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Ultra-Short-Wave Transmission and Atmospheric Irregularities

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Results of an ultra-short-wave fading study are here reported. Transmission was carried out in the range of 1.6 to 5.0 meters, over a 70 mile (112.6 kilometer) ocean path, on 106 days during a period of two years. Both horizontal and vertical polarizations were used and during part of the time a 6-megacycle amplitude, 120-cycle, frequency modulated transmission was added, for the cathode-ray tube observation of the frequency characteristics of the radio path. On 45 mornings records were taken, on vertically polarized radiations, during the flight period of the Mitchel Field Weather Bureau plane.

Fading was found present practically all of the time. Amplitude changes up to 40 db and fading rates up to 5 fades per minute were found. Simultaneous transmission of the same wave in two polarizations, and of two waves of different wave-length in the same polarization showed that the horizontally polarized component was practically always, and the shorter wave-length one was usually the worse fader of the pair. The greater part of the time there was no correlation between the fading of these radiation pairs; occasionally, however, and for the slow, smooth amplitude, undulating type of fading, coincidence was observed. The frequency sweep patterns showed multiple signal components to be present, with various degrees of relative phase retardation.

A tentative explanation is proposed for these phenomena. This theory assumes the presence of a refracted-diffracted signal component, transmitted along the earth's surface and calculable in the manner of Wwedensky, Van der Pol and Gray, and one or more signal components reflected from air mass boundaries. The airplane results are shown to be in reasonable agreement with the frequency sweep observations. Boundary heights from 5.5 kilometers down to 1.9 kilometers are measured; below 1.9 kilometers other boundaries are indicated. The receiver band, flat over two megacycles, sets the low height limit of resolution of reflecting boundaries at 1.9 kilometers. Most of the boundaries are at the lower heights.

A discussion is given of some observations of signal fading at various wave-lengths which have been reported by other observers, and which are apparently referable to the same mechanism as is here proposed.

Introduction

IN an earlier paper [1] experimental data were presented which indicated that the transmission of ultra-short-wave signals was dependent upon the state of the atmosphere, in particular upon its water vapor content. The present paper contains the results of a continuation of this work where a two-year survey of ultra-short-wave transmission over a 70-mile (112.6 km.) ocean path was carried out. Transmission was had on 106 days during this period.

In planning this work, preparation was made for seeking a correlation between atmospheric structure and signal intensity; but from the very first transmission fading was found, and this fading was so persistent and intense that the work became essentially a fading study.

In the following paragraphs there are discussed, in the order named, Antennas and Locations; Apparatus and Operation; General Characteristics of Fading, with samples of records taken; Polarization Effect on Fading, with sample records; Wave-length Effect on Fading, also with records; Distance and Antenna Height Effects on Fading; Frequency Sweep Patterns of Fading, with sample records; and the logs taken during the flights of the U. S. Weather Bureau airplane for taking free air data. The presentation of experimental data is then interrupted to present a theory which explains several of the experimental observations. This is followed by further experimental results and checks, and concluding remarks.

Antennas and Locations

Figure 1 shows the layout of the radio circuit. The transmitter was erected at Highlands, New Jersey on the edge of a steep hillside. This edge made an angle of about 45° with the transmitter-receiver direction. Below the edge of the hill lay a strip of land slightly above sea level (seven to eight feet) and beyond was Sandy Hook Bay. The altitude at the antenna foot was 119 feet. The antennas consisted of a vertical rhombic terminated in its surge impedance with carbon lamps, a horizontal rhombic with the same termination, an unterminated inverted "Vee" antenna and a half-wave doublet. This doublet was equipped with a flexible transmission line which permitted it to be raised to the top of the antenna supporting mast. These antennas were supported on a central 60-foot (18.3 meter) lattice mast surrounded by four 30-foot (9.15 meter) poles.

The receiver was located on a plot of land at East Moriches, Long Island, New York. This plot was immediately at the edge of Moriches Bay and was only slightly (approximately four feet) above sea level. The same antenna equipment was supplied here as at the transmitter. Except for the transits across Sandy Hook, Fire Island Beach and Smith Point, the wave path was over sea water. A second receiving site at West Sayville, at the edge of Great South Bay, was briefly occupied, using portable receiving equipment. This site was 52¾ miles (85 km.) from Highlands.

