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OVER-WATER TROPOSPHERIC SCATTER PROPAGATION INVESTIGATIONS UNDER WINTER CONDITIONS

[CONFIDENTIAL TITLE]

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NAVAL RESEARCH LABORATORY
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ABSTRACT
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During February 1956, studies of tropospheric scatter propagation and multipath effects over an all-seawater path were conducted to supplement information obtained in previous experiments and to provide a comparison with the results of investigations conducted during the preceding summer. The receiving installation, consisting of a 17-foot paraboloid antenna and highly sensitive receiving and signal-level recording equipment, was aboard the USS THUBAN (AKA-19). The test transmissions for the propagation studies covering three weeks originated at the Lincoln Laboratory Round Hill field station on the southern coast of Massachusetts. The transmissions consisted of a continuous carrier on 412.85 Mc from either of two transmitting facilities; a 10-kw transmitter feeding a 28-foot paraboloid antenna, or a 40-kw transmitter feeding a 60-foot paraboloid antenna. The transmitting systems had an effective radiated power of 8 megawatts and 100 megawatts respectively.

For what appeared to be pure scatter conditions, the median basic transmission loss (path loss) averaged about 202 db at 200 nautical miles with a loss rate of 0.18 db per nautical mile. The higher power transmissions were detectable out to a distance of 630 nautical miles. A comparison of these winter results with those obtained from a similar investigation in July 1955 shows the same loss rate but the mean scatter signal level was about 8 db higher for the summer results. The short-time probability distribution of the scatter signals followed the Rayleigh law. Periodic transmissions with voice and music modulation were received with excellent quality out to distances of about 300 miles for the lower power transmissions. The higher power transmissions increased the range by about 100 miles. At greater distances, short-period outages occurred during deep fades in the signal.

PROBLEM STATUS

This is a final report on one phase of this problem. Work is continuing on other phases.

AUTHORIZATION

NRL Problem R01-18
Project NR 414-001

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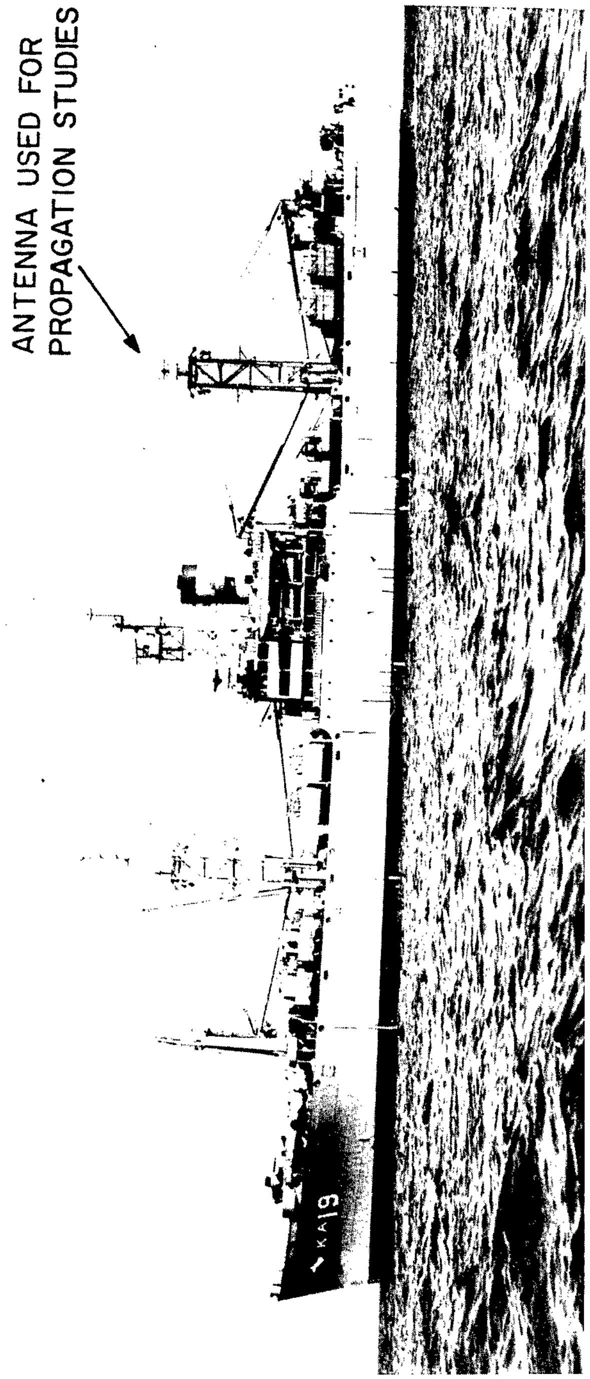

USS THUBAN (AKA-19) as equipped for propagation studies

OVER-WATER TROPOSPHERIC SCATTER PROPAGATION INVESTIGATIONS UNDER WINTER CONDITIONS
[Confidential Title]

INTRODUCTION

A considerable amount of literature has been published on the successful use of vhf-uhf tropospheric scatter transmissions between fixed points with over-land or mixed over-land and over-water paths. The Navy is interested in investigating this mode of propagation to determine its usefulness for communication and data transmission between naval vessels in a task force. Such an application would generally involve all over-water propagation paths and path lengths that would be variable out to ranges of 150 or 200 nautical miles.* Since very little scientific and engineering information was available for such an application, the Naval Research Laboratory, as a follow up to earlier work, set up this project in 1953 to study tropospheric scatter-mode propagation for Naval purposes.

The Laboratory made some preliminary investigations (1) in the Chesapeake Bay area using frequencies of about 200 Mc. More extensive experiments were then planned to utilize a transmitting site located near the shore of the Atlantic Ocean and a receiving site aboard a naval vessel. Such an arrangement would afford the convenience of a land-based transmitting site so that a high-powered transmitter and large transmitting antenna could be employed and still have the desired all over-water path with a mobile receiving installation.

The Lincoln Laboratory and the Air Force Cambridge Research Center, both of which had suitable transmitting facilities on the coast of Massachusetts located near Round Hill and Scituate, respectively, agreed to cooperate with NRL in the project. In July 1955 propagation data were obtained using these transmitting facilities and the USS ACHERNAR (AKA-53) as the receiving site. The transmissions used consisted of an unmodulated carrier on 385.5 Mc from Round Hill and a pulse-modulated signal on 220 Mc from Scituate. The path lengths varied from a few miles to approximately 425 miles. The results of that phase of the investigation have been reported (2).

The results of the July 1955 investigation were very encouraging; therefore, to obtain information as to the seasonal effect on this mode of propagation, it was decided to repeat part of those experiments during a winter month. For three weeks during February 1956 experiments similar to those of July 1955 were conducted using the Round Hill transmitting facility and the USS THUBAN (AKA-19) as the receiving site (Fig. 1). The transmissions consisted of an unmodulated carrier on 412.85 Mc.

SHIPBOARD INSTALLATION

The USS THUBAN was specially outfitted with a high-gain antenna and the necessary receiving and signal-level recording equipment. The antenna, a modified Model SK-3 radar antenna with its accompanying pedestal mount and controls, was mounted on the after quadrapost (Figs. 1 and 2) which was the highest point on the ship capable of supporting the unit. This location placed the center of the antenna 92 feet above the water. In the

*Nautical miles will be used throughout this report.

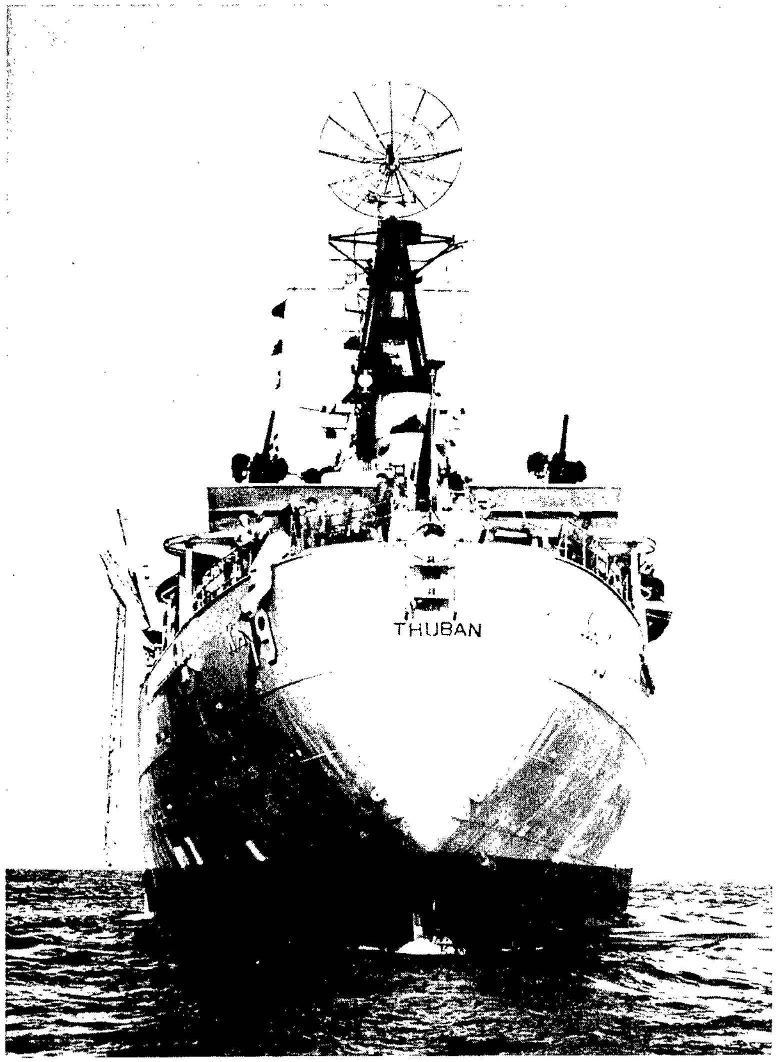

Fig. 2 - Stern view of USS THUBAN showing 17-foot paraboloid antenna used for propagation studies

horizontal plane the antenna beam was unobstructed by the ship's superstructure except when directed within a small sector (about 10 degrees) over the bow. For almost the entire time that the Round Hill transmissions were being recorded, the ship was so oriented with respect to the transmitting site that the antenna was directed either over the bow or over the stern. When directed over the bow, the received signal level was affected by the obstruction of the ship's superstructure, and this effect was taken into account in determining the true signal level. This effect will be discussed later in the report. The antenna, having a gain of 21 db referred to a half-wave dipole or about 23 db over an isotropic antenna, was coupled to the receiving equipment through 177 feet of 1-5/8-inch Styreflex transmission line. The system parameters are given in Table 1.

TABLE 1
System Parameters

Transmission Frequency		412.85 Mc
USS THUBAN (Receiving Facilities)		
Antenna Gain*		23 db
Antenna Height Above Sea Level		92 ft
Transmission Line Loss	approx.	1 db
ROUND HILL (Transmitting Facilities)		
28-ft Antenna		
Antenna Gain*		29 db
Antenna Height Above Sea Level		95 ft
Transmitter Power		10 kw
Transmission Line Loss		negligible
Effective Radiated Power		8 Mw
60-ft Antenna		
Antenna Gain*		35 db
Antenna Height Above Sea Level		113 ft
Transmitter Power		40 kw
Transmission Line Loss		1 db
Effective Radiated Power		100 Mw

*Gain over an isotropic antenna

The receiving equipment consisted of step attenuators, a receiver with very high sensitivity, dc amplifiers, various signal-level recording instruments, and a crystal-controlled signal generator for calibrating the system. The receiver consisted of an r-f amplifier, crystal-controlled local oscillator, mixer, and i-f preamplifier (30 Mc) which was coupled to an Army Signal Corps receiver R-390/URR. The bandwidth of the R-390/URR receiver, which controlled the overall bandwidth of the system, could be varied in discrete steps but most of the time was set at 1 kc.

