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13. ABSTRACT

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CONTENTS

ABSTRACT

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PROBLEM STATUS

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AUTHORIZATION

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TROPOSPHERIC FORWARD SCATTER OVER A SEAWATER PATH AT X-BAND, EMPLOYING DIRECTIONAL AND OMNIDIRECTIONAL ANTENNAS

INTRODUCTION

The Navy has been aware for some time of the desirability of an improved system of communications among ships in a task force that would not be subject to the limitations posed by presently employed systems. Communications among ships in a task force currently utilize chiefly the high-frequency (hf) or ultra-high-frequency (uhf) portions of the frequency spectrum. Transmissions in the hf region are considerably troubled by interference, the occurrence of skip zones, and the possibility of distant signal interceptions by unfriendly monitoring stations. The uhf systems are free from the latter problem but, as presently employed, are seriously limited in range to essentially line-of-sight service, which is not adequate for the communication requirements of a widely deployed naval task force.

Tropospheric forward scatter is a mode of electromagnetic wave propagation which could possibly be employed to overcome the limitations of hf and uhf transmissions for task-force communications. This mode of propagation, sometimes referred to as troposcatter, is accomplished by the transfer of a small portion of the radiated electromagnetic energy to distant points beyond the horizon as a result of the scattering of the energy in the troposphere by discontinuties in the atmosphere. Land-based systems employing troposcatter utilize high transmitter powers and extremely high-gain antennas to compensate for the inefficiency of this mode of transmission. These latter requirements pose major obstacles in adapting a troposcatter sytem for use at sea.

Preliminary investigations to determine the suitability of troposcatter for employment by naval task forces were made in the Chesapeake Bay area (1), and later more extensive experiments were conducted over seawater paths exceeding 400 naut mi, as reported by Garner and Dinger (2,3), and Dinger, et al. (4). The results of these experiments, which were conducted at frequencies between 200 and 400 MHz, demonstrated that troposcatter transmission circuits apparently perform quite satisfactorily over seawater paths in this frequency range, provided that high-gain antennas along with high-power transmitters are employed. However, the large physical size of the required antennas (a 60-ft-diameter shore-based antenna and a 17-ft-diameter antenna aboard ship were employed in the experiments mentioned above) poses a very severe problem to adopting such a system for shipboard use. The employment of frequencies in the microwave range was considered to offer opportunities for more compact antenna design, assuming that the greater antenna gains possible at the higher frequencies would offset the increased losses. A problem was established to develop and demonstrate a troposcatter transmission system to operate in the S-band range of frequencies (1.55 to 5.2 GHz).

Work was started in the late 1950's to obtain the components for demonstrating an S-band troposcatter system. In the early 1960's, preliminary field tests were begun with a 10-kilowatt S-band transmitter installed at the Naval Research Laboratory and with receiving equipment installed at a site 25 miles south of NRL near the Potomac River. Unfortunately, the experimental effort had scarcely commenced when the Chief of Naval Operations announced a new frequency-allocation plan which did not allow experimental emissions for troposcatter in the S-band of frequencies. Steps were then taken to continue the troposcatter investigations in the X-band (5.2 to 10.9 GHz), since this region of the frequency spectrum appeared to offer the most promise for a successful troposcatter system, in view of the limited frequency assignments available for the conduct of this work. Extensive modifications to the transmitter and other components were then undertaken to convert them from S-band to X-band operation; however, many items such as the antennas and waveguides had to be replaced by new hardware.

The desired characteristics of a troposcatter system, as outlined by CNO, included coverage out to a maximum distance of 300 naut mi with complete coverage at all lesser distances and with an omnidirectional antenna pattern in the horizontal plane required at least at one terminal of the circuit, and preferably at both terminals. The original objective of the problem was to determine the capabilities of such a troposcatter circuit by obtaining the necessary transmitter, receivers, antennas, etc., and by evaluating the performance characteristics of the system. The emphasis was later changed to evaluation of the propagation parameters involved in such a troposcatter circuit, as it became apparent that rapid advances in the state of the art would invalidate conclusions based on a particular set of microwave equipments employed in an experimental troposcatter circuit.

INSTRUMENTATION

The original S-band transmitter, with a continuous output power rating of 10 kW, is contained in 12 rack cabinets (Fig. 1). After conversion to X-band operations, a traveling-wave-tube amplifier and klystron cabinet were added. The transmitter exciter is designed for frequency-shift-keying capability using two highly stable oscillators spaced to give a 200-kHz shift when keyed. The original S-band operating frequency was 2290 MHz, and after conversion to X-band, the frequency was 7760 MHz.

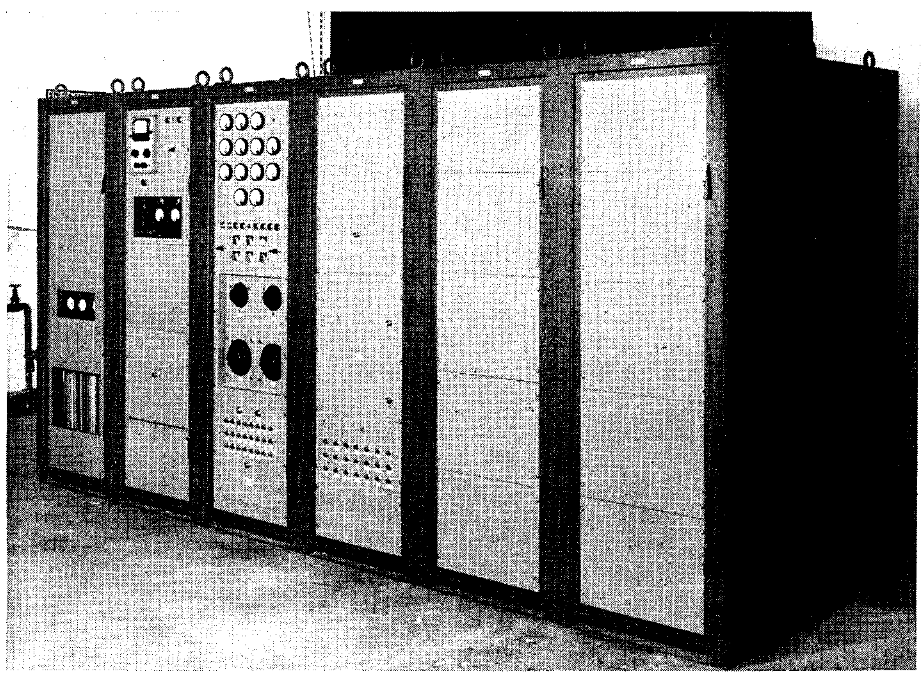


Fig. 1 - Levinthal 10-kW transmitter employed in troposcatter experiments as originally delivered for S-band operation

Figure 2 is a block diagram of the equipment as employed in conducting the experiments to determine transmission path characteristics at the X-band frequency. The antennas employed are designed to radiate simultaneously both horizontally and vertically polarized electromagnetic waves to allow an evaluation of the merits of polarization diversity for troposcatter circuits at X-band. The output waveguide from the transmitter is branched into two waveguide lines by a suitable transition section, allowing half of the output power to be supplied to each set of polarization elements at the antenna. At the receiving end of the circuit, the outputs from the horizontal and vertical sections of the antenna are connected to identical receiving systems consisting of a traveling-wave-tube amplifier, bandpass filter, and mixer-amplifier stage. The 30-MHz mixer output may then be connected to either the frequency-modulation receiver for receiving data transmissions or to the field-strength receiver for measuring received signal levels. The local oscillator was stabilized by means of a phase-lock system, which was found to be necessary in order to ensure that the 30-MHz intermediate frequency is centered in the bandpass of the field-strength receivers. Bandpass filters are required between the local oscillator and the mixer to prevent interaction between the two receiving systems.