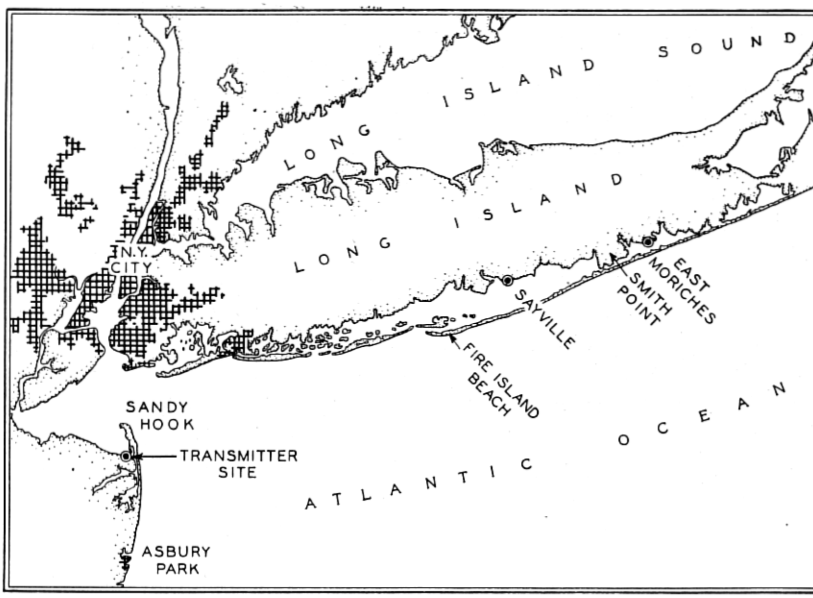


Fig. 1—Map of ultra-short-wave transmission path between Highlands, New Jersey, and East Moriches, Long Island.

Apparatus and Operation

In all, three transmitters were installed at Highlands. The first one, of 100 watts output, covered the wave-length range of 5.0 to 3.5 meters. It was equipped with a motor-driven single-turn short-circuit loop which, coupled with the tank circuit coil, produced a 120-cycle frequency modulation of six megacycles amplitude. For calibration purposes there was added a low-gain double-detection receiver which used an intermediate frequency of one megacycle and was connected so as to pick up an input from the transmitter. The beating oscillator of the receiver was set for the center of the transmitter frequency sweep and the receiver output triggered a gas tube connected to the transmitter tube grids. The transmitter grids thus received a voltage pulse each time that the transmitter frequency passed through one megacycle above or below the beating oscillator frequency. Each transmitter frequency sweep was thus marked with two pulses spaced two megacycles apart.

The second transmitter had Lecher wire tuning elements, covered the wave-length range of 3.5 to 1.2 meters and had a power output of 30 watts at 1.5 meters. It was in operation simultaneously with the first transmitter for six months and then was replaced by transmitter No. 3.

The third transmitter was coil tuned, covered the wave-length range of 4.9 to 2.8 meters and had a power output over this range of 55 watts down to 35 watts. It was operated simultaneously with the first transmitter except for the first six months.

All three transmitters were arranged for voice modulation through a simple grid input, and the first one was thus used for one-way communication during the entire period of operation.

Normally, unmodulated waves were transmitted and were observed as rectified direct current in the output of the double detection receivers. These receivers had attenuators, variable in steps of 1 db, in the intermediate frequency amplifier circuits and the attenuators were geared to the pens of manual recorders. The operators kept the output current constant by means of the attenuators just mentioned, and there resulted a record of signal amplitude versus time. Some use was made of the Esterline-Angus type of milliampere recorder for automatic recording but no linear scale recorder of this type could handle the amplitude range of the fading encountered.

For the reception of the frequency modulated transmission a tuned radio-frequency receiver, with a three-megacycle band-width centered on 66 megacycles (4.55 meters), was constructed and its rectified output was applied to one pair of plates of a cathode ray oscillograph. A linear sweep voltage, manually synchronized with the transmitter 60-cycle power voltage, was applied to the second pair of plates. The oscillograph pattern thus pictured the frequency-amplitude characteristic of the radio circuit in toto. Over the frequency range where the receiver band was flat (two megacycles) the curve gave the apparent ether characteristic. With a motion picture camera this characteristic was permanently recorded.

Fading Characteristics, General

The fading was always slow compared with that observed on short waves. Except for the rapid fluctuations produced by airplane reflections, a record speed of $\frac{5}{8}$ inch (1.6 cm.) per minute was sufficient. This was our standard speed. Amplitude changes up to 40 db and fading rates up to 5 fades per minute were observed.

It is difficult to describe the fading in any other way than by the records. From a transmission standpoint a curve giving the per cent of time during which the signal is above the abscissa value is useful.