The output of the receiver was fed through dc amplifiers to several signal-level recording instruments. The signal level was continuously recorded on two Esterline-Angus strip recorders: one operating with a chart speed of three-quarters of an inch per minute, and the other at three inches per hour. The slower chart recorder, the circuit of which had a time constant of approximately 12 seconds, was primarily used for a continuous recording of the median level. The circuitry of the faster chart recorder had a very short time constant so that the fading characteristics of the received signal were reasonably well reproduced, and these charts were used to categorize the signals as to their fading characteristics. Periodically the signal level was recorded on an additional strip recorder. This was a high-speed Edin recorder which along with its circuitry was capable of accurately recording signal levels with fading rates in excess of 60 per second. The probability distributions of the signal levels were determined by recording the total time that various predetermined signal levels were exceeded. This was done by the use of a ten-channel level distribution recorder (LDR) previously called a signal level time totalizer (2) which was normally operated for sampling periods of 50 minutes. The receiving and signal-level recording setup as used for this investigation had a sensitivity such that an input of -138 dbm (db above one milliwatt) was detectable on the strip charts. This input (-138 dbm) is equivalent to 0.028 microvolt across the 50-ohm input of the receiver. Except for the LDR (Fig. 3), the receiving and signal-level recording equipment (Fig. 4) was furnished by Lincoln Laboratory.

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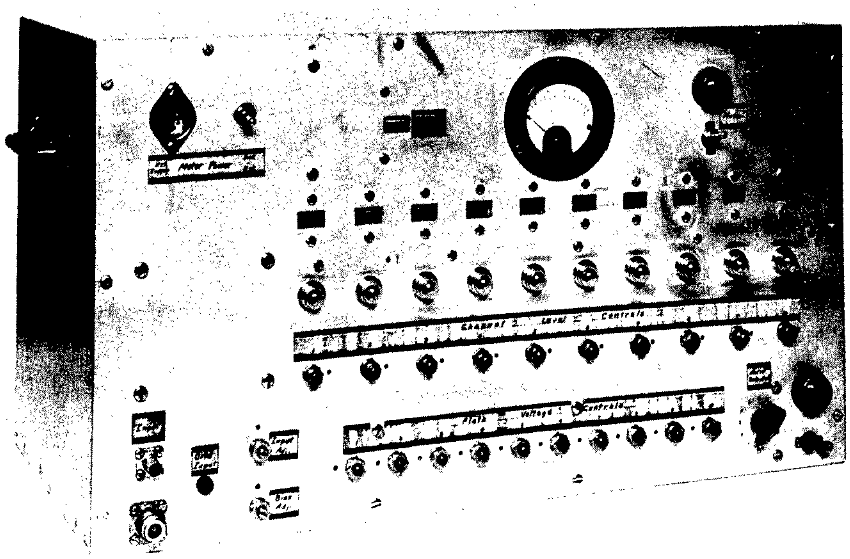


Fig. 3 - Level distribution recorder

The receiving equipment also included an FM demodulator which was periodically connected to the i-f output of the R-390/URR receiver, using the 16-kc bandwidth setting, to receive FM voice and music test transmissions. These transmissions, consisting of two minutes of a prerecorded voice and music magnetic tape test sample repeated every four hours, were tape recorded aboard the ship to demonstrate the communication quality of the transmissions at various distances.

TRANSMITTING FACILITIES

The transmitting facilities were located at the Lincoln Laboratory field station at Round Hill, on the southern coast of Massachusetts. During this investigation two transmitting systems (Table 1) were used; however, all transmissions were on a frequency of 412.85 Mc and were horizontally polarized. One system consisted of a 10-kw transmitter

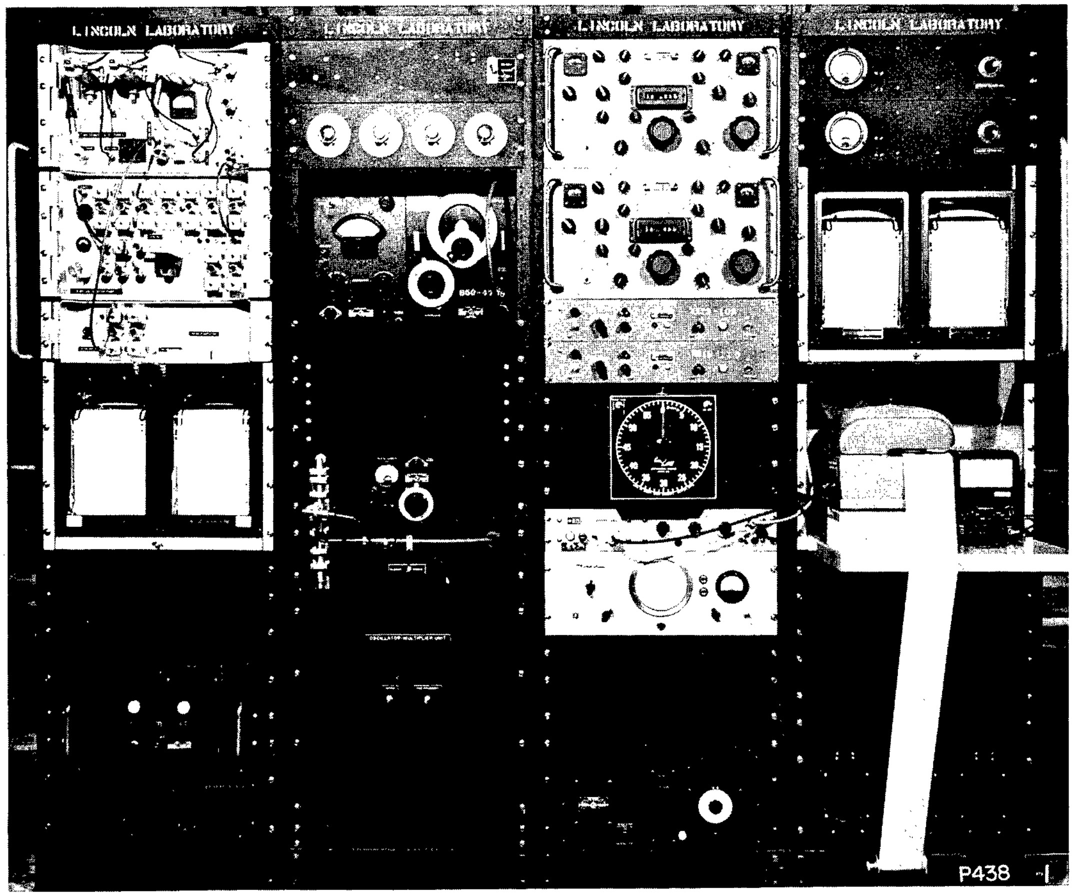


Fig. 4 - Signal level measuring and recording equipment installed aboard the USS THUBAN

feeding a 28-foot paraboloid antenna with a gain of 29 db over an isotropic antenna and a height of 95 feet above sea level. The other system was a 40-kw transmitter feeding a 60-foot paraboloid antenna with 35 db gain and a height of 113 feet above sea level. Both antennas as directed for this investigation had an unobstructed path to the horizon.

OPERATIONAL PROCEDURE

The USS THUBAN left Norfolk, Virginia, on the morning of 30 January 1956 and headed easterly to a point approximately 200 miles and at a bearing of 184 degrees true from Round Hill. The ship then headed toward Round Hill and the recording of the signal level of the transmissions from the 10-kw transmitter and 28-foot antenna was started. When the ship was approximately 15 miles from the transmitting site, the horizontal pattern of the receiving antenna and the effect of the ship's superstructure on the received signal level were determined. The ship then proceeded to a point 30 miles and on a bearing of 148 degrees true from Round Hill. The transmitting antenna was redirected to a bearing of 148 degrees true. The ship then headed away from the transmitting site on a great-circle course with this bearing from Round Hill. The signal levels of the transmissions were recorded on the ship while making several runs out and back on this bearing. One run was out to a distance of 660 nautical miles (760 statute miles); however, the signal became undetectable at approximately 630 miles. For the distances beyond about 350 miles, the 40-kw transmitter and 60-foot antenna were used. The ship then returned to Norfolk at the end of the second week via the 184-degree true bearing from Round Hill used previously. During the following week the ship was engaged in another operation. During the fourth week the signal levels of the transmission from the 40-kw transmitter and 60-foot antenna were recorded while the ship made several runs on a great-circle bearing of 209 degrees true from Round Hill and at distances between 250 and 600 miles (Fig. 5). Operational data pertaining to the Round Hill transmissions are given in Table 2.

ANALYSIS OF RESULTS

The Esterline-Angus chart recorders, each with a different chart speed (3 inches per hour and three-quarters inch per minute), were operated continuously during the three weeks of this investigation. The level distribution recorder (LDR) was operated almost all of the time during the first two weeks but not during the last week. The Edin recorder was operated intermittently to determine fading rate and magnitude.

The LDR was operated generally for 50-minute sampling periods — from thirty minutes before the hour until twenty minutes past the hour. The remaining ten minutes were used for recalibrating and adjusting the equipment and for periodically tape-recording the voice and music modulation tests. In analyzing the results the median signal level was generally taken from the LDR data. This value was checked against the slow Esterline-Angus chart recordings, and for periods when the LDR was not operating, the median levels were determined directly from those charts. The medians were usually recorded for periods of 50 minutes to an hour except when there was a significant change in level, and then shorter periods were used. The LDR data were also used to plot the probability distributions of the signal level.

One of the objects of this investigation was to determine the attenuation of the tropospheric scatter propagated signal with distance. It is well established that signals on frequencies in the range of that used in this study are often propagated for very great distances by ducting. If signal-level data of waves so propagated were averaged in with scatter propagation data, the result would be very optimistic, particularly for comparatively short-time investigations such as this. Accurate separation of the true scatter propagated signals from those enhanced by ducting is practically impossible. The fading characteristic, however, appears to be indicative of the propagation conditions existing over the path. The scatter propagated signals are associated with rapid fading usually with total excursions of 10 or more db. It is not to be inferred, however, that every fade is of this magnitude. Signals propagated by ducting conditions are relatively steady with possibly an occasional slow, deep fade. The signal-level data were therefore categorized according to type of fading of the received signal during the particular period. The fading characteristic data were obtained from the faster Esterline-Angus charts (three-quarters inch per minute).