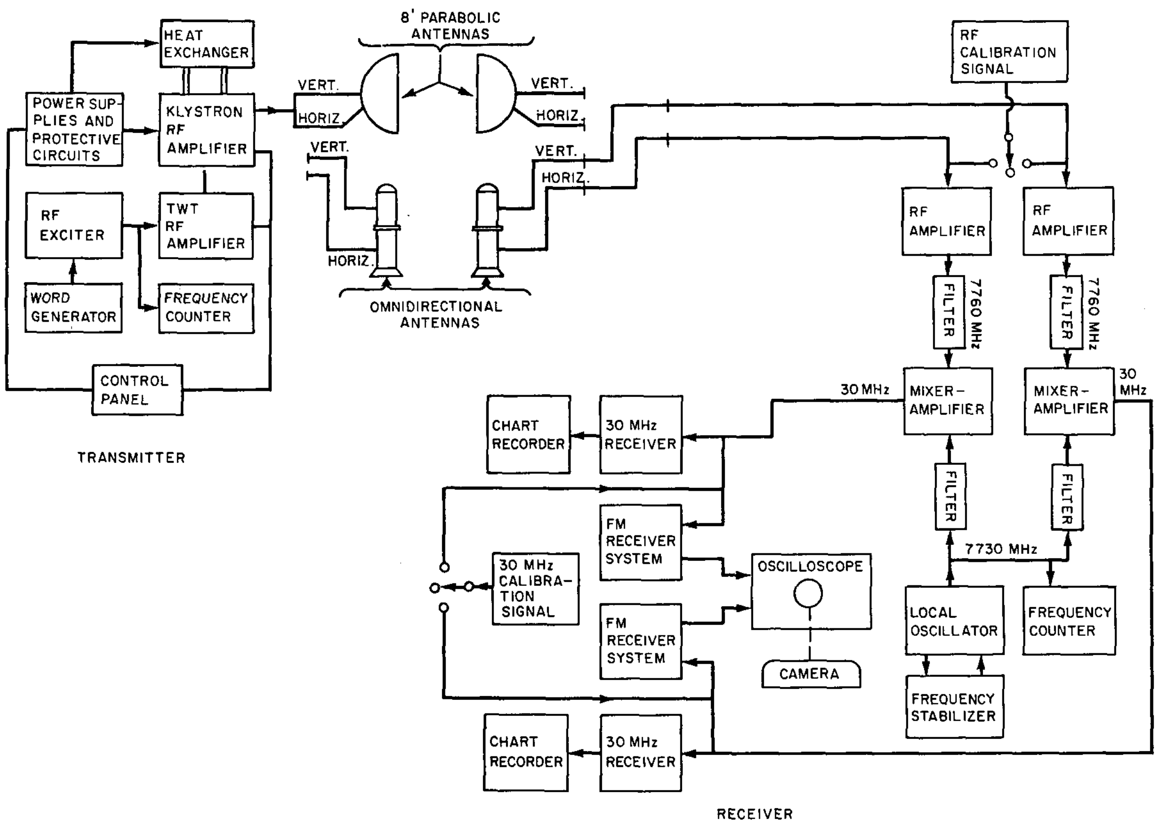


Fig. 2 - Functional block diagram of equipment employed in investigating troposcatter at X-band over a 72.8-naut-mi predominatly seawater path

EXPERIMENTAL PROGRAM

Sites

The transmitting equipment was installed at the National Aeronautics and Space Administration (NASA) Station, Wallops Island, Virginia. Use was made of an existing building and steel tower. The eight-foot-diameter parabolic antenna was installed on the side of the tower 60 ft above sea level, and the omnidirectional antenna was secured to the top of the tower about 70 ft above sea level (Fig. 3). The antenna location provided an unobstructed view to the horizon in the direction of the receiving terminal.

The receiving terminal was located at the Fleet Anti-Air Warfare Training Center, Dam Neck, Virginia. A van trailer was used to house the receiving equipment, while the antennas were secured to a 50-ft tower erected adjacent to the trailer (Fig. 4). The height to the center of the parabolic antenna was about 55 ft and to the omnidirectional antenna about 60 ft above sea level. Again, as at the transmitting site, the path to the horizon was unobstructed toward the direction of signal propagation. The antenna heights employed of between 50 and 70 ft are fairly representative of the heights normally feasible for shipboard installations.

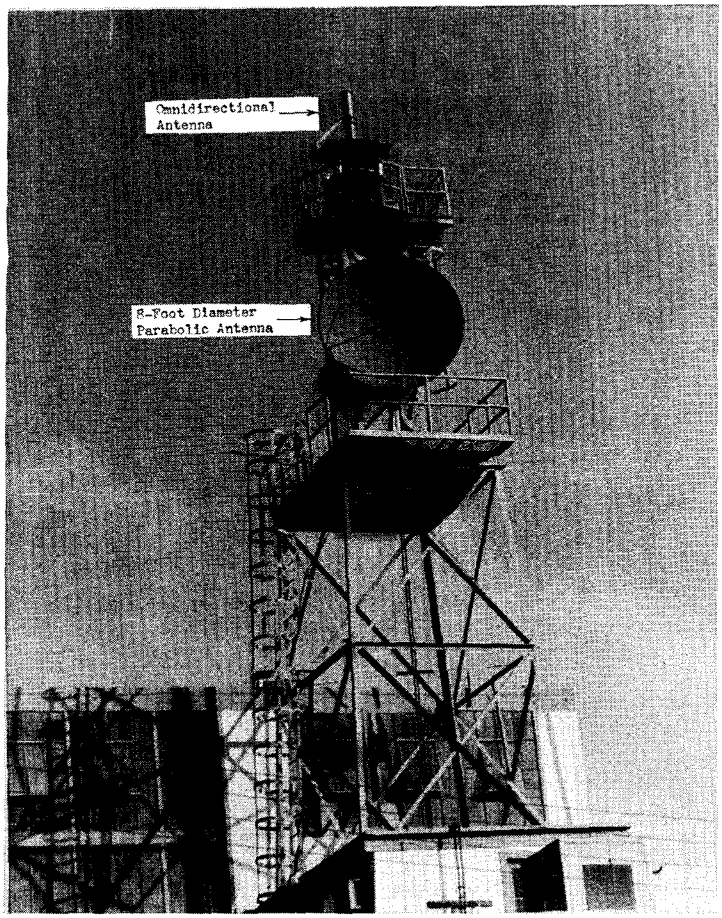


Fig. 3 - Transmitting antennas mounted on tower at Wallops Island, Virginia

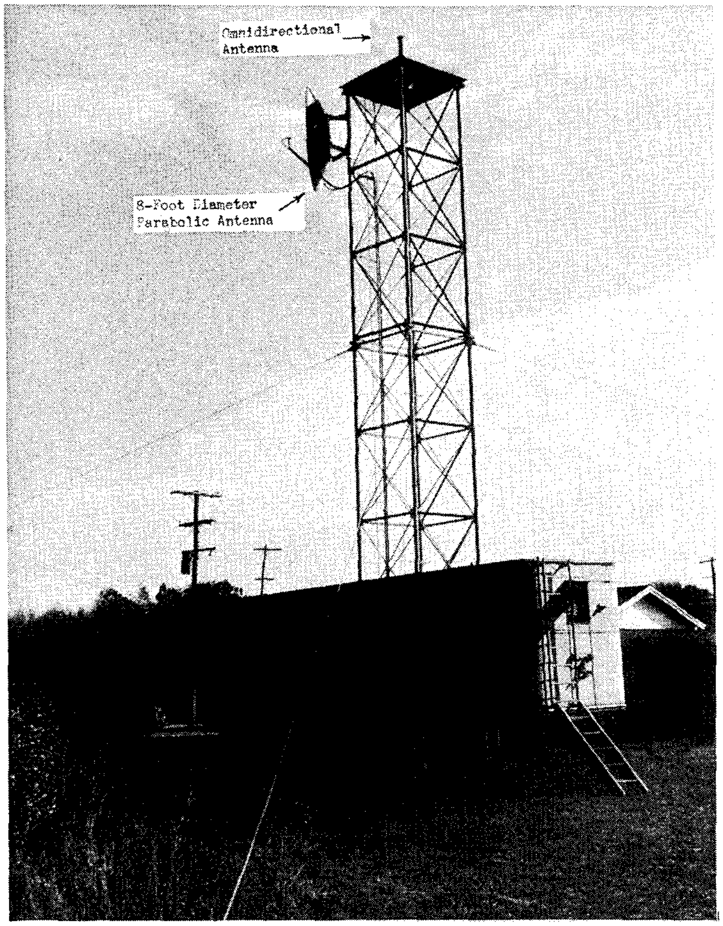


Fig. 4 - Receiving sit at Dam Neck, Virginia, showing trailer housing the equipment and the antennas mounted on the 50-ft tower