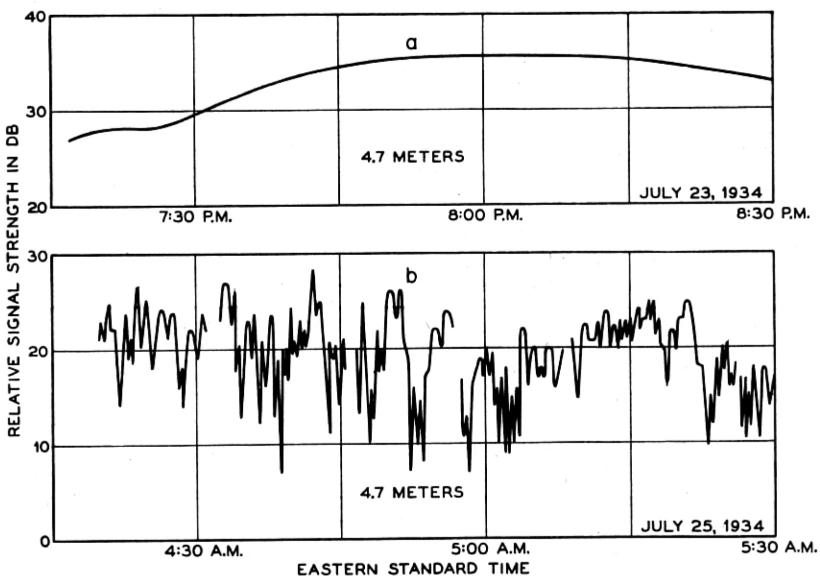


Fig. 2—Fading extremes, vertically polarized transmission; inverted "V" antennas.

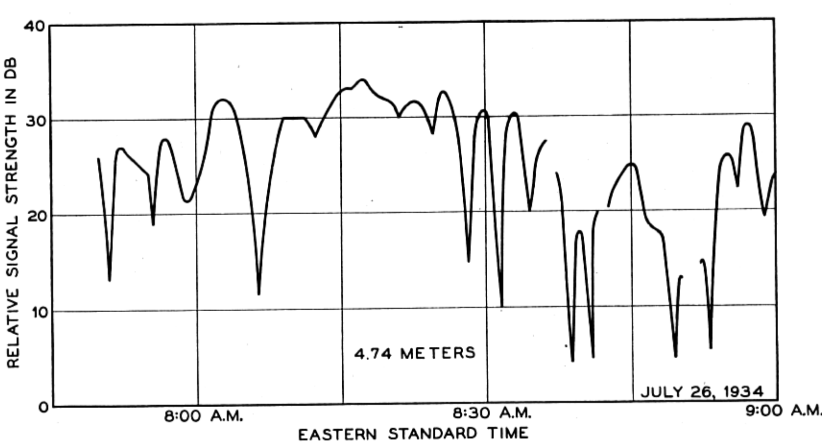


Fig. 3—Extreme amplitude, normal fading rate, vertically polarized transmission; inverted "V" antennas.

