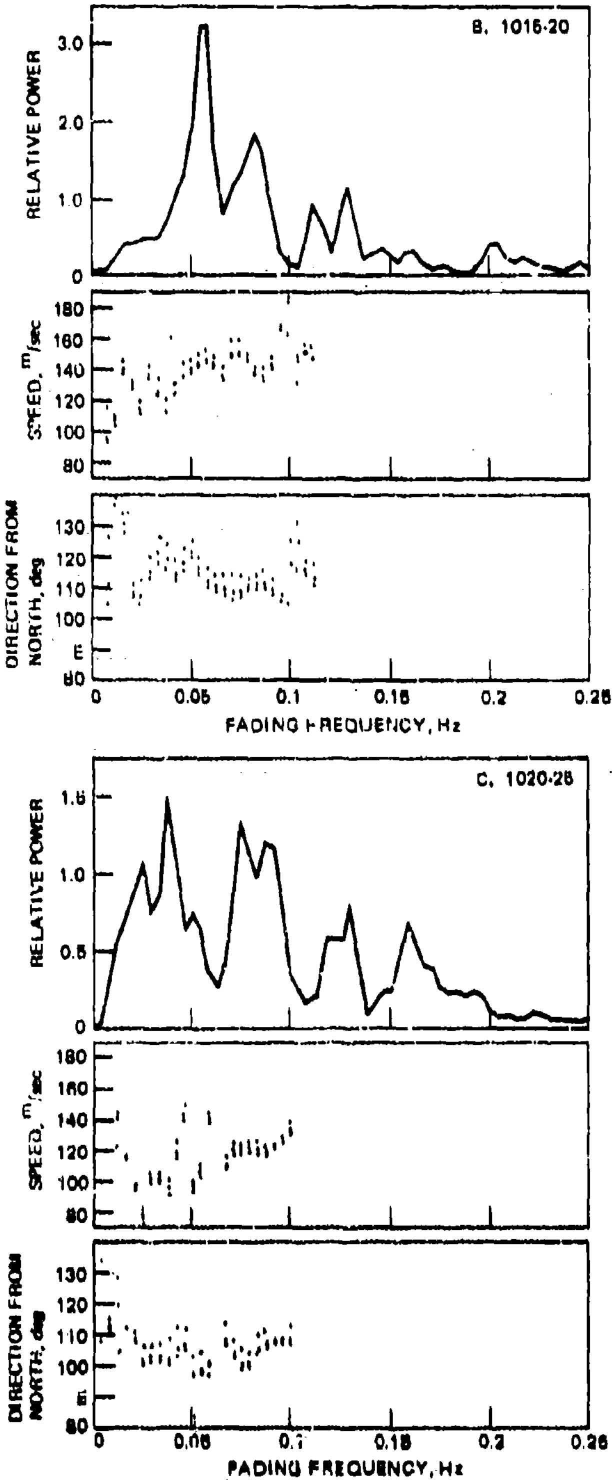


Figure A4. Drift velocity as a function of fading frequency; TACSAT uhf beacon, Guam, 28 October 1971 GMT.