Path Description

The transmission path between the terminals at Wallops Island and Dam Neck, Virginia, has a total length of 72.8 naut mi. The major portion of the path is over the coastal waters of the Atlantic Ocean, with some low land and very low-lying islands being traversed near the Wallops Island terminus. The aerological conditions prevailing over the path are not truly maritime, but represent a region where rapid modification of the air-mass structure is taking place. Under the influence of the prevailing westerlies, air from the North American Continent flows offshore and out over the sea surface. In the winter season, the generally warmer water tends to create instability in the lower layers of the cold air mass, thus promoting turbulence and considerable mixing of the air at different elevations. By contrast, in the summer season, the warm air moving over the relatively cool water tends to create a stable condition with cool, moist layers of air, several hundred feet in thickness, forming adjacent to the sea surface. This type of condition is conducive to superrefraction. The average temperature and humidity structure of the lower portion of the troposphere overlying the transmission path is probably not representative of the average conditions prevailing over the ocean areas of the world, especially for the summer season. The results of the propagation data obtained from this experimental link will, in general, be optimistic with regard to the incidence of superrefractive conditions. However, the frequent storminess and unsettled weather of this region, especially in the winter, should provide many periods when troposcatter is the prime mode of propagation. The values of basic transmission loss, obtained during troposcatter "only" conditions on this circuit, should not differ appreciably from that which would be obtained in other ocean areas, and can be considered representative of many areas of the world in which a naval task force might be deployed.

Path Loss

The basic mean scatter transmission loss (L_{bms}) between isotropic antennas can be calculated using the methods given in Ref. 5, employing the relation

$$L_{bms} = 30 \log f - 20 \log d + F(d\theta) + H_o + A_a$$

with L_{bms} being in decibels. In the preceding relation, $30 \log f$ is a frequency term with f expressed in megahertz; $20 \log d$ is the total distance term, with d being in statute miles; $F(d\theta)$ is the attenuation function, with this value being determined by the total angular distance and average refractivity (N_s) along the path;* H_o is the frequency gain function, being a measure of how much energy is sent above the horizontal ray crossover by reflections from the surface; and finally, A_a is an atmospheric absorption loss term. Calculations of path loss were made for summer and winter conditions using the average values of refractive index applicable for the Wallops Island to Dam Neck path.

Following is a summary of the conditions assumed for the Wallops Island to Dam Neck path in calculating the transmission losses.

Antenna height at transmitter	h_t = 70 ft
Antenna height at receiver	h_r = 70 ft
Total path distance	d = 83.7 statute miles
Frequency	f = 7760 MHz
Refractivity, winter	N_s = 350
Refractivity, summer	N_s = 315

The calculated basic mean scatter transmission losses based on the parameters given above are 219.5 dB for winter and 216.5 dB for the summer season.

Since the total path length of this experimental link was relatively small in comparison with the usual troposcatter circuit, a calculation of the contribution of the diffracted radio-wave energy to the received signal was performed. The results of this calculation showed that the diffracted basic transmission loss was more than 100 dB greater than the basic tropospheric forward-scatter transmission loss. Thus, it is apparent that the mechanism of diffraction should not have any appreciable effect on the experimental values of transmission loss observed over this path.

The experimental data indicated that superrefractive conditions of some degree were present on the path a fairly high percentage of the time. Signal enhancements from superrefractive conditions were found to be somewhat more prevalent in the summer season, as would be expected from the meteorological considerations previously

*Refractivity N is related to the index of refraction n by the relation:

$$N = (n - 1) 10^6.$$

Quantity N_s indicates a refractivity derived from surface observations.

discussed; however, some moderately strong superrefractive conditions were also encountered in the wintertime. It should be pointed out here that evidence of signal enhancement by superrefraction was inferred by examining the data for a pronounced increase in the received signal level along with a change in the fading characteristics. Specific examples of various fading characteristics will be given later. Means were not available for making refractive-index soundings along the propagation path to confirm the existence of superrefractive conditions from meteorological measurements.

Continuous transmission data on the Wallops Island to Dam Neck path were taken for a three-day span in February 1969, and the results are presented in Fig. 5 with several periods of superrefraction being indicated. Both horizontally and vertically polarized signals were transmitted and received; however, since no significant differences were found in the propagation characteristics for the two polarizations, the discussion to follow will be limited to the horizontally polarized component of the wave. Looking at Fig. 5 for Feb. 4, it is observed that the path loss is close to the calculated value for the first nine hours, but after 1600 EST there is a sudden decrease in transmission loss (signal enhancement), which continued for about seven hours. This change would indicate that superrefractive conditions were being experienced along the path, and an examination of the fading characteristics during this period definitely tended to confirm the existence of superrefractive conditions. Similarly, on examining Fig. 5 for Feb. 5, it is observed that the basic transmission loss, after remaining near the calculated value for about 17 hours, shows a signal enhancement beginning at 1700 EST, eventually reaching a maximum level 54 dB less than the calculated mean value of basic transmission loss. It is of interest here to note that the U.S. Weather Bureau reported that a strong cold front had moved off the east coast and was positioned almost coincident with the Wallops Island to Dam Neck path at 1900 EST on Feb. 5, 1969. Observations by many experimenters have tended to show that strong superrefractive conditions, producing large signal enhancements, are quite often experienced along a weather front; however, Albrecht (6) presents experimental data to indicate that tropospheric propagation paths perpendicular to a cold front often exhibit subnormal signal levels. Figure 5 for Feb. 6 shows superrefractive conditions existing for most of the day on Feb. 6, except for a six-hour period between 0500 and 1100 EST, while on Feb. 7, after a few hours of superrefractive conditions around 0200, the transmission loss increased to a level 13 dB greater than the calculated value. The existence of any specific type of recurring diurnal pattern is not to be inferred from Fig. 5, since the propagation mechanism is directly dependent upon the meteorological conditions existing along the path, and this region during the winter season is subject to very active cyclonic conditions which would usually predominate over any diurnal temperature and humidity variations.

Later in the month of February, transmission data were taken on the 25th, 26th, 27th, and 28th; and as can be seen in Fig. 6, no evidence of any superrefraction is indicated. On Feb. 25 and 26, (Fig. 6), the transmission loss is close to or slightly greater than the calculated value, but on Feb. 27, the transmission loss is about 8 dB greater than the calculated value, indicating subnormal tropospheric scatter propagation conditions for the entire 11-hour sample period. Note also the extremely low levels on Feb. 28. Extended periods of extremely low signal levels during the winter season have been reported on many land-based troposcatter circuits and apparently will also be experienced on over-seawater circuits. The magnitude and duration of these periods of subnormal signal level are an important factor in designing a troposcatter circuit, for if the design is just marginal for the normal mean level, long periods of outage may be experienced during the winter season.

In considering the design of a troposcatter circuit with regard to minimum acceptable signal levels, the winter season results must be given the most weight, since all indications are that the maximum transmission losses will occur in the winter season.