RESULTS

Fading Characteristics

The fading characteristics of the received signal have been divided into three groups: fast fading, slow fading, and relatively steady. This grouping is arbitrary and the recordings often showed characteristics intermediate to the three types, but for simplicity in

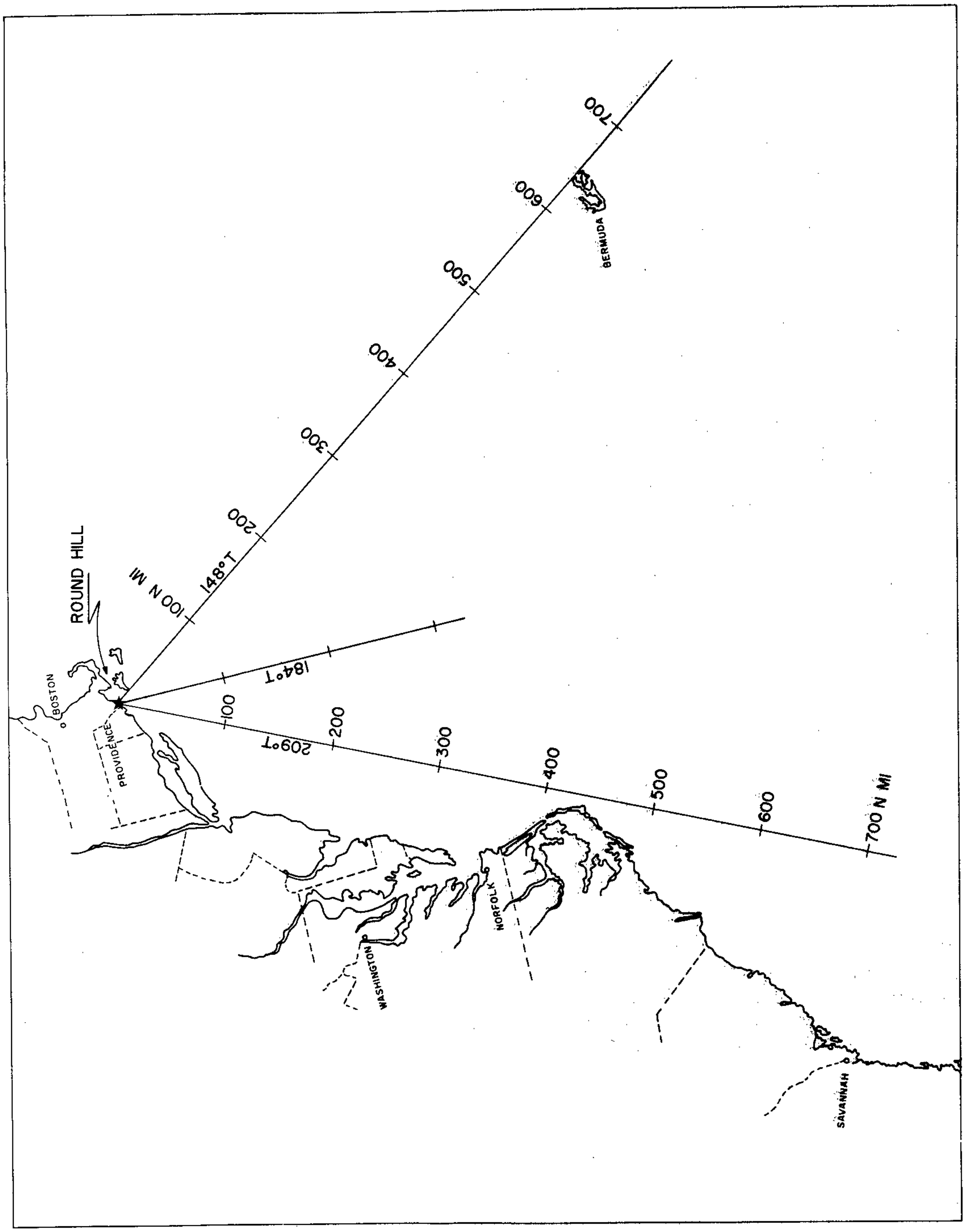


Fig. 5 - Transmission paths

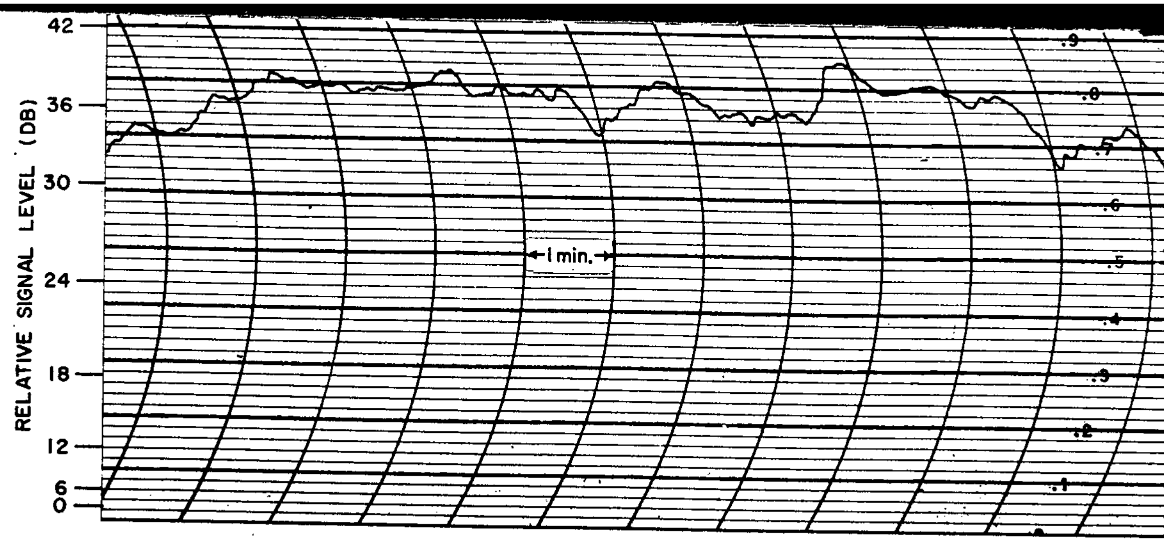
TABLE 2
Operational Data

Date/Time (Feb/GMT)		Distance (nautical miles)		Bearing from Round Hill (degrees true)	Transmitting System	
From	To	From	To		Power (kw)	Antenna Diameter (ft)
31*/1400	01/1100	197	25	184	10	28
01/1400	02/0000	30	195	148	10	28
02/0000	02/1200	195	50	148	10	28
02/1200	03/2100	50	360	148	10	28
03/2100	04/1800	360	660	148	40	60
04/2100	05/1200	660	460	148	40	60
05/1800	06/1700	380	57	148	10	28
06/1700	07/0500	57	200	148	10	28
07/0500	07/1500	200	50	148	10	28
07/1800	08/1800	50	313	184	10	28
20/2300	21/2200	317	640	209	40	60
21/2200	23/0000	640	255	209	40	60
23/0000	23/0700	255	345	209	40	60

*This date is in January, all others are in February.

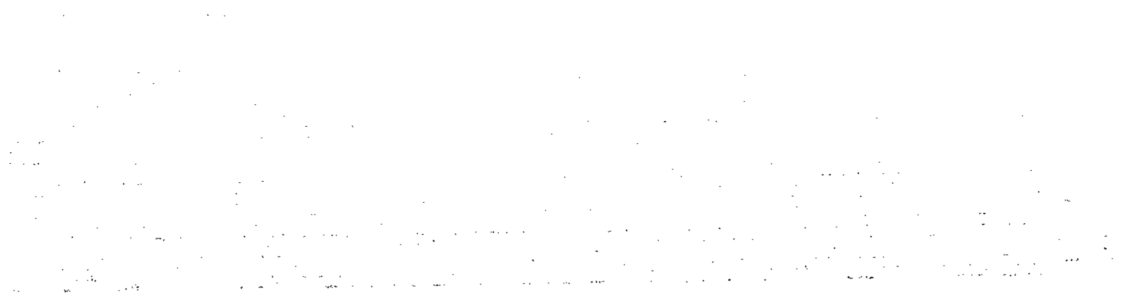
reporting, all data have been categorized into one of the three general groups. The fast fading type is indicative of the more pure scatter propagation condition, while the relatively steady type is the result of ducting conditions and in general is associated with a higher signal level. The slow, often called roller, type of fading appears to be an intermediate condition to the other two in fading characteristic and signal level. Photographs of portions of Esterline-Angus charts showing sample recordings of the received signal level with each type of fading characteristic are presented in Fig. 6.

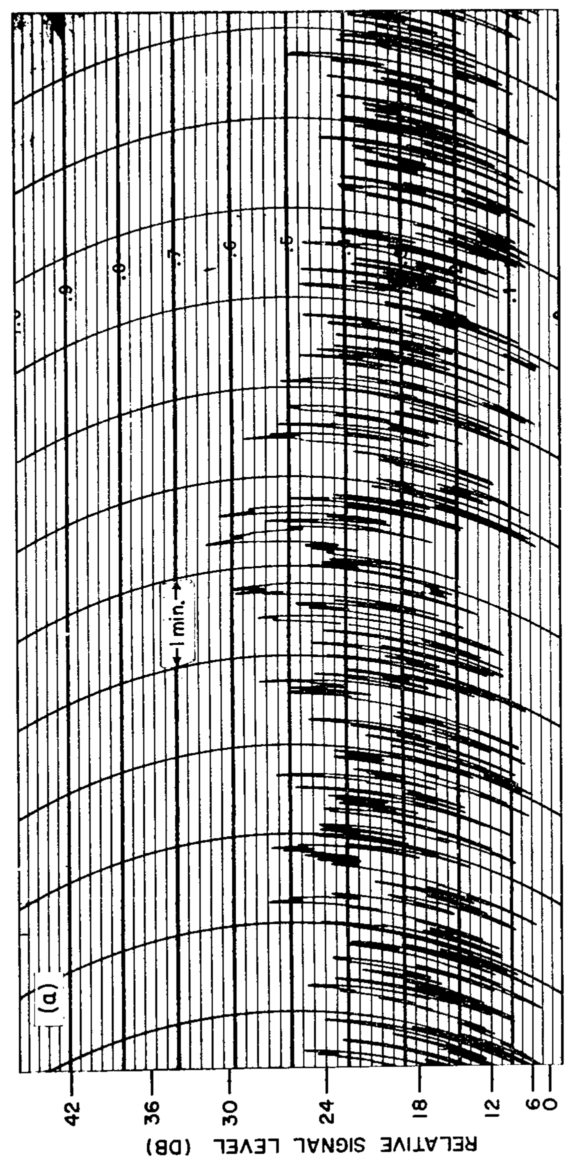
The chart samples used in Fig. 6 are the same as those used in Reference 2 since the characteristic groupings are applicable to both phases of the investigation. There were, however, periods of fading with much faster rates (Fig. 7) noted during these winter studies than during the summer. Also, as expected, the February recordings showed a fast fading characteristic for a much higher percentage of the time. During one period of slow fading, some of the fades were 40 db; however, slow fading is usually associated with a somewhat higher median signal level. During the summer operation (2), the Round Hill signal was recorded a total of 93 hours at distances greater than 75 miles. Of this total time, the received signal had a fading characteristic of the fast type 38 percent of the time, the slow type 41 percent, and the relatively steady type 21 percent. In the subject



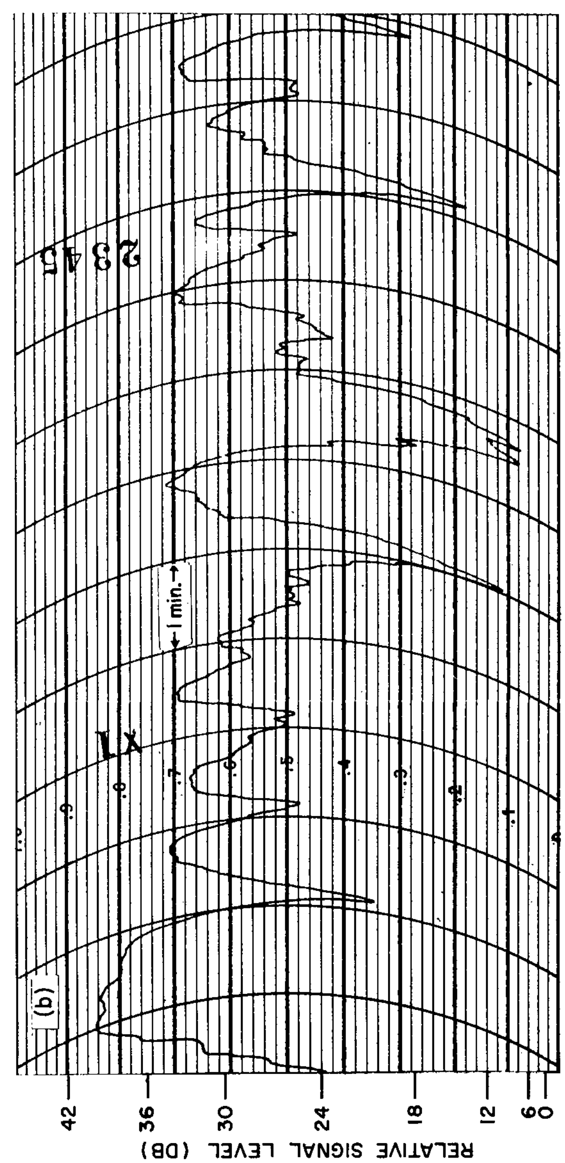
c - Relatively steady

Fig. 6 - Esterline-Angus recordings showing fading characteristics of received signal