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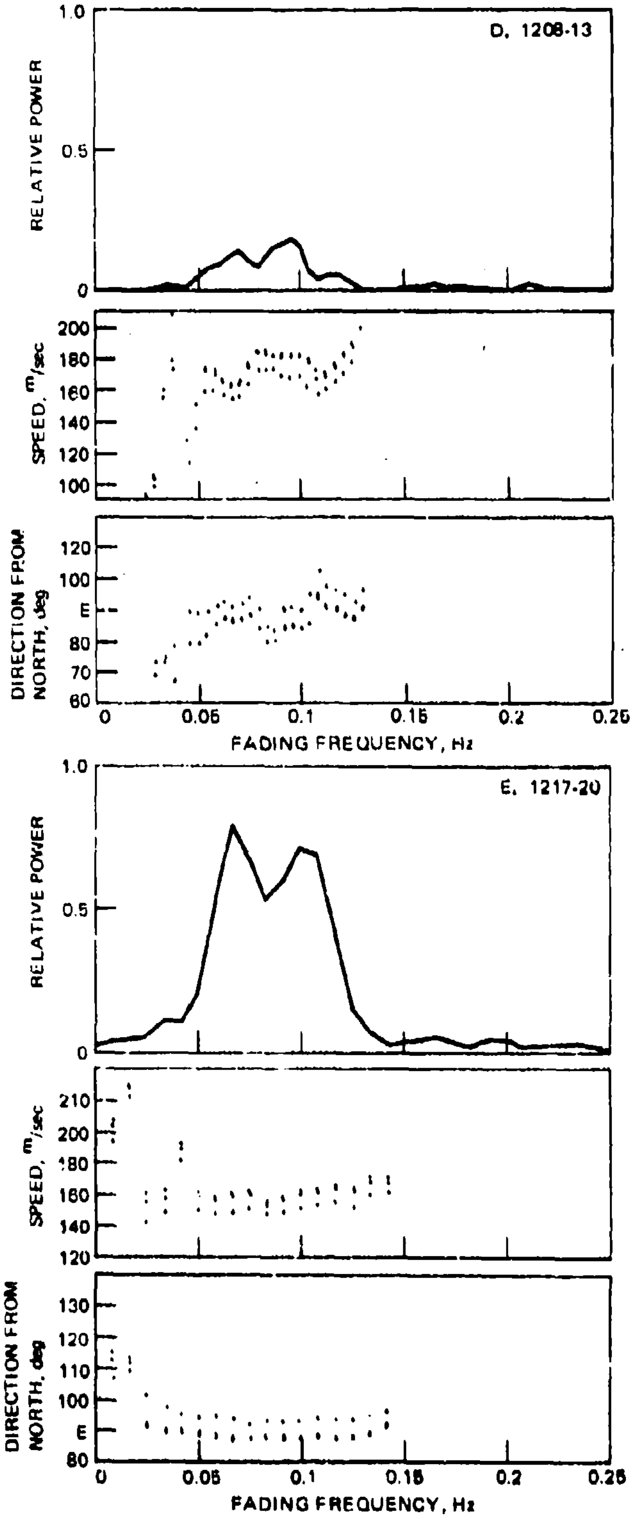

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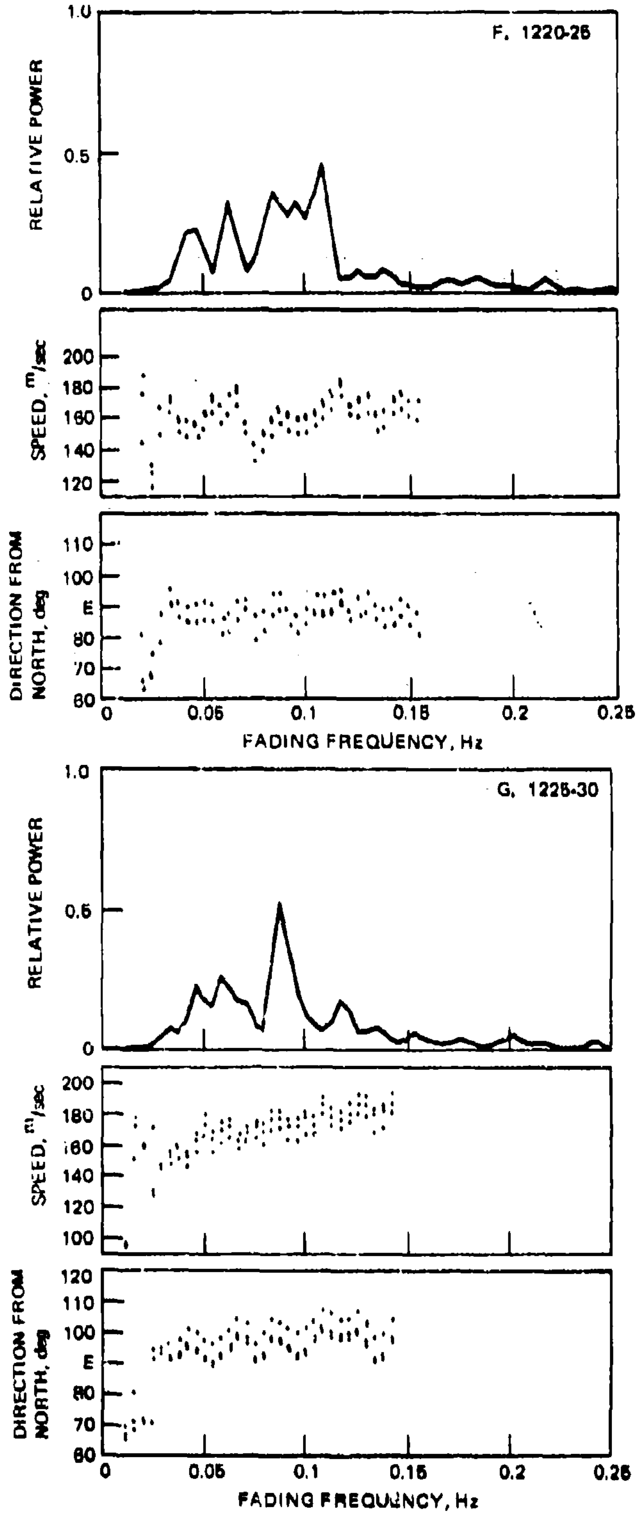