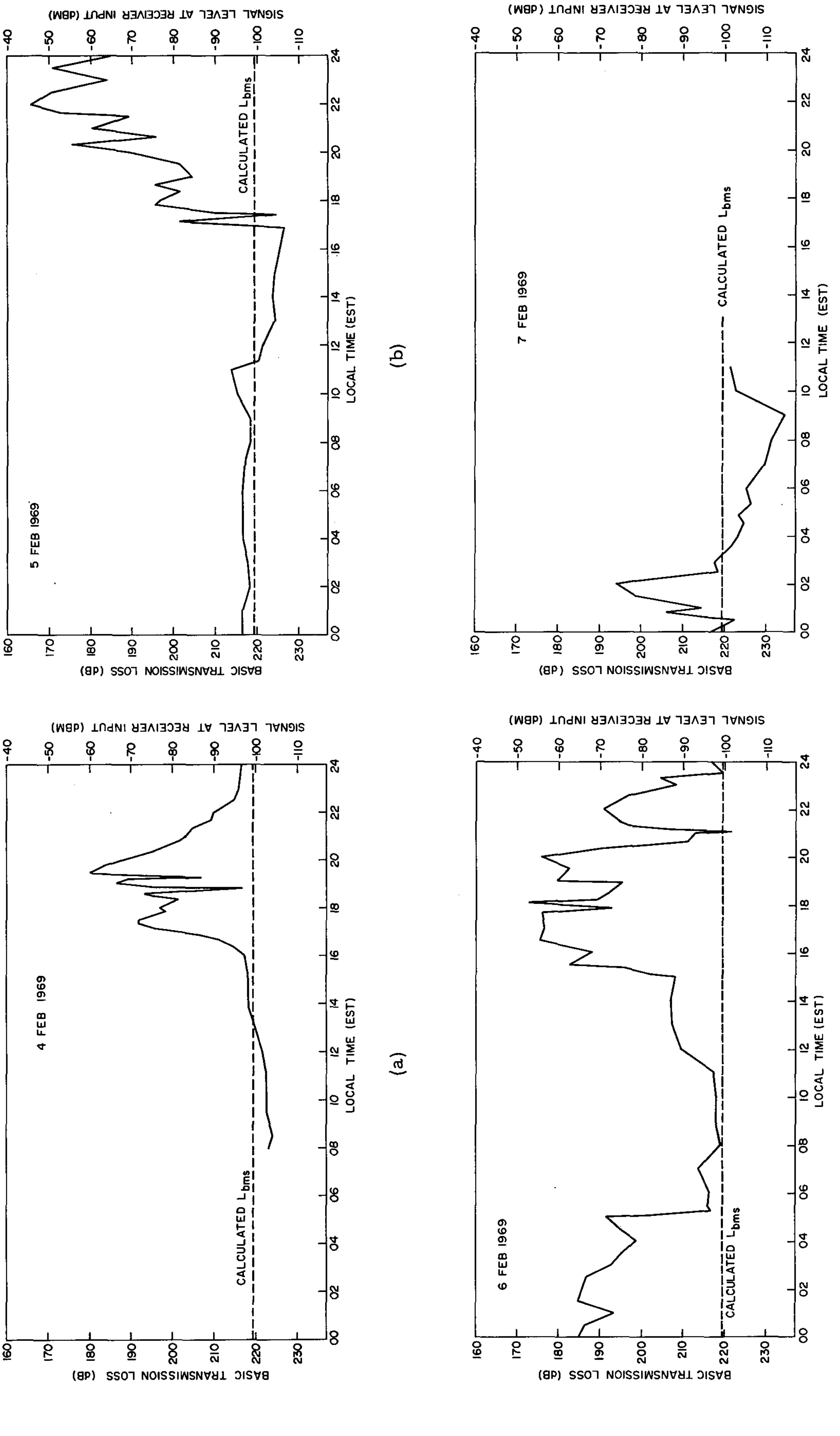


Fig. 5 - Variation with time of basic mean transmission loss for the Wallops Island to Dam Neck, Virginia, troposcatter circuit from Feb. 4 to 7, 1969; horizontal polarization, path length 72.8 naut mi

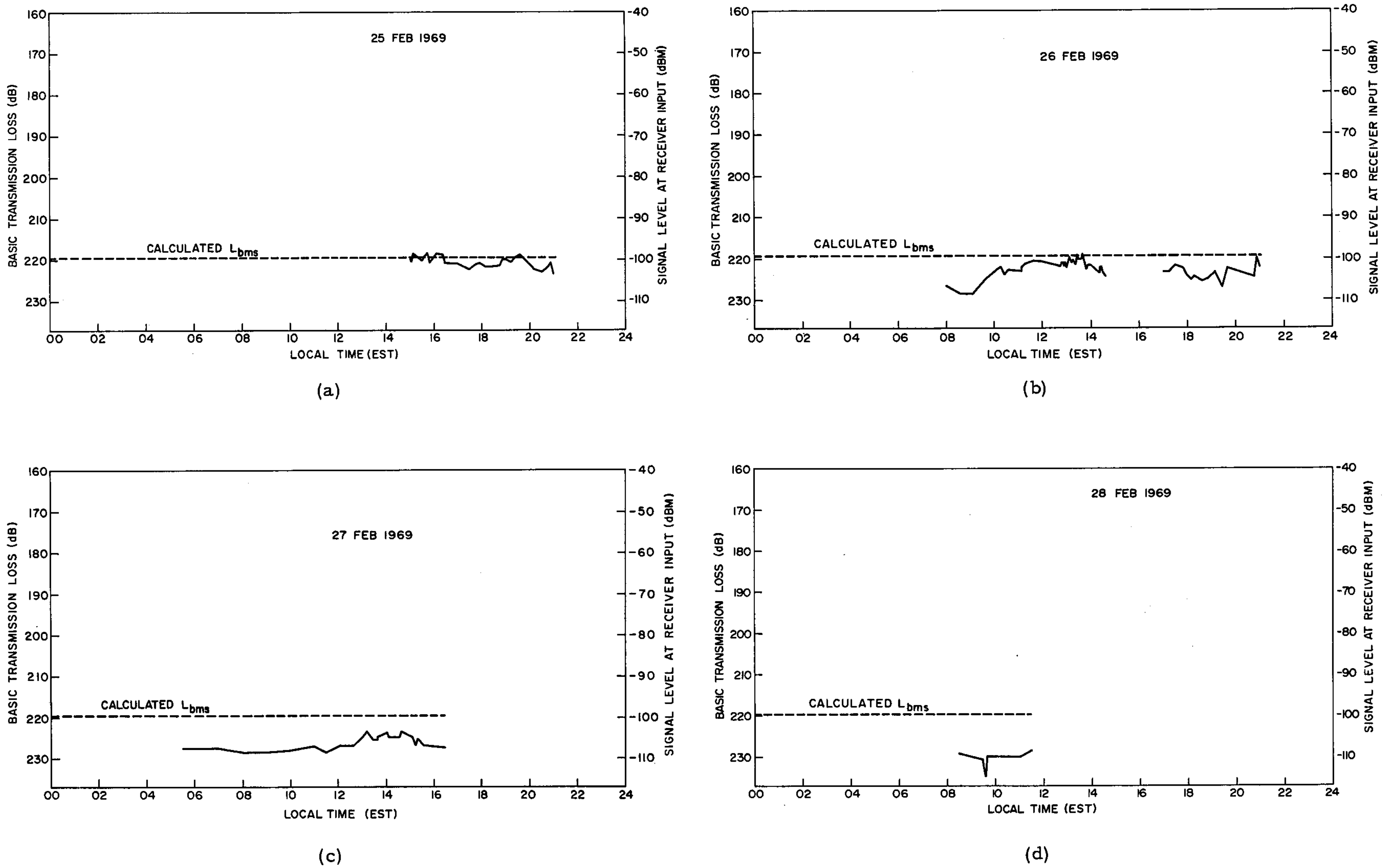
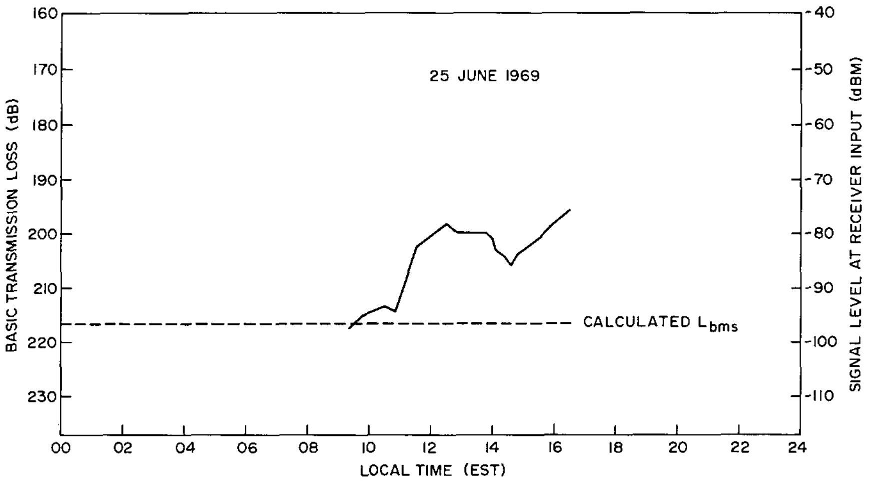
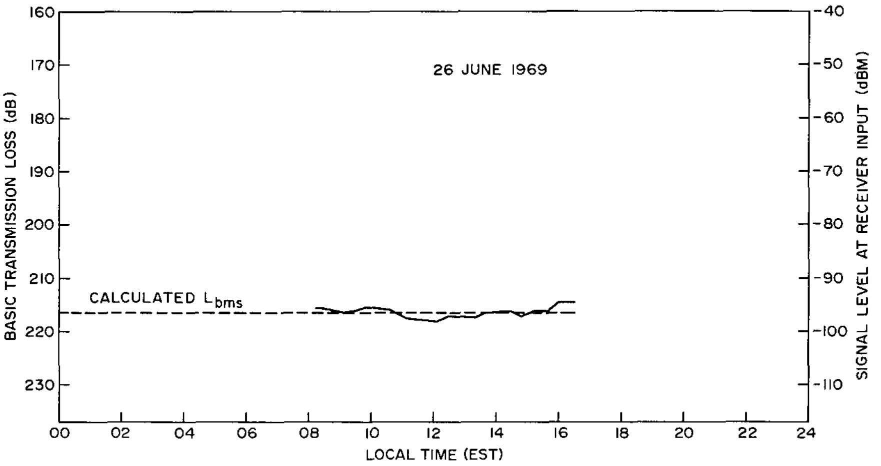