a - Fast fading



b - Slow fading

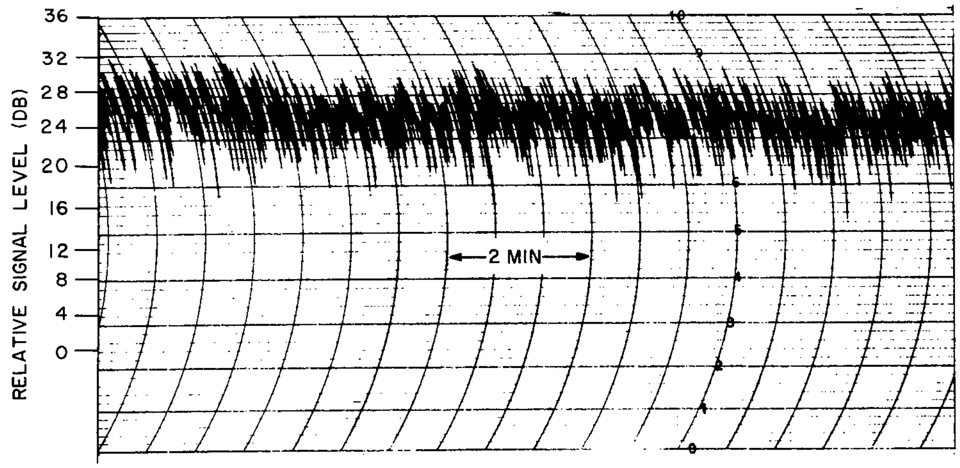


Fig. 7 - Esterline-Angus recording showing received signal with extremely fast fading

investigation the signal was recorded for a total of 218 hours, of which 198 hours were at distances greater than 75 miles. At these greater distances the received signal had a fast fading characteristic 87 percent of the time and a slow fading characteristic the remaining 13 percent of the time. There were no indications of good ducting conditions. The 87 percent quoted for the fast fading type includes 13 percent of the very fast fading shown in Fig. 7 and the other 74 percent was of the ordinary fast type shown in Fig. 6a. It should be noted that the Esterline-Angus recorder cannot follow the true magnitude with fading rates as high as those shown in Fig. 7, but the recording is representative for comparing relative fading characteristics.

The probability of having ducting conditions in the winter, over the path used in this investigation, is much less than during the summer months. The stratified air and other meteorological conditions necessary for producing ducts are much less prevelant in the winter months in this path area. Also, the high percentage of fast fading (scatter) signals and the lack of ducting possibly can be further explained by the presence of high winds over the transmission path. During the three weeks of this investigation, of the 198 hours of signal-level recording beyond 75 miles, the wind velocity recorded aboard ship was equal to or greater than 20 knots 65 percent of the time. The wind often exceeded 30 knots, and other weather observations in the same general area indicated that high winds were prevelant throughout the path area at least at the lower altitudes. The high wind velocities may have extended to the higher altitudes since the fading characteristic correlated well with wind velocity. During periods when the received signal was of the slow fading type (Fig. 6b), the wind velocity was low; when the signal was of the very fast fading type (Fig. 7), the wind velocity at the ship was between 20 and 40 knots.

Fading Rate

Fading rate, as used here, is defined as the number of times per second that the slope of the envelope of the received signal level changes from positive to negative. The maximum fading rate observed from the periodic Edin recordings was about 6. A photograph of a portion of an Edin chart showing a recording made during a period when the fading rate was about the fastest is presented in Fig. 8. This chart recording was made

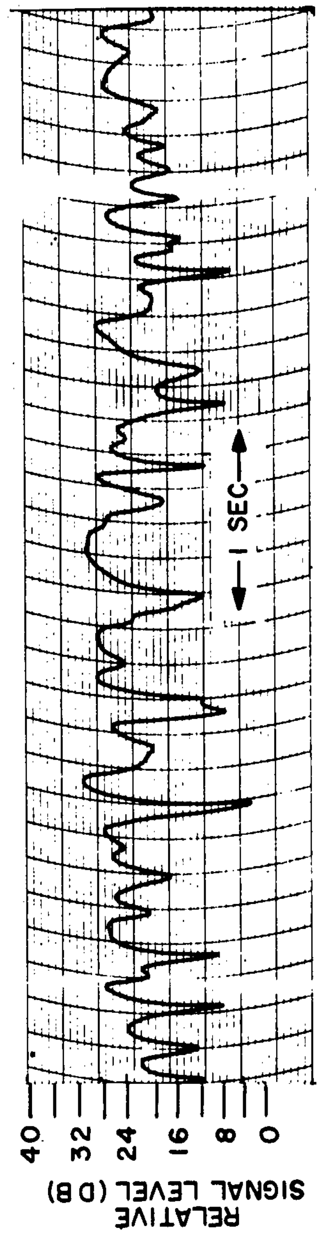


Fig. 8 - Edin recording showing sample of fastest signal fading observed

simultaneously with a portion of the Esterline-Angus chart shown in Fig. 7. It can be seen from this chart sample that even when the fading rate was about 5 some of the individual fades were 10 db or more. During the July 1955 operation the maximum rates observed were 2 or 3, but when the fading magnitude was of 10 db or more the rate was only about one per second.

Signal Levels

The median signal levels recorded during the three weeks of operation have been plotted in several forms against distance in Figs. 9 through 14. The signal levels are plotted in db above one milliwatt (dbm) output of the antenna. Since other quantities are often used for expressing signal levels, the following conversion data are given. One microvolt across a 50-ohm load is equal to -107 dbm. Also, for the receiving antenna system used, the field strength in db above one microvolt per meter is equal to the signal level in dbm plus 107 db. Therefore, since the receiver input and antenna system were all 50 ohms, the field strength in microvolts per meter is numerically equal to the signal level at the output of the receiving antenna in microvolts.

In Fig. 9a through 9f the median signal levels are plotted against distance showing the individual trips of the ship. The data are, in general, the median signal levels over a period of 50 minutes to a maximum of one hour; however, when significant changes in the level occurred, shorter periods were used. The data recorded while the receiving antenna was directed over the bow of the ship have been corrected to allow for the effect of the ship's superstructure on the received signal level (5-db decrease) and are indicated on the graphs by solid symbols. The fading characteristic of the received signal is denoted by the different symbols used in plotting the data. The observation times (GMT) are shown for some of the data to give a rough indication of the speed of the ship and how the signal level varied with time and distance. The first two digits of these date/time groups represent the date in January or February 1956 and the last four digits give the mean time of the sampling period in GMT. It should be noted as indicated on the graphs that the data were obtained along several great-circle paths from Round Hill, Massachusetts, and that two transmitting facilities were used.

The data presented in Fig. 9a through 9d have been combined and plotted as Fig. 10a, which shows the composite of all data recorded while using the 10-kw transmitter and 28-foot antenna. This transmitting system gave an effective radiated power (ERP) of 8 megawatts or 99 dbm. The data in Figs. 9e and 9f have been combined and plotted as Fig. 10b. These data were obtained while using the 40-kw transmitter and 60-foot antenna, which gave an ERP of 110 dbm.

Also included in Figs. 9 and 10 are ordinates giving the basic transmission loss in db. By plotting propagation data in the form of basic transmission loss the results can be easily applied to any transmitting and receiving system. The received signal level, P_a, expressed in dbm, can be calculated for any transmission circuit from

$$P_a = P_r + G_t + G_r - L_b \qquad (1)$$

where

P_r = power in dbm available for radiation from the transmitting antenna

G_t = transmitting antenna gain in db

G_r = receiving antenna gain in db

L_b = basic transmission loss in db.

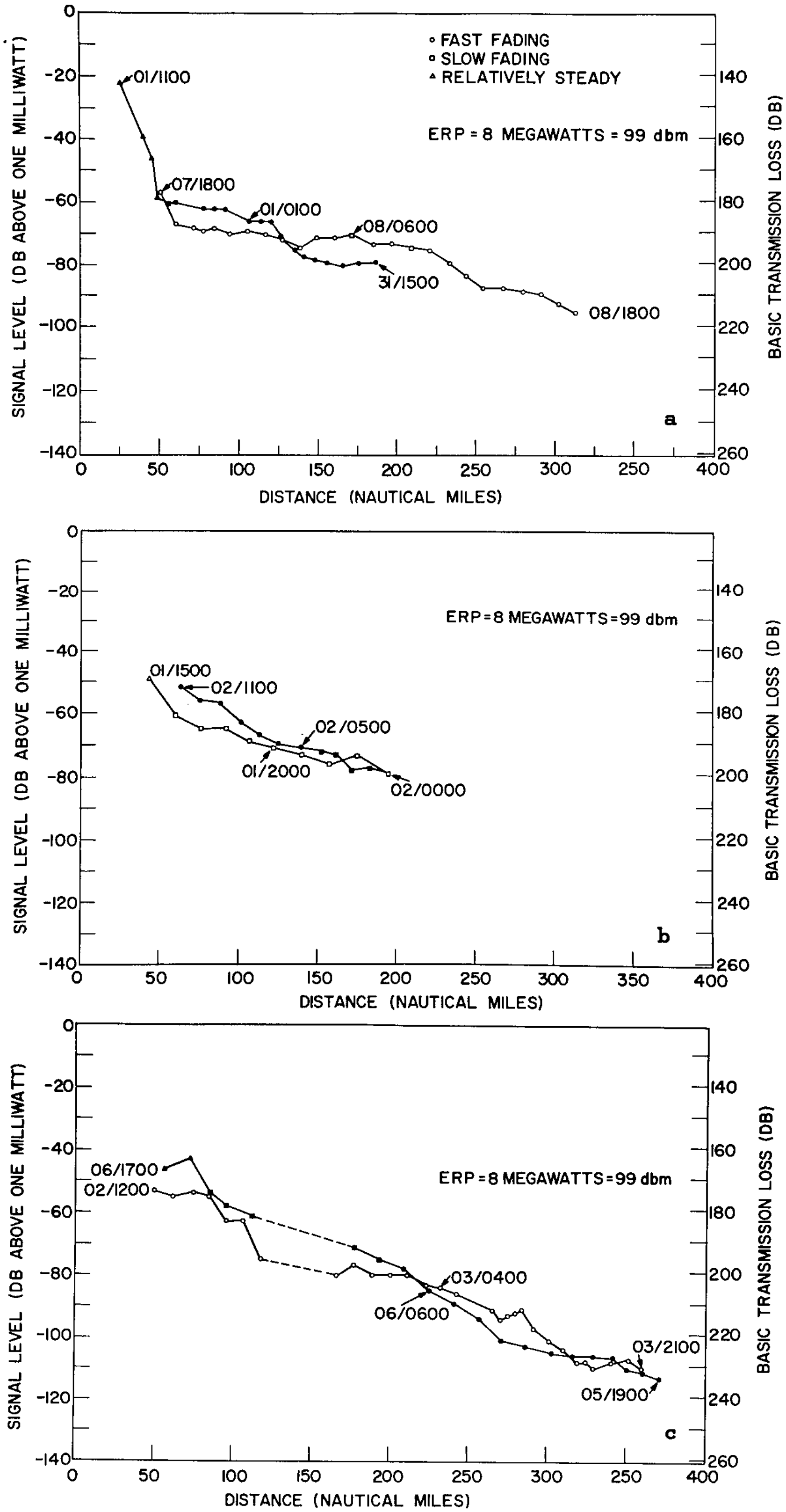


Fig. 9 (Continued)