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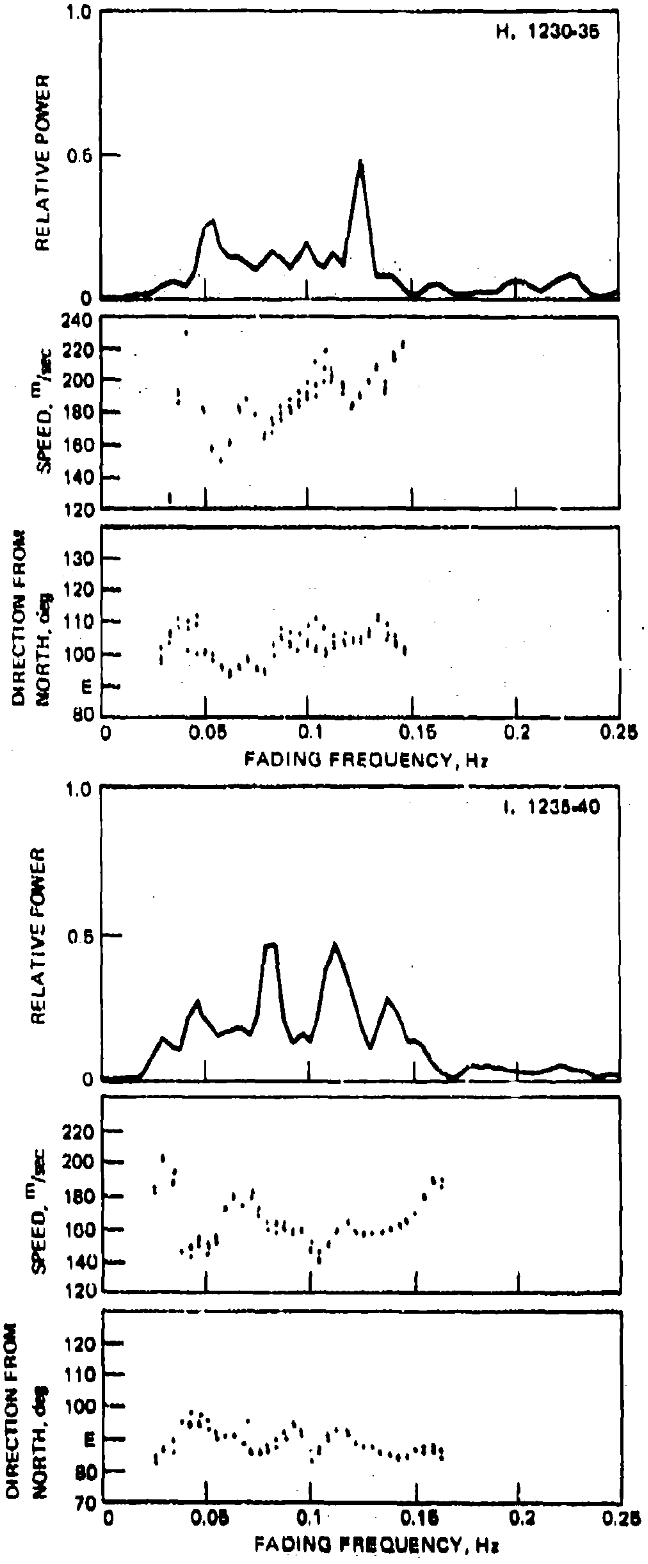