Fig. 6 - Variation with time of basic mean transmission loss for the Wallops Island to Dam Neck, Virginia, troposcatter circuit for portions of Feb. 25, 26, 27, and 28; horizontal polarizations, path length 72.8 naut mi

Data were taken all seasons of the year, however, and Fig. 7 shows some summer season results for two successive days in June 1969. On June 25, a superrefractive condition developed soon after beginning the data recording and continued throughout the day. On the following day, June 26, scatter-type transmission characteristics were experienced throughout the eight-hour data period, with the level being very close to the calculated value of basic mean scatter loss for this period. As previously discussed, a rather high percentage of superrefractive-type transmission (55 percent of the total time data were recorded) was observed during the summer, but extended periods of subnormal propagation were not experienced. On several occasions heavy rain observed at either or both terminals resulted in large increases in the path loss, from 10 to 15 dB, but the signal always recovered rapidly to near previous levels when the rain had stopped.



(a)



(b)

Fig. 7 - Variation with time of basic mean transmission loss for the Wallops Island to Dam Neck, Virginia, troposcatter circuit for portions of June 25 and 26 1969; horizontal polarization, path length 72.8 naut mi

A cumulative distribution of all path-loss data (including superrefractive conditions), observed at various periods from September 1968 to September 1969 for the Wallops Island to Dam Neck, Virginia, circuit, is presented in Fig. 8. It is interesting to note that the path loss varied over a total range of 74 dB, and in many instances, relatively rapid changes in path loss were observed. This range of values is of significance in designing a troposcatter system, as it shows the need for a large dynamic-range capability in the receiving system. The lowest value of path loss was only 10 dB greater than the free-space loss (156 dB), while the maximum measured path-loss values were as much as 20.5 dB greater than the calculated basic mean transmission loss.

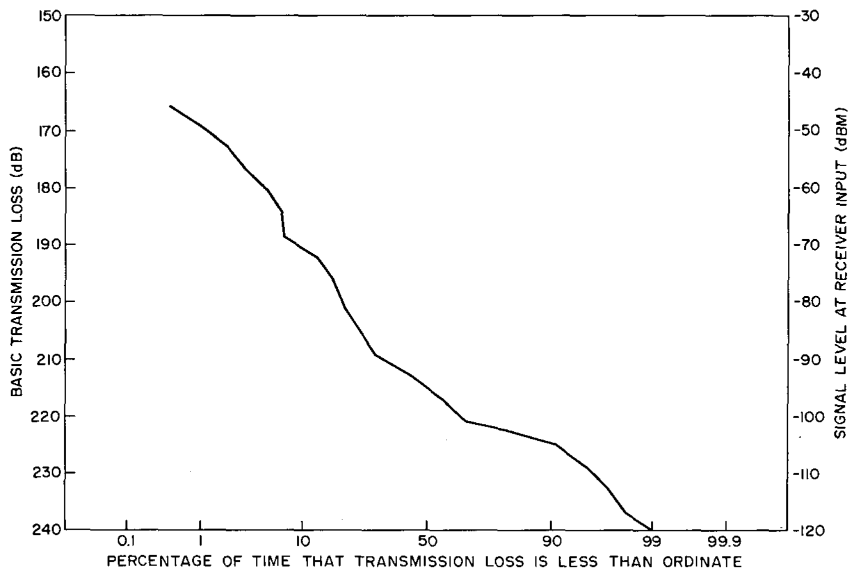
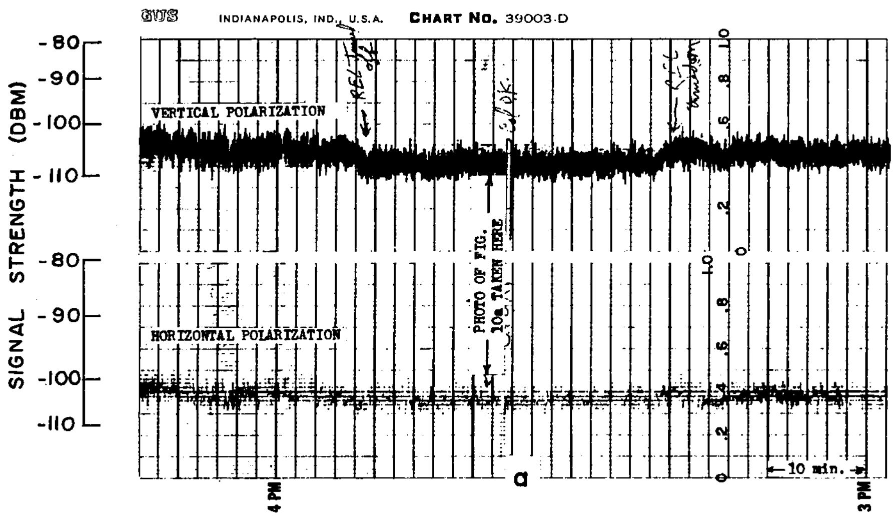


Fig. 8 - Cumulative distribution of the basic mean transmission loss for the experimental X-band troposcatter circuit

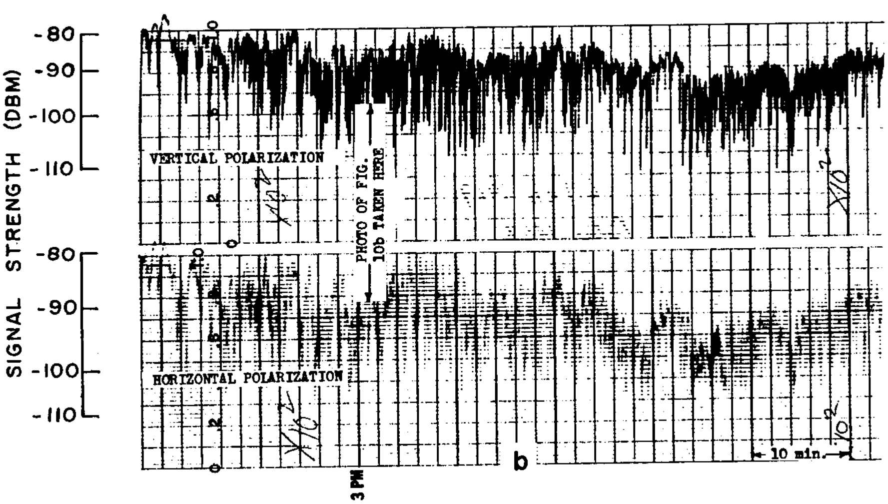
Fading Characteristics

The fading characteristics of the troposcatter mode of propagation have been thoroughly investigated by numerous experimentalists and theoreticians; therefore, no studies of this aspect of troposcatter were pursued. The fading characteristics of the received signals, however, were employed as the principal indicators for determining whether the primary mode of propagation was troposcatter, superrefraction, or an intermediate condition. Also, in order to be able to predict the performance characteristics of a troposcatter circuit in the X-band frequency range from the mean signal level variations, it should be verified that the signal fading distributions at X-band are similar to those encountered at vhf and uhf, where the fading characteristics are well known.