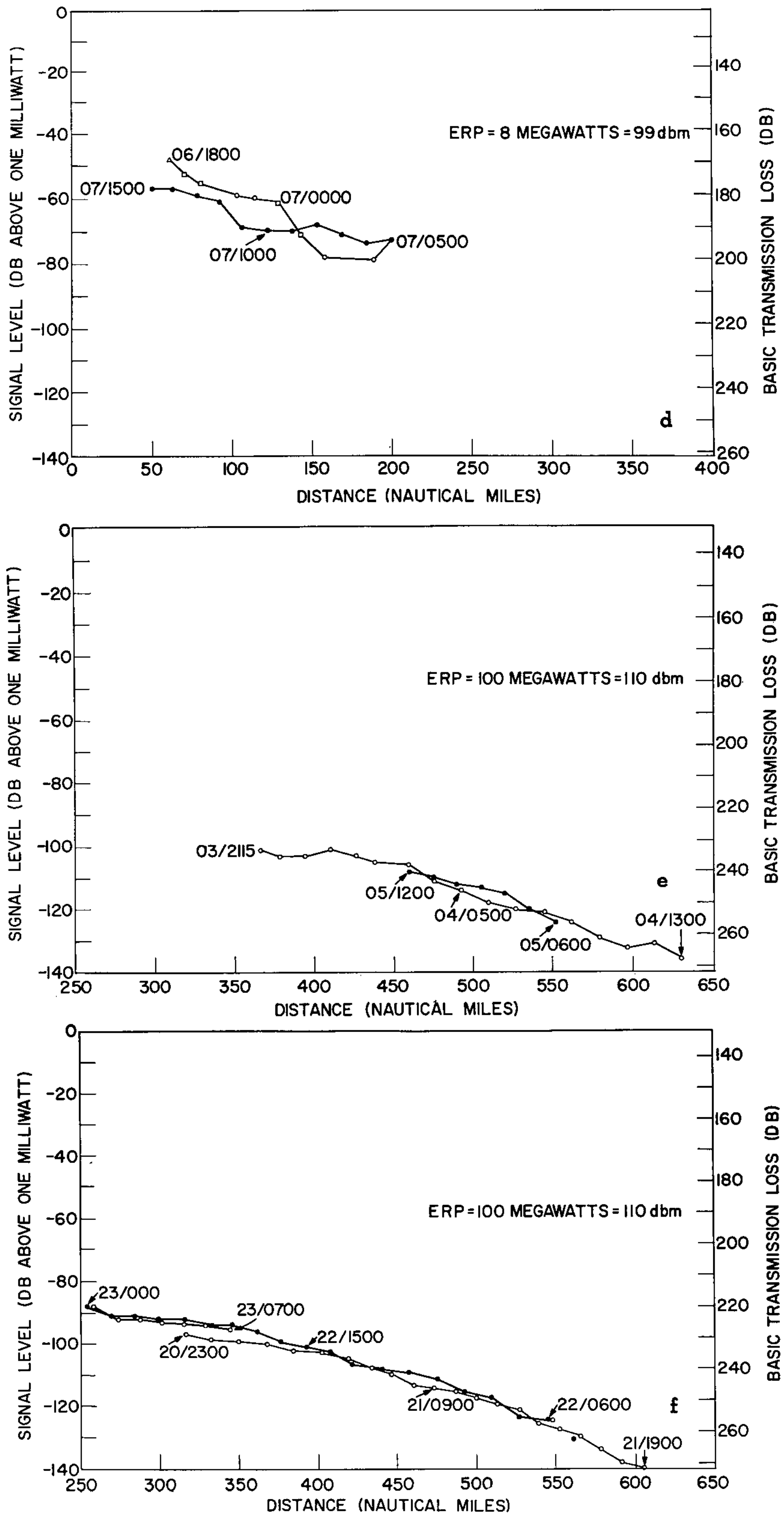
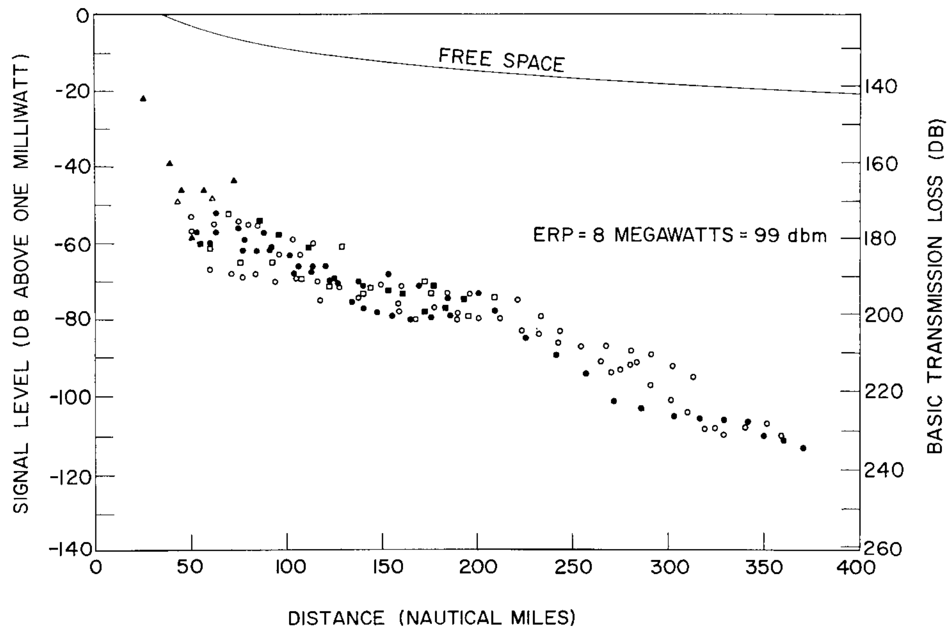
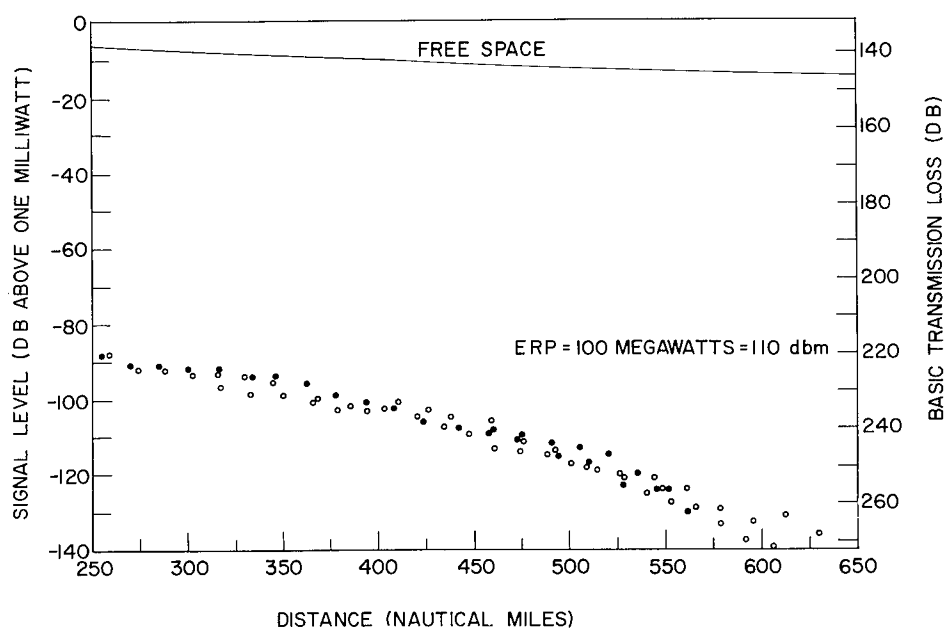


Fig. 9 - Median signal levels versus distance.



a - Data presented in Fig. 9a, b, c, and d



b - Data presented in Fig. 9e, and f

Fig. 10 - Composite of data presented in Fig. 9

The antenna gains, G_t and G_r, are expressed in db relative to an isotropic antenna. The gain of an antenna over an isotropic antenna is equal to its gain over a half-wave dipole plus 2.15 db. The basic transmission loss in free space, L_{bf} is given by

$$L_{bf} = 37.81 + 20 \log_{10} D + 20 \log_{10} f \qquad (2)$$

where

D = the distance in nautical miles between the isotropic antennas

f = the frequency in Mc

The antenna gains used in Eq. (1) are the "effective gains" but the free-space gain can be used to give a good approximation. Much of the literature on scatter propagation, and in particular the early theoretical studies, state that when the propagation mode is predominently scatter the free-space gain of a large aperture antenna will not be realized in practice. However, it has been found in this investigation and in others conducted by the Lincoln Laboratory that for paraboloid antennas with diameters up to 60 feet and operating on frequencies near 400 Mc, the free-space gain is generally realized for scatter propagated signals out to distances of about 600 miles. Once during this investigation the change from the lower-power to the higher-power transmitting facility was practically instantaneous and the ship was at a distance of 365 miles. The radiated powers of the two facilities differed by 11 db, and of this, 6 db was the difference in antenna gains. Examination of the strip chart recordings just prior to and immediately after the change showed a gain in signal level of about 11 db which indicates that the gain difference of the two transmitting antennas was realized, at least at that time. In Reference 3 the relative gains of a 28-foot dish and a 5.5-foot dish operating at 505 Mc were measured over a 150-mile path. Hourly median levels recorded while using both antennas for 650 hours and many instantaneous level comparisons showed that the difference varied over a considerable range. The median difference in antenna gains for the scatter transmissions was 13 db which is only 1 db less than the free-space gain difference of 14 db. However, 10 percent of the time the gain difference exceeded 16 db and 90 percent of the time it exceeded 10 db.

The meteorological conditions prevalent during the three weeks of operation were very favorable for studying the tropospheric scatter propagation mode. There was little evidence of ducting as shown by the high percentage of fast fading signals. This is further exhibited by the close grouping of the data as plotted in Fig. 10. The spread in signal level is no greater than 8 db for the data in Fig. 10 and about half of the data was taken on a different path and approximately 10 days later. Figure 11 gives a comparison of the spread in signal levels recorded during the winter and those recorded during the summer (2). The probability of having ducting conditions is much higher in the summer and generally lower signal levels during the winter have been frequently reported.

The relatively good repeatability of the winter data makes a mean signal level versus distance curve more practical and meaningful. Such a curve is shown in Fig. 12 which gives the mean of all data having a fast fading characteristic. All the data were normalized for an ERP of 100 megawatts or 110 dbm. A straight line with a slope of 0.18 db per nautical mile is also included; this line appears to give a satisfactory loss rate although it is a little pessimistic for distances greater than 400 miles. The region of discontinuity in combining the two sets of data (two transmitting facilities) near 300 miles cannot be definitely explained. Only once during the investigation were the transmitting powers switched instantaneously and at that time the change in signal level was as calculated (11 db). The fact that the two sets of data were recorded at different times appears to be the only explanation at present.