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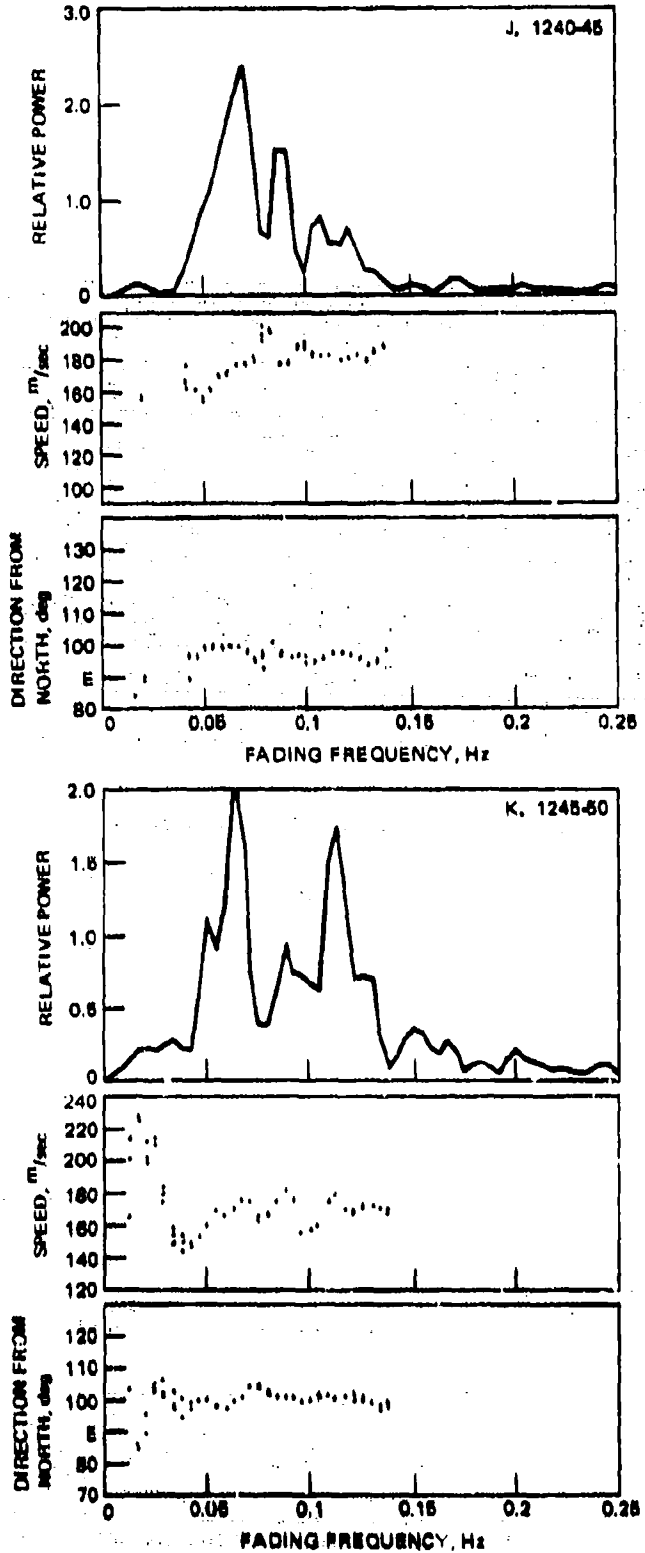