In Figs. 9 and 10, three conditions of fading are illustrated. Figure 9 shows three sections of strip-chart recordings under different propagation conditions. The chart is a record of the weighted receiver output voltages, with the time constants employed having a characteristic of 600 milliseconds charge and discharge time. The chart recording shows the medium- and long-time fading, but due to the relatively long-time-constant limitation, cannot show the rapid fades. The latter are illustrated in Fig. 10, where photographs were obtained employing an oscilloscope connected to the 30-MHz i-f output of the wideband FM receiver, and should closely approximate the true signal envelope. Each of the photographs in Fig. 10 corresponds in time to a portion of the strip

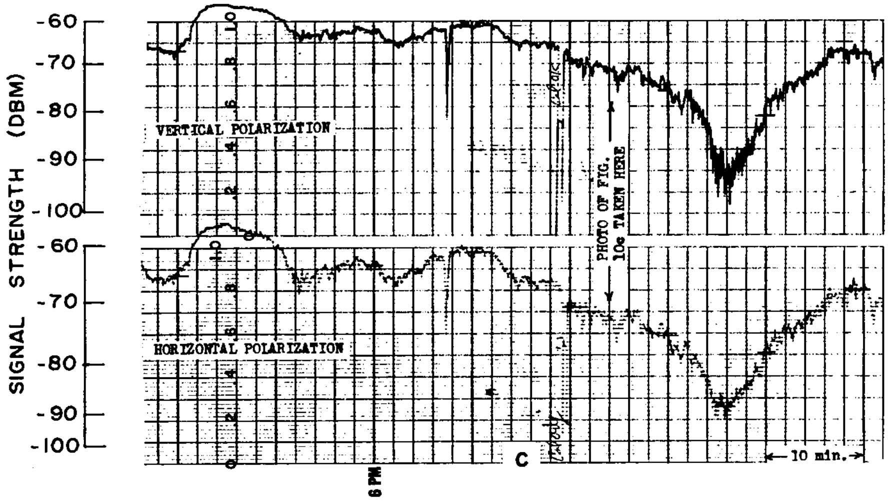


(a) Rapid fading characteristic of troposcatter



(b) Medium fading rate with occasional deep fades

chart displayed in Fig. 9. Figures 9a and 10a illustrate troposcatter conditions with many fades per second, while Figs. 9c and 10c are for a period of rather intense superrefraction with almost no short-time fading. Figures 9b and 10b are for a condition where both the troposcatter and superrefraction modes appear to be providing contributions to the received signal. In summarizing the data in Table 1, only transmissions exhibiting the type characteristics illustrated in Figs. 9a and 10a are considered to be troposcatter. All other data are considered to be enhanced to some degree by superrefractive effects. The total sample period is relatively small, consisting of about 100 hours of observation for each season but is fairly ... ll scatt r d throughout ... ch ... on



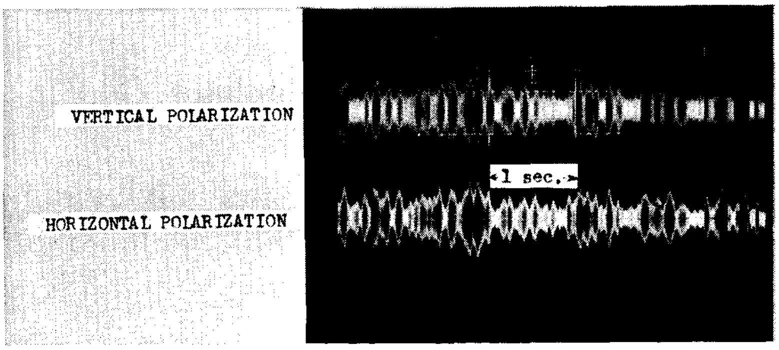
(c) Relatively steady for short periods but with long-time fades

Fig. 9 - Strip-chart recordings showing the average signal-level variations for three types of fading conditions observed on the X-band troposcatter circuit between Wallops Island and Dam Neck, Virginia

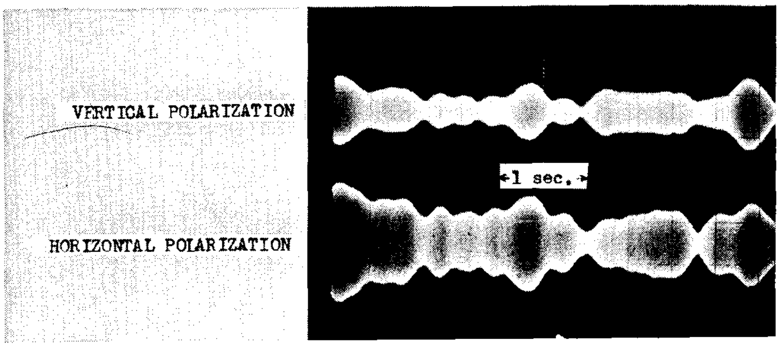
As shown in Table 1, the incidence of superrefractive conditions is substantially higher in the summer season than at other times of the year. The spring and fall seasons were grouped together, since the meteorological conditions for these two transitional seasons are somewhat similar.

The distributions of the weighted mean signal-level variations during two periods for which the dominant mode of propagation was judged to be forward scatter are shown in Figs. 11 and 12 and are plotted employing Gaussian distribution coordinates. A commonly used criterion for the fading range of a signal is the difference in signal levels, expressed in decibels, exceeded 10 and 90 percent of the time. Figure 11 shows a fading range of 10 dB, which is somewhat greater than was observed for the majority of the test transmissions. Figure 12 shows 3.1 dB fading range, which is a more typical distribution for the data recorded on this circuit.

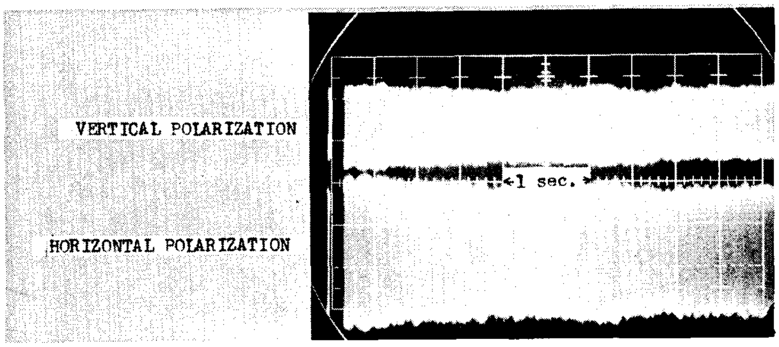
As seen in Figs. 11 and 12, the weighted mean values exhibit the expected normal distribution, but theory, as well as a considerable amount of past experimental data concerned with troposcatter propagation (7), has shown that the actual signal envelope of rapid fading when analyzed over a small interval of time (not exceeding several minutes, usually) exhibits a Rayleigh distribution. Figure 13 shows this to be the case for a distirbution derived form the oscilloscope data for a five-second period of time of the data envelope during a typical period of scattermode propagation. A straight line drawn through the points as plotted on Rayleigh Statistical Paper results in the 13.4-dB differential between the 10 and 90 percent ordinate values, as required for a Rayleigh-type distribution.



(a) Rapid fading



(b) Moderate fading



(c) Relatively steady

Fig. 10 - Oscillograms showing the short-term fading characteristics of a portion of the corresponding sections of strip-chart records as illustrated in Fig. 9

Table 1
Incidence of Superrefractive Transmission Conditions at Different Seasons of the Year

Season (1968-1969)	Percentage of Time Superrefractive Transmissions are Observed
Winter	32
Spring-Fall	28
Summer	56

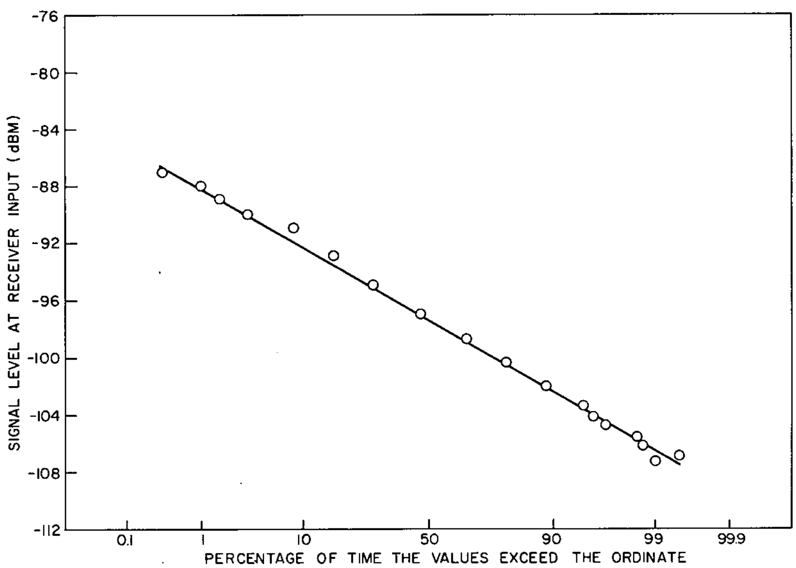


Fig. 11 - Signal-level distribution for a one-minute sample of troposcattermode transmission on June 27, 1968. The levels plotted are mean values derived from a detector circuit having time-constant characteristics of 600 milliseconds charge and discharge.