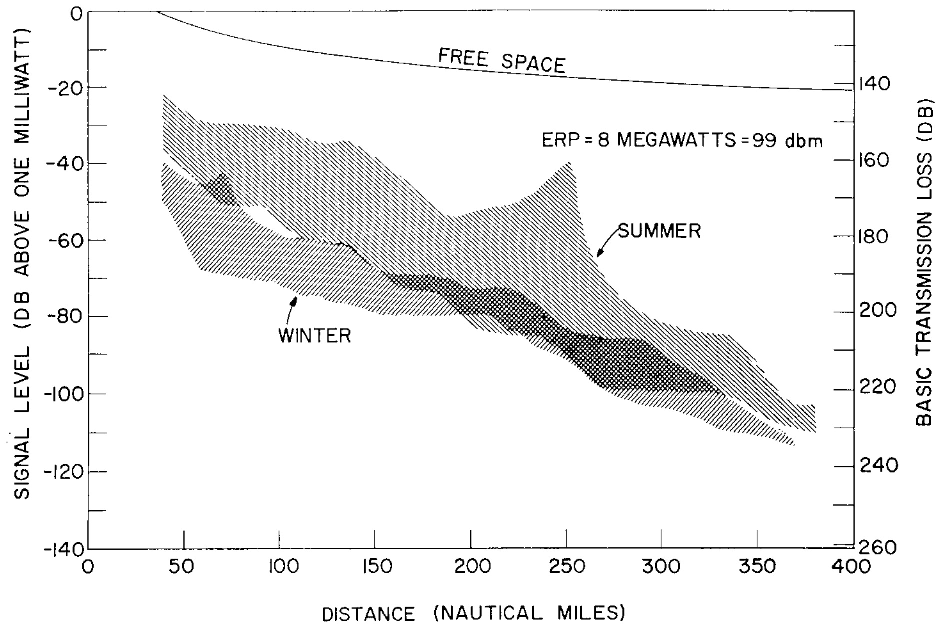


Fig. 11 - Spread of received signal levels for summer and winter

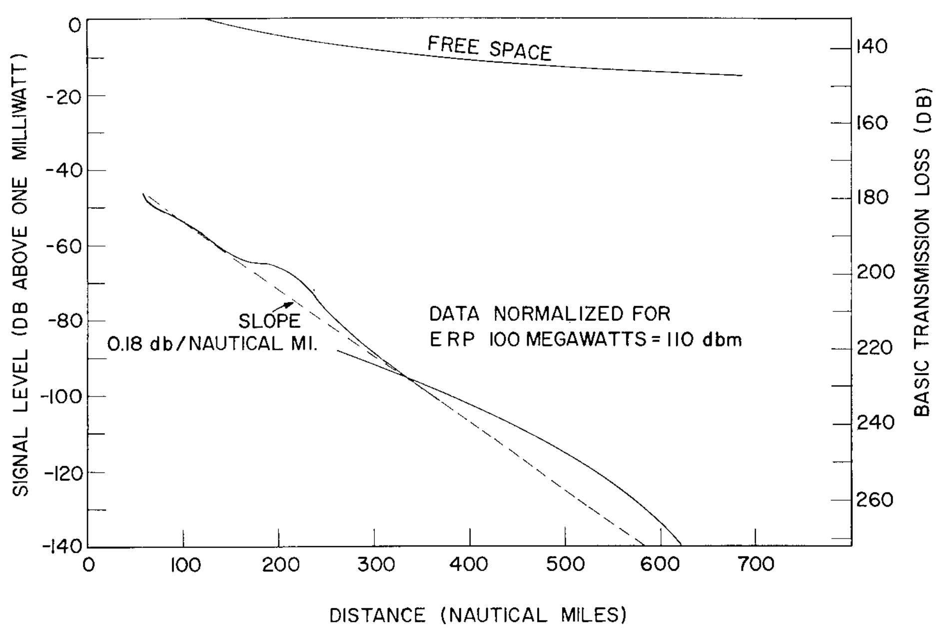


Fig. 12 - Mean scatter signal level versus distance

The average difference in signal level from summer (2) to winter, for signals believed to have been propagated by tropospheric scatter, can be seen in Fig. 13 to be approximately 8 db. The loss rate of 0.18 db per nautical mile appears to fit well for both sets of data. The "hump" in the winter curve at 200 miles is rather interesting, although there is no immediate explanation for it. There is a similar hump in the summer curve but at 240 miles. However, the summer average curve is somewhat less reliable because there was less data unaffected by ducting. It is of interest to note that a similar hump also appears in the results reported by Megaw (4) and shown for comparison in Fig. 14. The two curves are very similar in shape but with different loss rates. Megaw's results show a loss rate of 0.23 db per nautical mile while the results reported herein show 0.18 db per nautical mile. There is no apparent explanation for this difference. The frequencies of the two investigations differ by nearly 10 to 1 (Megaw used 3000 Mc) but the results published by other authors (5) show that the loss rate is largely independent of frequency. Megaw's measurements were made in the summer, but he stated that data which appeared to be affected by ducting had been disregarded. By doing so, the summer conditions would have affected the overall signal level, but the loss rate probably would not have been materially affected as found in this investigation and shown in Fig. 13. Gerks (5) in consolidating the results published by four sources found the average loss rate to be approximately 0.14 db per nautical mile.

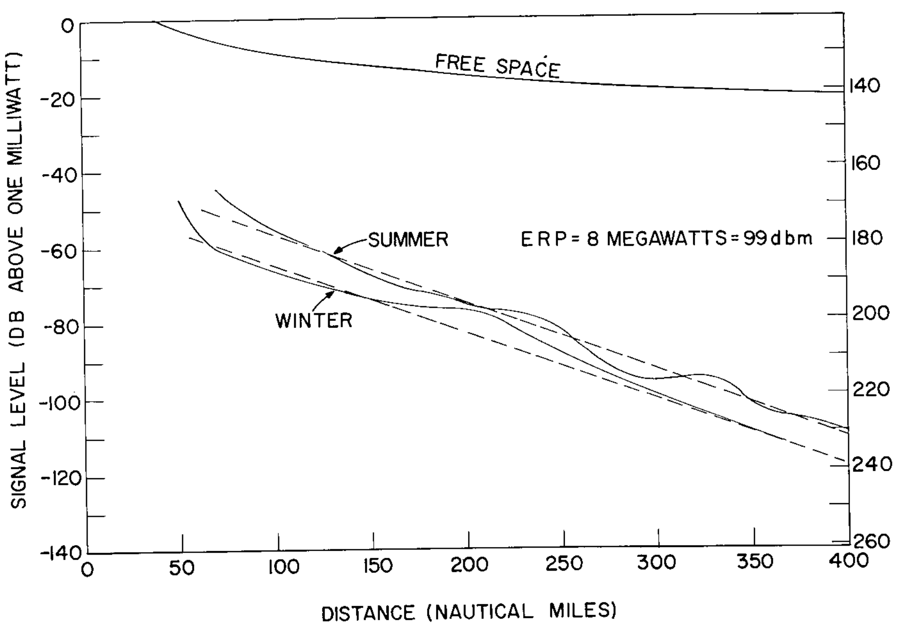


Fig. 13 - Comparison of mean scatter signal level versus distance for summer and winter

The results given in Reference 3 are for a point-to-point study for a mixed over-water and over-land path. The median signal level over approximately a year for hourly medians recorded on 505 Mc showed a basic transmission loss of 199 db over a path of 150 miles. The highest monthly median was recorded in June with a basic transmission loss of 190 db. The lowest month, March, showed a loss of 210 db. Results are also given for a 255-mile path but for a shorter period of time, from June to October. The monthly medians varied from 205 to 212 db basic transmission loss.

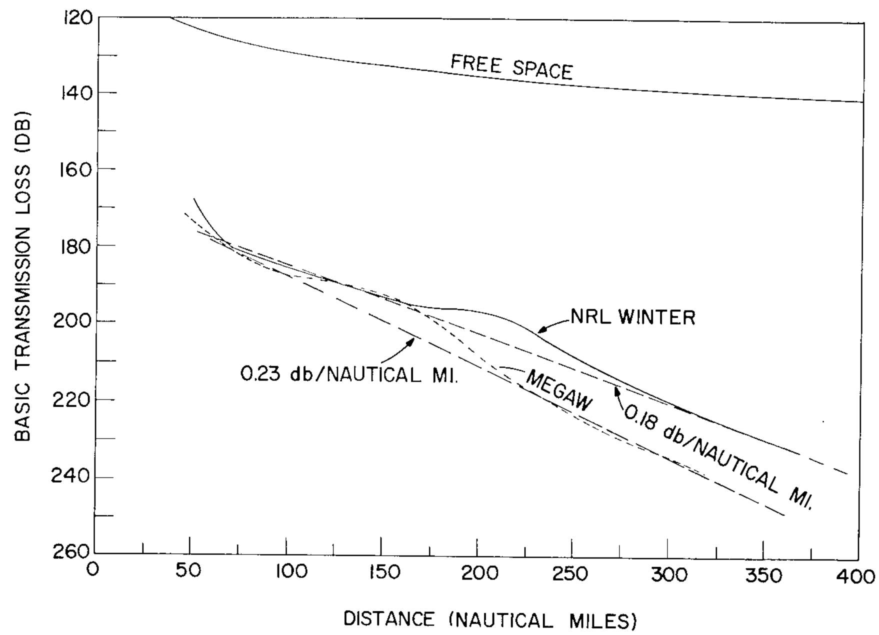


Fig. 14 - Comparison of winter curve shown in Fig. 13 with data published by Megaw in Reference 4

A comparison of the results reported herein and in Reference 2 with those of References 3, 4, and 5 shows a general tendency for the former two results to be a little higher than those published in the latter three. There is, however, no significant difference in the results whether the path was over land or over water.

Probability Distribution

In the preceding section, the signal level was discussed in terms of the median value. It has also been shown that the received signal propagated by tropospheric scatter fades at a rather fast rate and that these fades are of considerable magnitude. Therefore, in designing a communication circuit for better than 50 percent reliability, more information is needed concerning the time distribution of the received signal levels for short-time fading.

The signal-level data recorded on the LDR were plotted as cumulative probability distribution curves. Since primary interest in this project was to obtain information on signals propagated by the tropospheric scatter mode, the discussion of the probability distributions of the received signal levels will be confined to data obtained while the ship was at distances greater than 120 miles. It was found, as was also reported in Reference 2 that the short-time fading of scatter propagated signals is best represented by the Rayleigh distribution. The winter data showed no evidence of ducting while the ship was at distances greater than 75 miles and therefore no information was obtained on the distribution of signals propagated under such conditions. With very limited data, it was reported in Reference 2 that such signals appeared to be log-normally distributed. Such information is mostly academic since with ducting conditions, the signal level is generally enhanced and fading very slowly (Fig. 6c).

The cumulative probability distributions (Rayleigh) of the received signal level for three sampling periods while the ship was headed away from the transmitting site and the receiving antenna was unobstructed by the ship's superstructure, are shown in Fig. 15. The data in Fig. 15a were obtained while the received signal had a very fast fading characteristic (Fig. 7), and the transmitting system consisted of the 10-kw transmitter and the 28-foot antenna. The recorder chart samples shown in Figs. 7 and 8 cover portions of the sampling period presented in Fig. 15a. The 40-kw transmitter and 60-foot antenna were being used, and the received signal had a fast fading characteristic (Fig. 6a), during the sampling period presented in Fig. 15b. The sampling period for the data of Fig. 15c was for a period during which the received signal had a slow fading characteristic (Fig. 6b) and the 10-kw transmitter and 28-foot antenna were being used. These three distribution curves were randomly chosen from the approximately 150 sets of LDR data to be representative of the various conditions of transmitting facility and signal fading, and for periods when the receiving antenna was unobstructed by the ship's superstructure. Under these latter conditions, the data for all sampling periods plotted as Rayleigh distributions.

The term "distribution" as used in this reported refers to the integral of the probability density. The probability density, P, following Rayleigh's law is given by

$$P = 2\,KE\,e^{-KE^2} \tag{3}$$

where E is the signal level in microvolts and the constant K can be found from the relation

$$K = \frac{0.693}{E_m^2} \tag{4}$$

where E_m is the median signal level in microvolts. Therefore, the equation for the distribution curve following Rayleigh's law is given by

$$T = \int_E^\infty 2\,KE\,e^{-KE^2}\,dE = e^{-KE^2} \tag{5}$$

or

$$T = e^{-0.693\,(E/E_m)^2} \tag{6}$$

where T is the fraction of the time that the signal level E will be exceeded. When Eq. (6) is plotted on Rayleigh coordinate graph paper (log log versus log)* as used for Fig. 15, where the ordinate is the signal level expressed in db, the resultant curve is a straight line with a slope such that the ratio of the signal levels exceeded 10 and 90 percent of the time is 13.4 db. This ratio is often referred to as the fading range of the received signal level. From Eq. (6) it can be determined that, if the fading of the received signal level follows the Rayleigh distribution, the signal level exceeded 90 percent of the time is 8.2 db below the median level. Also, the level exceeded 99 percent of the time is 18.4 db below the median. Therefore, the median scatter signal level versus distance data presented in Figs. 9 through 14 could be converted to the signal level exceeded any desired percentage of the time by applying the proper correction factor determined from Eq. (6).