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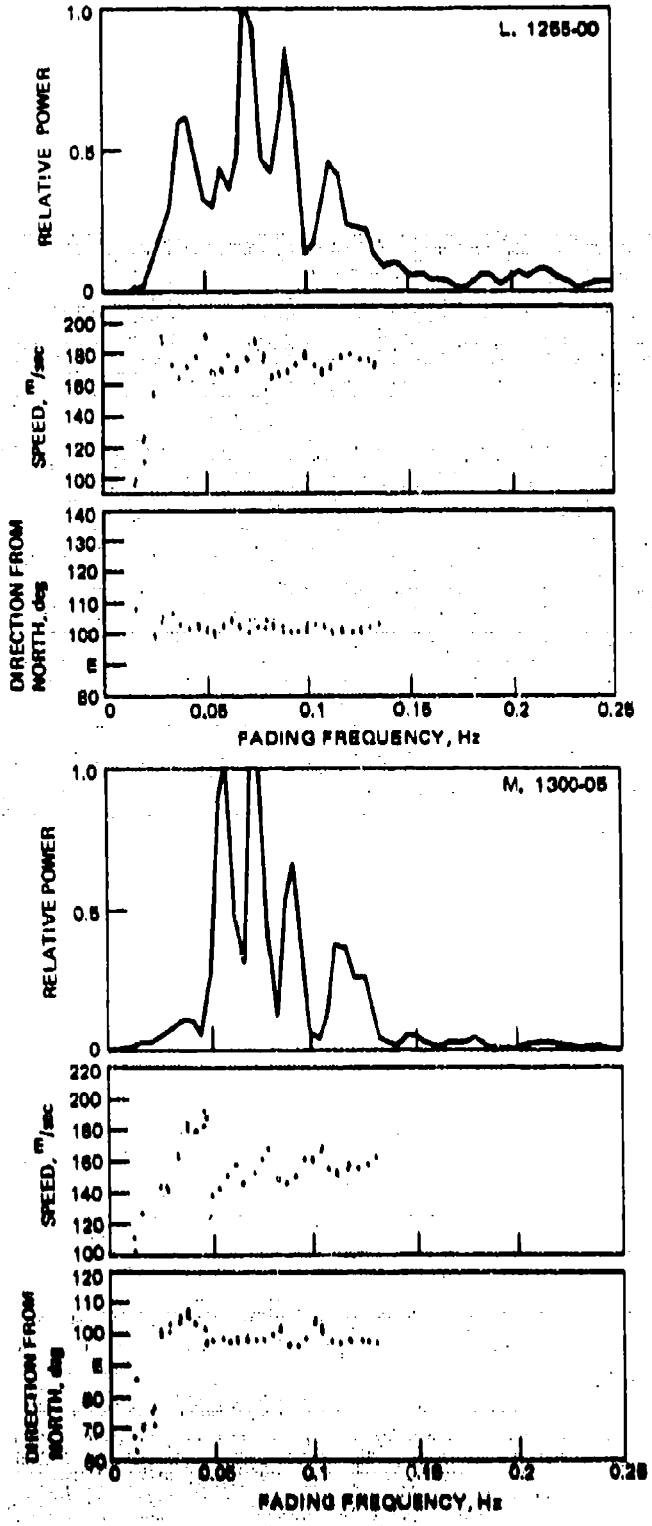

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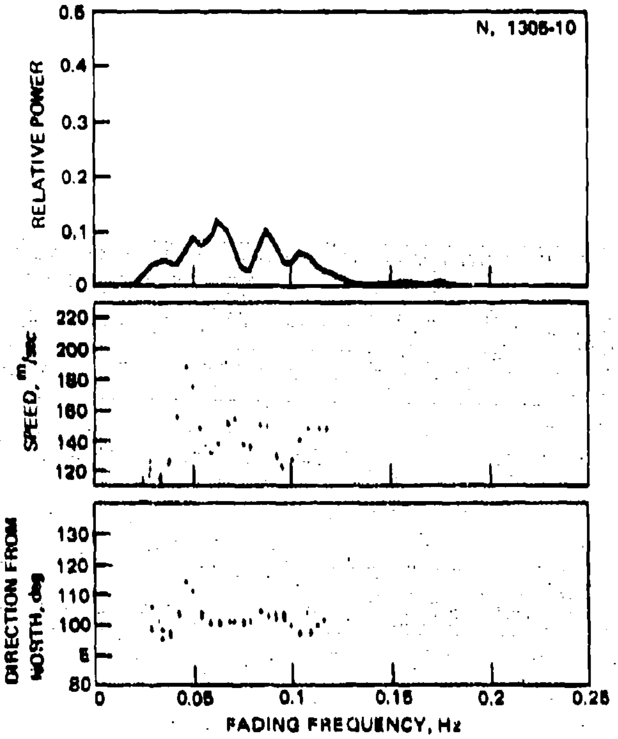