Polarization Diversity

The improvement in data transmission resulting from the employment of space and/ or frequency diversity in the operation of a troposcatter link has been demonstrated over the years and is now a widely accepted technique. However, these systems require two or more antennas, which are spaced an appreciable distance apart, at each terminal of the circuit. Polarization diversity can be accomplished by using a single antenna structure (but with two feedlines) at each terminal, thus offering significant space-saving advantages over the more commonly used diversity systems. Information regarding the effectiveness of polarization diversity at X-band frequencies is rather sparse. Therefore, an investigation of polarization diversity was made in connection with the operation of the Wallops Island to Dam Neck troposcatter circuit. However, because of certain design limitations in the error-counting equipment, only qualitative results can be reported. Figure 10 is quite typical of the many oscillograms taken of the received signal envelopes

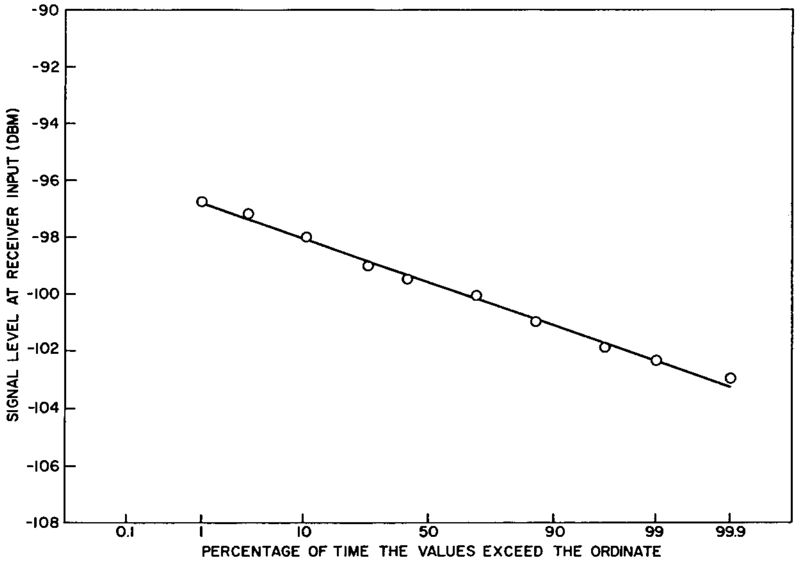


Fig. 12 - Signal-level distribution for a one-minute sample of troposcattermode transmission on Oct. 10, 1968. The levels plotted are mean values derived from a detector circuit having time-constant characteristics of 600 milliseconds charge and discharge.

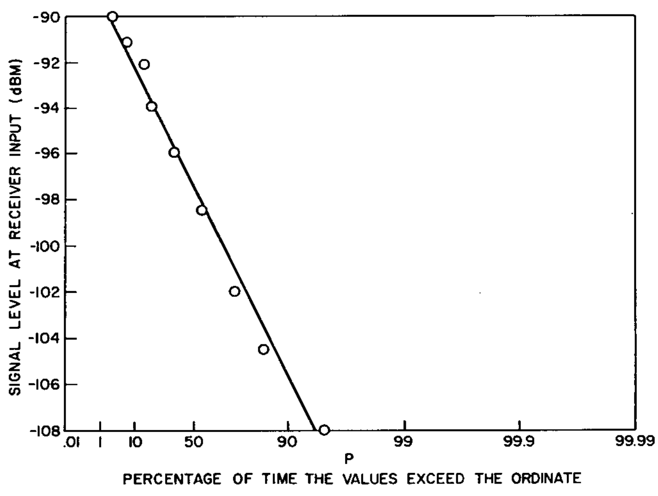


Fig. 13 - Signal-level distribution for a five-second sample of troposcatter-mode transmission on Oct. 18, 1968. The levels plotted are derived from an oscillogram of the amplified intermediate-frequency envelope.

under various propagation conditions, and in general, when comparing the vertical and horizontal envelopes, a rather high degree of correlation is observed. It must then be concluded that combining the two polarizations would not produce a very significant improvement in fading characteristics. Perhaps over longer paths than investigated herein, the technique would offer increasing advantages because of the greater scatter dispersion of the two polarization components.

Meteorological Effects

Probably the most serious effect observed on the experimental troposcatter link which would be of concern in the employment of an X-band troposcatter system by the fleet was the complete disappearance of the signal during periods of heavy rain. Another problem previously mentioned concerns the periods of subnormal propagation observed during the winter season.

There is a rough correlation of superrefractive conditions and surface wind velocity, since calm wind conditions obviously favor stratification of the atmosphere. In Fig. 14, the wind velocity is plotted for a three-day period in February 1969, during which continuous recordings were made over the Wallops Island to Dam Neck circuit. The bars plotted along the top of the graph indicate periods during which superrefractive transmission conditions were observed. The wind speeds are from the Norfolk Municipal Airport, which is located about 12 miles west of the propagation path. It is seen, in general, that periods of superrefraction tend to occur during the minimum wind-speed periods; however, the correlation is not very precise. Examination of the data taken intermittently over a one-year period in connection with the circuit showed that there were instances when superrefraction occurred during rather windy conditions, but interestingly, these occurrences were usually around the time of a cold-front passage across the propagation path. In conclusion, it might be stated that the correlation of superrefractive conditions with low wind velocities, while showing a definite trend, is far from being a thoroughly reliable indicator.

RESULTS

In order to evaluate the results of this experiment, some graphs predicting transmission loss under various conditions are presented and compared with the values observed on the Wallops Island to Dam Neck circuit. The graphs are derived using the methods given in Ref. 5.

Figure 15 shows the values of transmission loss as a function of distance in the scatter region out to 300 naut mi. The family of curves shows the percentage of time over a year that the transmission loss will be equal to or less than the indicated value. Referring back to Fig. 8, which is the plot of the cumulative distribution of the transmission loss for all the data observed over the circuit, a comparison of the predicted and observed values is presented in Table 2.

For the 99-percent level, the observed transmission loss is higher than the predicted value by 6 dB, while at the 90-percent and median levels, the observed losses are slightly less than the predicted losses by 1.5 dB and 3 dB respectively. This observation would indicate that for the median level, the methods of Ref. 5 give good agreement with the experimental results, but caution would have to be employed in designing for the system sensitivity required, since the theoretical predication tends to be optimistic. Except for the limitation as mentioned previously, the curves should be a useful guide in predicting transmission loss at X-band frequencies out to a distance of 300 naut mi. The lower levels of transmission loss to be experience ten percent and one percent of the time are not of much importance in designing a troposcatter circuit, except as an indication of the

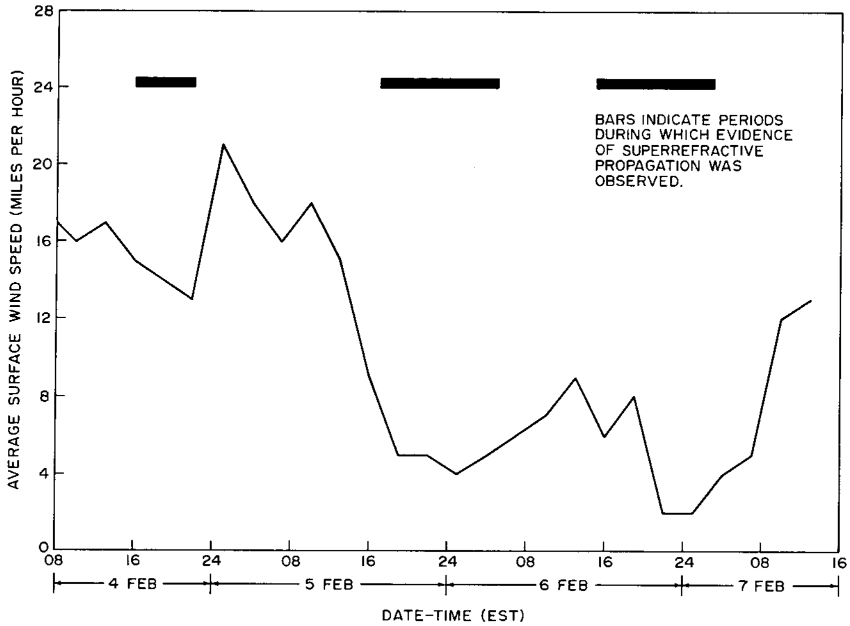


Fig. 14 - Incidence of superrefraction on the experimental troposcatter circuit as related to average surface wind velocity for a three-day period in February 1969