*The abscissa for Rayleigh coordinate graph paper can be plotted using the Equation: $D = k\,[\log 4 - \log(2 - \log P)]$ where D is the distance from the origin (P = 0.01%) to the percentage point P, and value of k is determined by the units employed.

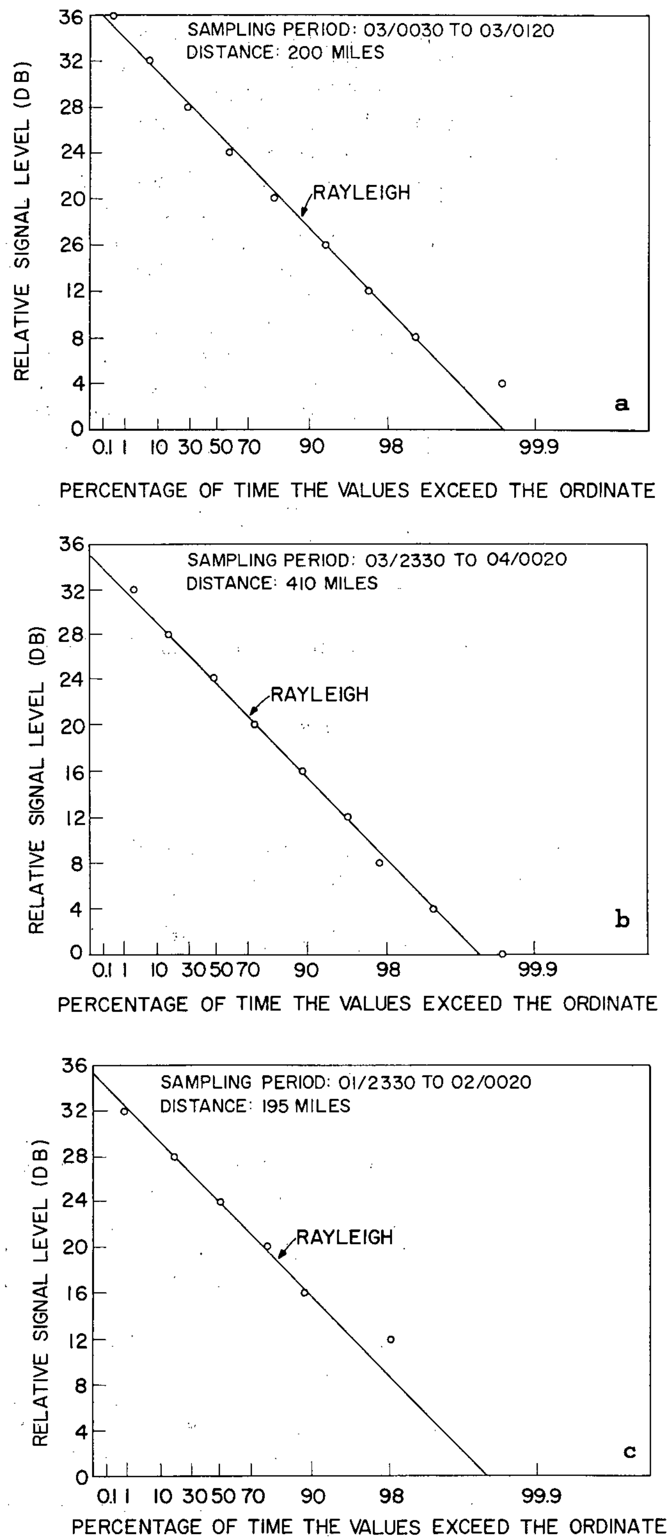


Fig. 15 - Probability distribution of received signal level; receiving antenna directed aft.

When the ship was headed toward the transmitting site, the receiving antenna was partially obstructed by the ship's superstructure. During such times the received signal consisted of two components, that received directly by the antenna, and that which was reradiated by portions of the ship's superstructure. The recorded signal level was therefore the resultant of these two Rayleigh distributed components. The LDR data recorded under these conditions were plotted on Rayleigh coordinate graph paper. The loci of the points were very well represented by a straight line but often had a different slope from that given by Eq. (6). The results appeared to indicate that at distances less than approximately 200 miles the fading range averaged about 9.5 db while at greater distances the fading range was that expected for a Rayleigh distribution, 13.4 db. A plot of the distribution of the signal level for a representative period while the antenna was partially obstructed is shown in Fig. 16. The ship was at a distance of 175 miles during this period and the fading range given by the curve is 9.5 db.

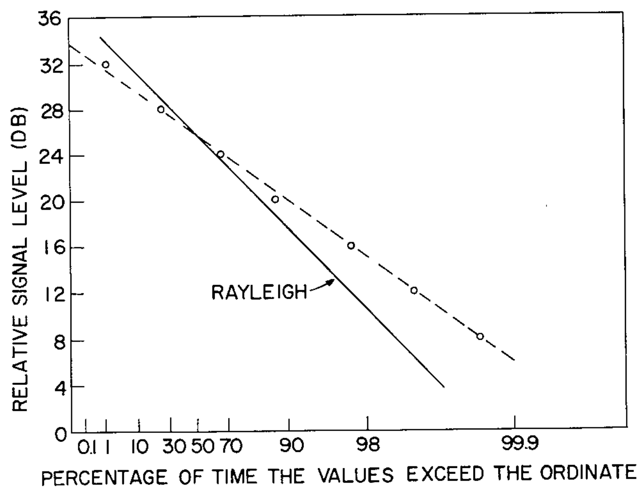
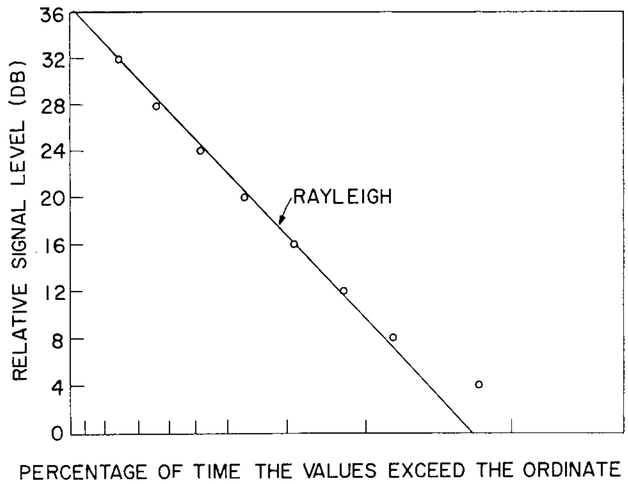


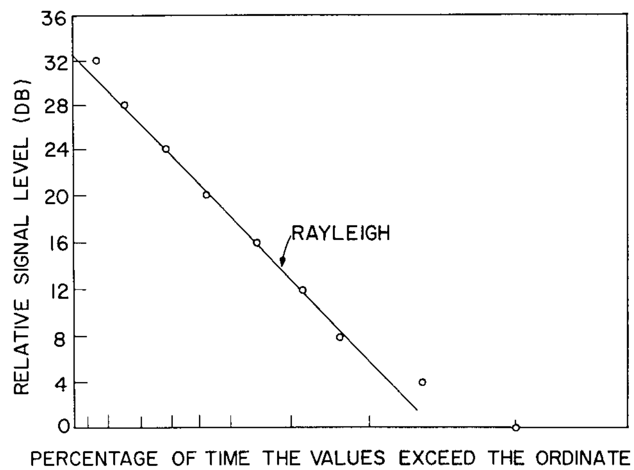
Fig. 16 - Probability distribution of received signal level; receiving antenna directed forward

All sampling periods discussed thus far concerning probability distribution have been for 50 minutes. Such periods were found to be technically feasible and operationally convenient. In Reference 6 the investigation of 3670-Mc tropospheric scatter propagation showed that the sampling period should be no longer than about one minute to determine the distribution of the short-time fading. When the periods were longer, the distribution deviated from Rayleigh toward a log normal. The results obtained using frequencies of about 400 Mc and reported herein and in Reference 2 show that 50-minute sampling periods produce a good Rayleigh distribution and the period must be extended to about two hours before substantially deviating from Rayleigh. Thus, it appears that there is a definite frequency dependency in the sampling time for determining the short-time distribution of the signal levels in studying tropospheric scatter propagation.

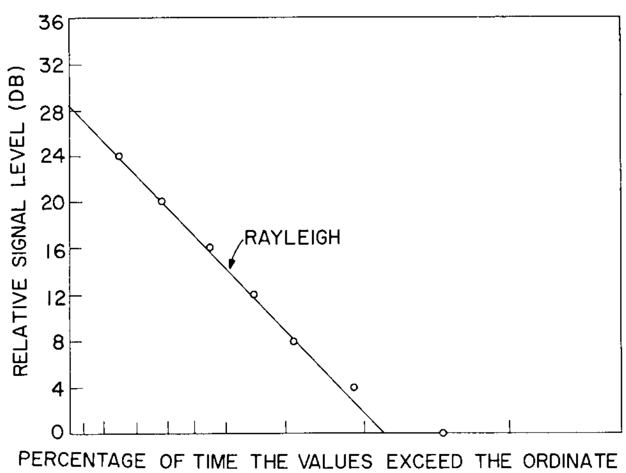
The effect of lengthening the sampling time on the distribution is demonstrated in Figs. 17 and 18. Figure 17 shows the Rayleigh distribution of six consecutive 50-minute periods. These individual periods fit the Rayleigh curve very well. During the total time



a - Sampling period: 03/1330 to 03/1420
Distance: 301 miles



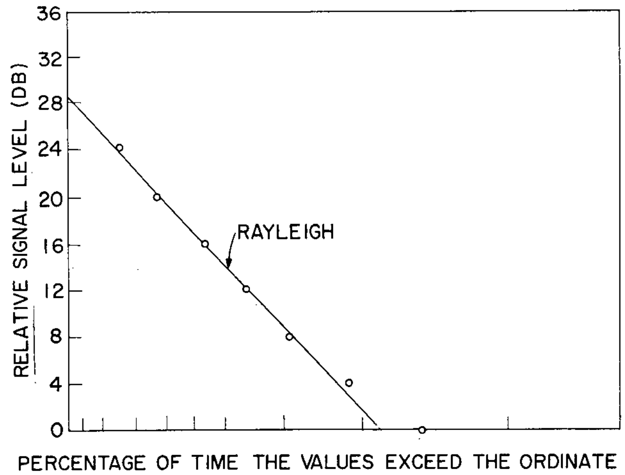
b - Sampling period: 03/1430 to 03/1520
Distance: 310 miles