Figure A4. (Continued)

SUMMARY

The cross-correlation method of analyzing the spaced-receiver data indicates that the observed fading of the signal was primarily caused by movement of the diffraction pattern rather than time changes of its structure. The speed and direction of movement changed somewhat from one 5-minute sample to the next. In the two occurrences of fading, the speed decreased as the fading died out.

The cross-spectrum-analysis results show good agreement with the cross-correlation results. In general, all frequencies in the fading spectrum appear to move in the same direction with about the same speed. While this is true for the data presented here, it is possible that, at times, different fading frequencies might move in different directions or with different speeds. If this occurred, this analysis technique should show it.

The results of both types of analysis showed a drift velocity which varied from about 130 to 180 meters per second in a direction which was east or slightly south of east.

The object of this brief study was to get a measure of the drift or changes in the diffraction pattern which cause scintillation and to get background information which would be useful for planning future fundamental studies of the phenomena.

APPENDIX B: REFERENCES

1. Kent, G. S., and J. R. Koster, "Some Studies of Night-time F-Layer Irregularities at the Equator Using Very High Frequency Signals Radiated from Earth Satellites," *Annales de Geophysique*, v. 22, no. 3, p. 405-17, 1966.
2. Koster, J. R., "Ionospheric Studies Using the Tracking Beacon on the 'Early Bird' Synchronous Satellite," *Annales de Geophysique*, v. 22, no. 3, p. 435-39, 1966.
3. Aarons, J., H. E. Whitney, and R. S. Allen, "Global Morphology of Ionospheric Scintillations," *Proceedings of the IEEE*, v. 59, no. 2, p. 159-72, 1971.
4. Aarons, J., "Geophysical Aspects of Radio Star and Satellite Ionosphere Scintillations," p. 247-66 in North Atlantic Treaty Organization AGARDograph 95, *Spread-F and Its Effects upon Radiowave Propagation and Communication*, P. Newman, ed., 1966.
5. Golden, T. S., *A Note on Equatorial Ionospheric Scintillation at 136 MHz and 1550 MHz*, GFSC Report X-520-70-397, October 1970.
6. Craft, H. D., Jr., and L. H. Westerlund, *Scintillation at 4 and 6 GHz Caused by the Ionosphere*, paper presented at AIAA 10th Aerospace Sciences Meeting, San Diego, California, 17-19 January, 1972.
7. Naval Electronics Laboratory Center Technical Note 1837, *An Investigation of Equatorial Fading of TACSAT I UHF Signals*, by M. R. Paulson and J. C. Tyner, 14 April 1971.*
8. Naval Electronics Laboratory Center Technical Note 2032, *Scintillation of TACSAT I UHF Signals: A Study of the Latitude and the Elevation Angle Dependence of Equatorial Fading*, by M. R. Paulson and R. U. F. Hopkins, 22 May 1972.*
9. Briggs, B. H., and others, "The Analysis of Observations on Spaced Receivers of the Fading of Radio Signals," *Physical Society of London Proceedings*, v. 63, p. 106-121, February 1950.
10. Kent, G. S., and Koster, J. R., "Some Studies of Night-time F-layer Irregularities at the Equator Using Very High Frequency Signals Radiated from Earth Satellites", p. 333-356 in North Atlantic Treaty Organization AGARDograph 95, *Spread-F and Its Effects upon Radiowave Propagation and Communication*, P. Newman, ed., 1966.
11. Naval Electronics Laboratory Center Technical Document 136, *Guide to Computation and Use of Cross Spectra in Geophysics and Radio Physics*, by E. E. Gossard and others, 22 July 1971.

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13. ABSTRACT

Field investigations and analyses are conducted to define the characteristics of equatorial scintillation fading and its effects on satellite communications (SATCOM) systems. A data base for use in evaluating optimum SATCOM techniques is generated.

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