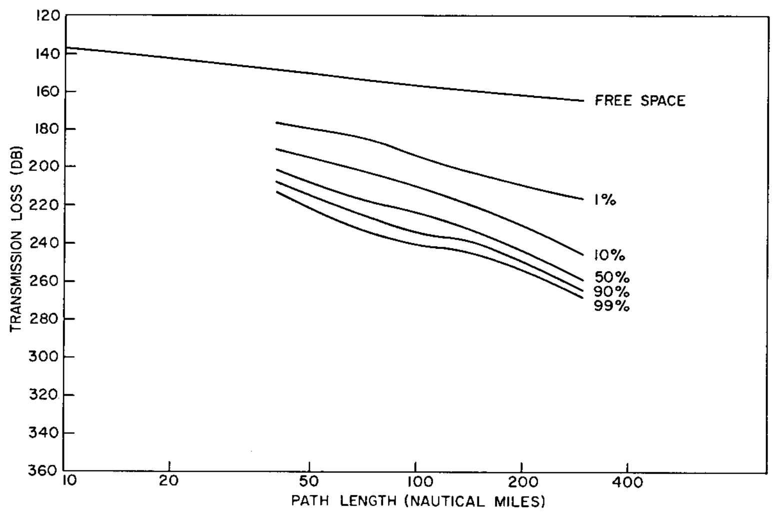


Fig. 15 - Calculated values of transmission loss as a function of distance, with curves showing various percentages of time that the transmission loss will be equal to or less than the ordinate

Table 2
Comparison of Predicted and
Observed Transmission Loss Values

Time Transmission Loss is Equal To or Less than Value Indicated (percent)	Transmission Loss (dB)	
	Predicted	Observed
99	234	240
90	226	224.5
50	218	215
10	203	190.5
1	186	169

total expected amplitude range of the received signal. As all transmission levels, including superrefractive conditions, were totaled in the distribution of Fig. 8, the observed losses at ten percent and one percent are somewhat lower than predicted, if the latter values are based on the scatter mode only.

Some further comparison of the predictions of troposcatter circuit performance based on the methods given in Ref. 5 and the results observed on the experimental circuit are now presented. The grade of service to be expected from various antenna combinations, with a specified set of transmitter and receiver characteristics, is given in Fig. 16, approximating the conditions for the Wallops Island to Dam Neck circuit. The parameters here are as follows:

Transmitter power	10 kW
Frequency	7760 MHz
Antenna heights	70 ft
Receiver input sensitivity (for data transmission)	-98.5 dBm
Data rate	4800 bits per second

The calculations included the reduction in the theoretical antenna-pattern gains at increasing distances resulting from phase incoherence over the aperture of the antenna. The largest antenna considered was the eight-foot-diameter parabolic, since antennas larger than this probably would not be acceptable aboard ship.

The experimental results obtained from the Wallops Island to Dam Neck troposcatter circuit, as shown by the cumulative distribution of received power (Fig. 8), indicate that 60 percent of the time the signal levels would be adequate for successful data transmission based on the minimum power level input necessary to operate the system. This percentage value is plotted (x) on Fig. 16 and falls very close to the curve for the eight-foot parabolic-to-omnidirectional antenna case, lending confidence in the application of the methods of Ref. 5. The curves of Fig. 16 indicate quite definitely that with the receiving system employed and a transmitter power of 10 kW, the goal of employing an omnidirectional antenna at one of the circuit terminals for path distances out to 300 naut mi is not feasible. The big obstacle in attempting to design a troposcatter system employing at least one omnidirectional antenna is the great reduction in antenna gain of the latter compared to even a modest size parabolic antenna. In the experimental link, here being considered, even though the omnidirectional antenna employed was specially designed to

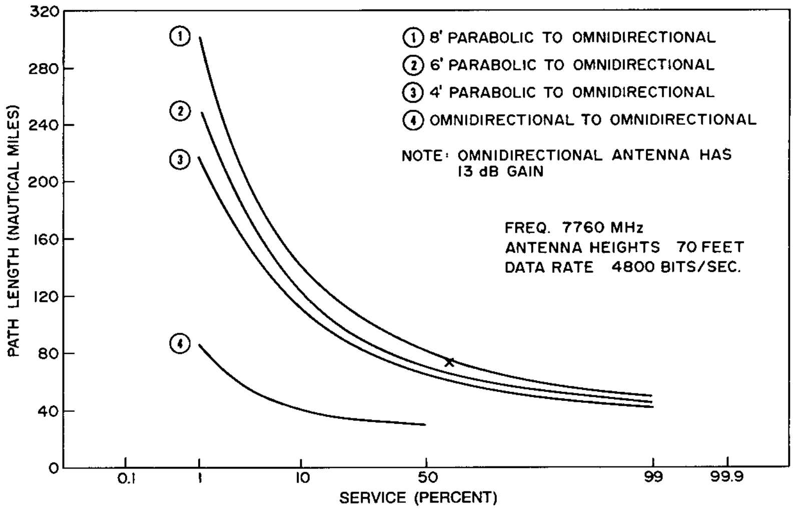


Fig. 16 - Calculated values for grade of service as a function of path distance employing various antenna combinations. The x indicates the percent service indicated by the experimental results on the Wallops Island to Dam Neck circuit.

have a gain of 13 dB, it was nevertheless still 30 dB lower in gain than the eight-foot parabolic antenna. It is not feasible to make up this difference in gain by employing increased transmitter power, as 10 kW would be about the maximum allowable aboard a naval vessel to avoid excessive interference to other services aboard ship. The receiving-system noise figure is appoaching the theoretical limits for the bandwidth employed; thus, only relatively small improvements are indicated as being possible from further receiver developments. It seems, therefore, that if any substantial improvements in system performance are to be made, they would lie in the development of more efficient modulation techniques and improved diversity systems.

The omnidirectional-to-omnidirectional antenna case is extremely unpromising, as can be seen by referring to Fig. 16, which shows that at the 72.8-naut-mi path distance of the experimental link, the service would be only about 1-1/2 percent. Attempts to operate the experimental link with omnidirectional antennas at each terminal gave negative results, with the signals at the receiver being below the threshold of detectability on all occasions for which such transmission was attempted.

Transmission and reception on the experimental troposcatter circuit, with eight-foot-diameter parabolic antennas, gave close to the theoretical 30-dB increase in signal being realized, as compared with the eight-foot parabolic-to-omnidirectional antenna case. The former antenna combination would result in the circuit having a signal input to the receiver in excess of the minimum system requirements somewhat more than 99 percent of the time.

CONCLUSIONS

The transmission-loss values experimentally determined intermittently over the one year of operation of the troposcatter link were in good general agreement with the predicted values obtained by employing the methods of Ref. 5. In predicting the performance of future contemplated troposcatter circuits, it is recommended that the methods of Ref. 5 be applied to determine the possible success of such systems.

From the results obtained on the 72.8-naut-mi X-band troposcatter link between Wallops Island and Dam Neck, Virginia, it was found that data transmission over this link would be only marginal when employing an omnidirectional antenna at one terminal of the circuit. Therefore, the originally stated requirement of operation at ranges for task-force communications out to 300 naut mi would not be realized. The conclusion, of course, is based entirely on the terminal equipment employed in this experiment and could be subject to modification with advances in receiving equipment and the development of more sophisticated modulation and diversity techniques. For example, the spread-spectrum concept, which operates by repeatedly sampling transmission effectiveness on a number of different frequencies and automatically selecting the optimum frequency to use for short bursts of information transmission, promises a considerable improvement in system capability. As previously mentioned, since the basic mean transmission-loss values obtained during these experiments are only a function of the propagation medium, they should be useful in determining the operating capabilities of future systems which might be proposed.

ACKNOWLEDGMENTS

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