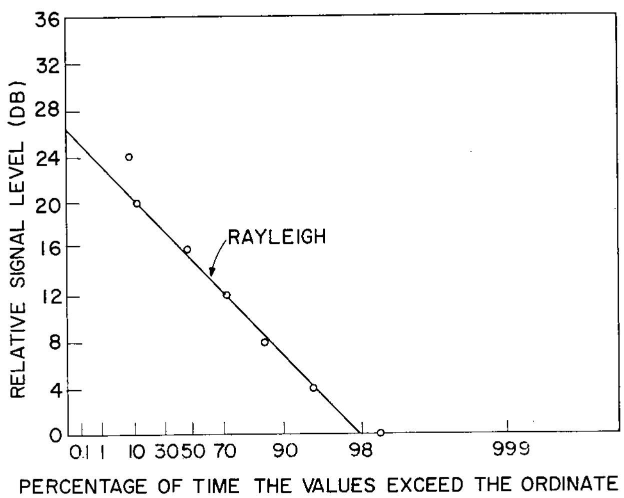


c - Sampling period: 03/1530 to 03/1620
Distance: 319 miles

Fig. 17 (Continued)

d - Sampling period: 03/1630 to 03/1720
Distance: 324 miles





e - Samplinᶜ period: 03/1730 to 03/1820
Distanᶜe: 330 miles

f - Sampling period: 03/1830 to 03/1920
Distance: 340 miles

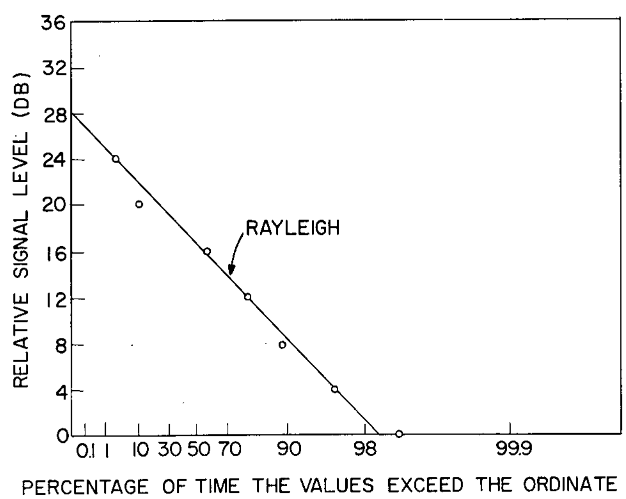


Fig. 17 - Probability distribution of received signal level for six consecutive sampling periods; receiving antenna directed aft.

of these six periods the ship's distance from the transmitting site varied from 300 to 340 miles and the median level varied from -101 to -110 dbm. Such changes in the median should have little effect on the results because the summation of two Rayleigh distributions with different medians is also a Rayleigh distribution. Figure 18a shows the sum of the periods of Fig. 17a and b for a total sampling period of 100 minutes and the distribution still fits the Rayleigh distribution. Figure 18b is the summation of the periods of Fig. 17a, b, and c for a total of 150 minutes and the deviation from Rayleigh is becoming apparent. The summation of four and six consecutive periods for totals of 200 and 300 minutes, respectively, are shown in Fig. 18c and e. The deviation from a Rayleigh distribution is greater for these longer periods, but as shown in Fig. 18d and f the data does not fit the log-normal distribution either.

Communication Intelligibility Transmissions

The test transmissions were periodically modulated so that general information concerning the communication quality of the transmissions might be obtained. The modulation was narrow-band FM and consisted of a previously recorded voice and music magnetic tape test sample. These modulated transmissions were tape recorded aboard ship at various distances from Round Hill. The FM demodulator used on the ship was not of particularly good quality but the results were adequate for communication intellegibility demonstrations. When the low-powered transmitting facility was used, the shipboard recordings showed excellent quality at distances out to about 300 miles. This agrees with the results of the July 1955 operation. With the high-powered transmissions, the distance for excellent quality was increased to about 400 miles and was of fair quality with short-period fading outages out to 500 miles.

FUTURE PLANS

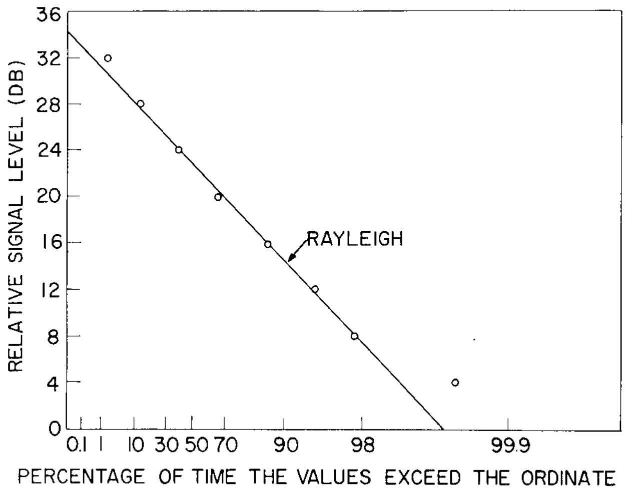
Arrangements are now being made to conduct long-time investigations between fixed points. During these investigations it is intended to employ various types of communication and data transmission systems and to determine the complete system reliability by making error-count measurements. The receiving terminal will consist of a suitably equipped trailer which will be moved to various locations to determine the system reliability dependency on distance of transmission path. Various receiving antennas will also be investigated including antennas with omnidirectional patterns at least in the horizontal plane. It is conceivable that ship-to-ship communication may require that at least the receiving antenna have an omnidirectional horizontal pattern. The results of some tropospheric scatter investigations indicate that the fading rates of the received signal may be increased by the use of broader beam antennas.

ACKNOWLEDGMENTS

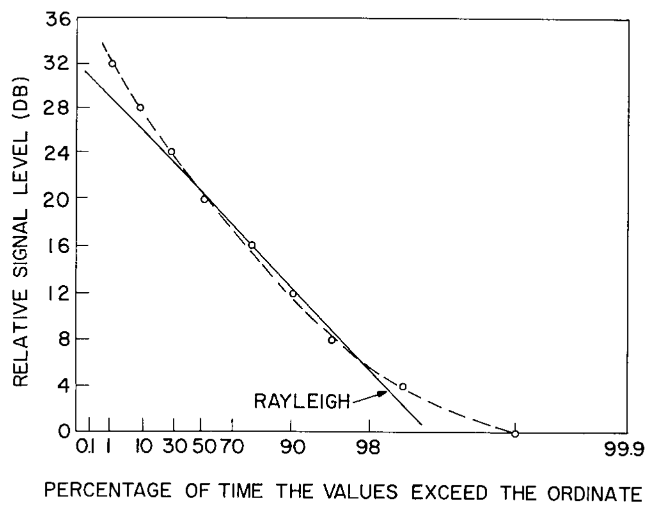
The cooperation of many individuals and their organizations contributed to the success of this project. Without the facilities supplied by the Lincoln Laboratory and their well-qualified personnel who participated in the shipboard operations and the operation of the transmitting facilities at Round Hill this project could not have been pursued with the desired scope and throughness. Thanks are also extended to the Lincoln Laboratory for the use of the photographs shown in Figs. 1, 2, and 4.

The authors also gratefully acknowledge the efforts of the following Naval organizations: The NRL liaison officers for their handling of the arrangements and details concerning the naval operations involved; CNO for the assignment of a suitable ship; the Industrial Manager of the Fifth Naval District for handling the shipboard installations; Captain Mann together with the other officers and crew of the USS THUBAN for providing excellent arrangements, operational facilities, and the precise navigation required.

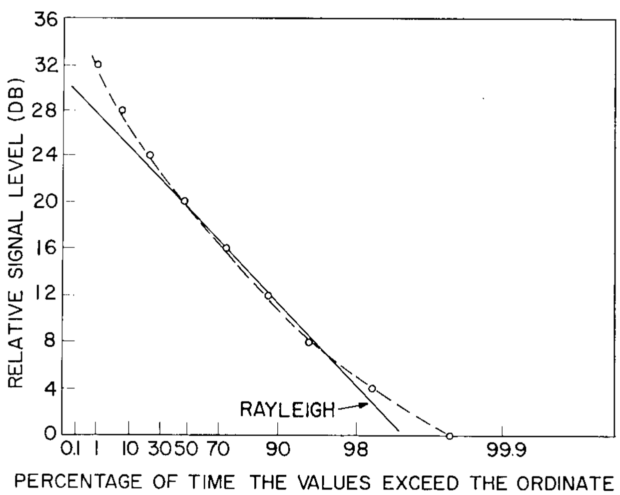
The overall program was established by Mr. L. C. Young and coordinated by Mr. J. D. Wallace of NRL. Other NRL personnel who contributed materially to the project were: J. E. Raudenbush, W. C. O'Keefe, F. C. Kahler, H. R. Johannesson, and J. A. Awramik.



a - 100-minute sampling period (Fig. 17 a, and b)

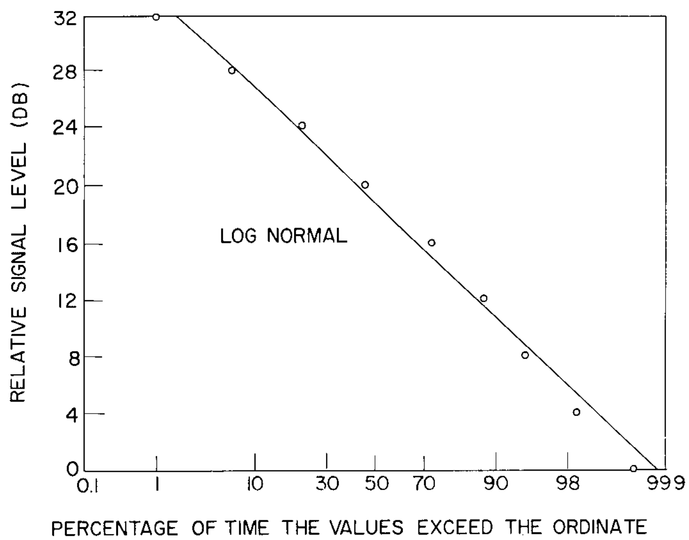


b - 150-minute sampling period (Fig. 17a, b and c)

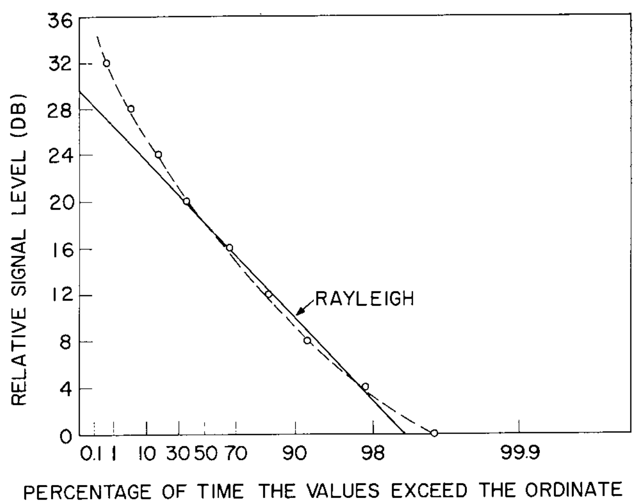


c - 200-minute sampling period (Fig. 17 a, b, c, and d)

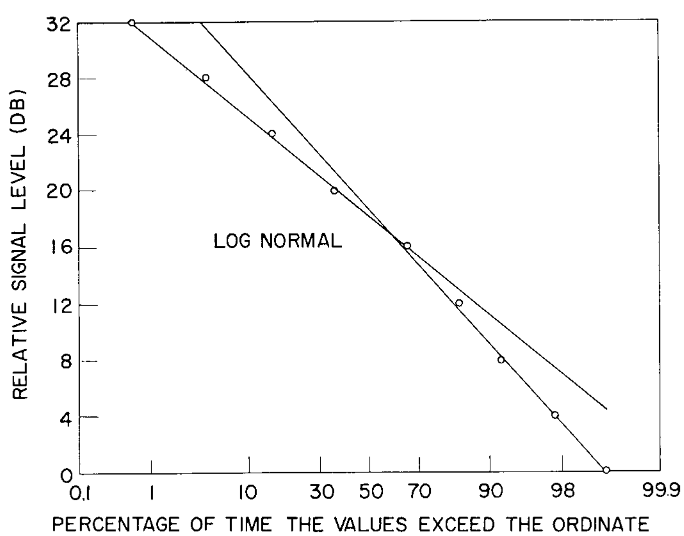
Fig. 18 (Continued)



d - 200-minute sampling period (Fig. 17 a, b, c, and d)



e - 300-minute sampling period (Fig. 17a through 17f)



f - 300-minute sampling period (Fig. 17a through 17f)

Fig. 18 - Summation of consecutive sampling periods shown in Fig. 17

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