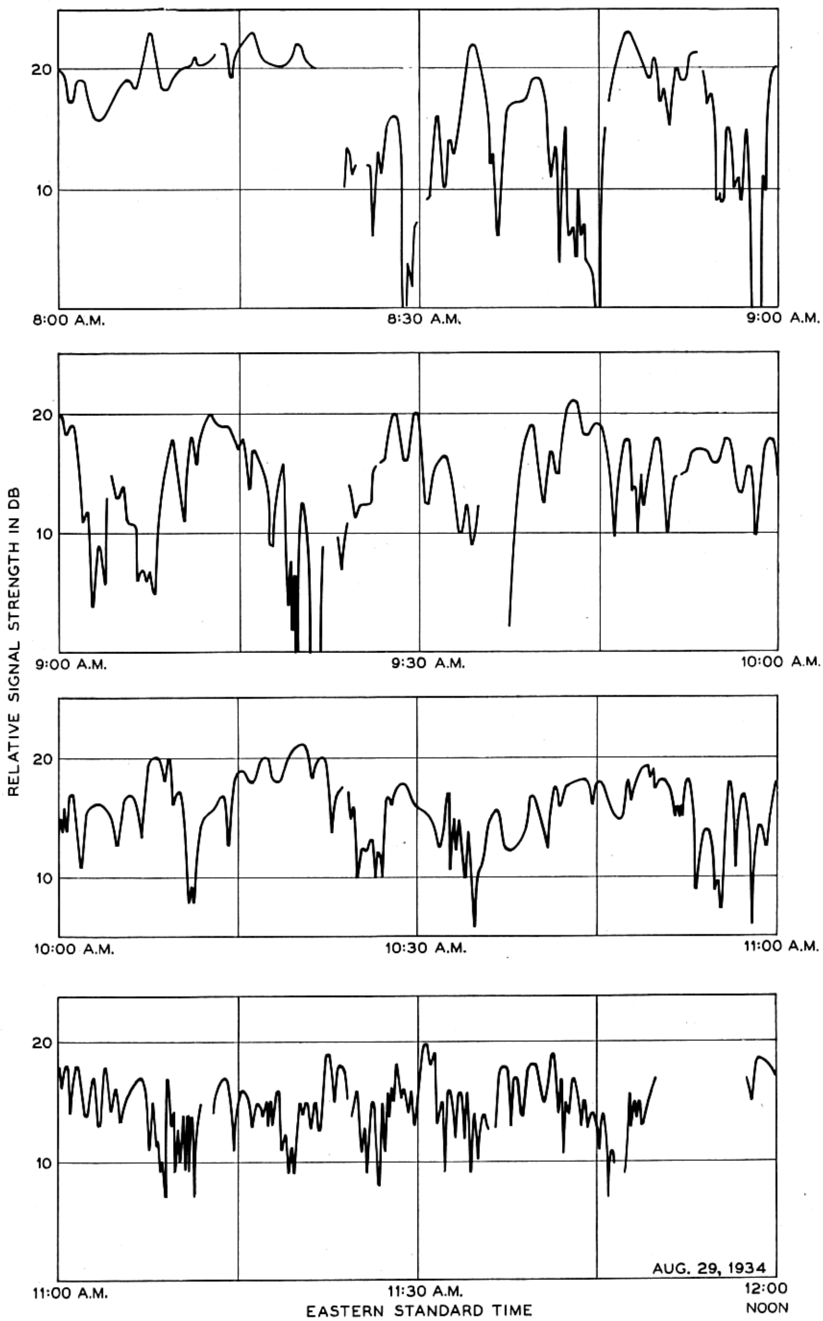
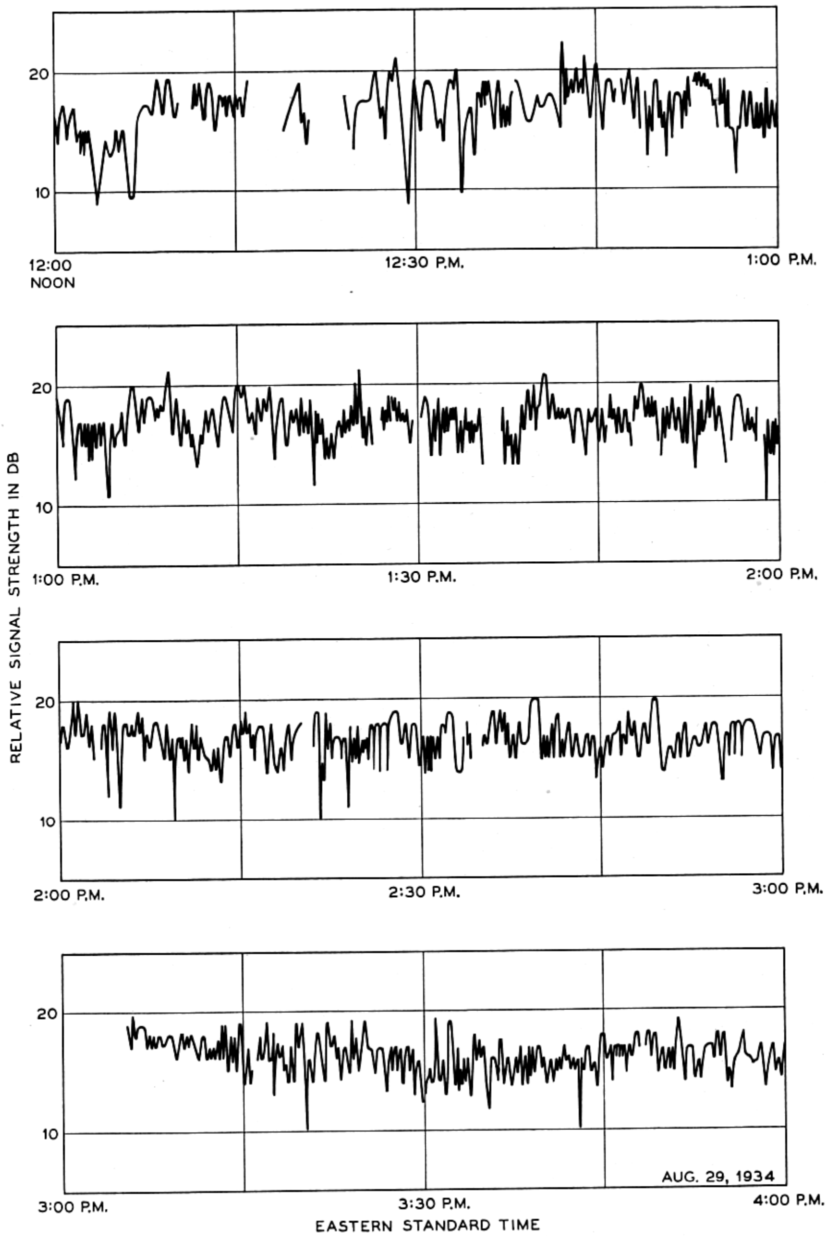


Fig. 4—Development of "scintillation" fading on vertically polarized



transmission, 4.74 meters wave-length; inverted "V" antennas.

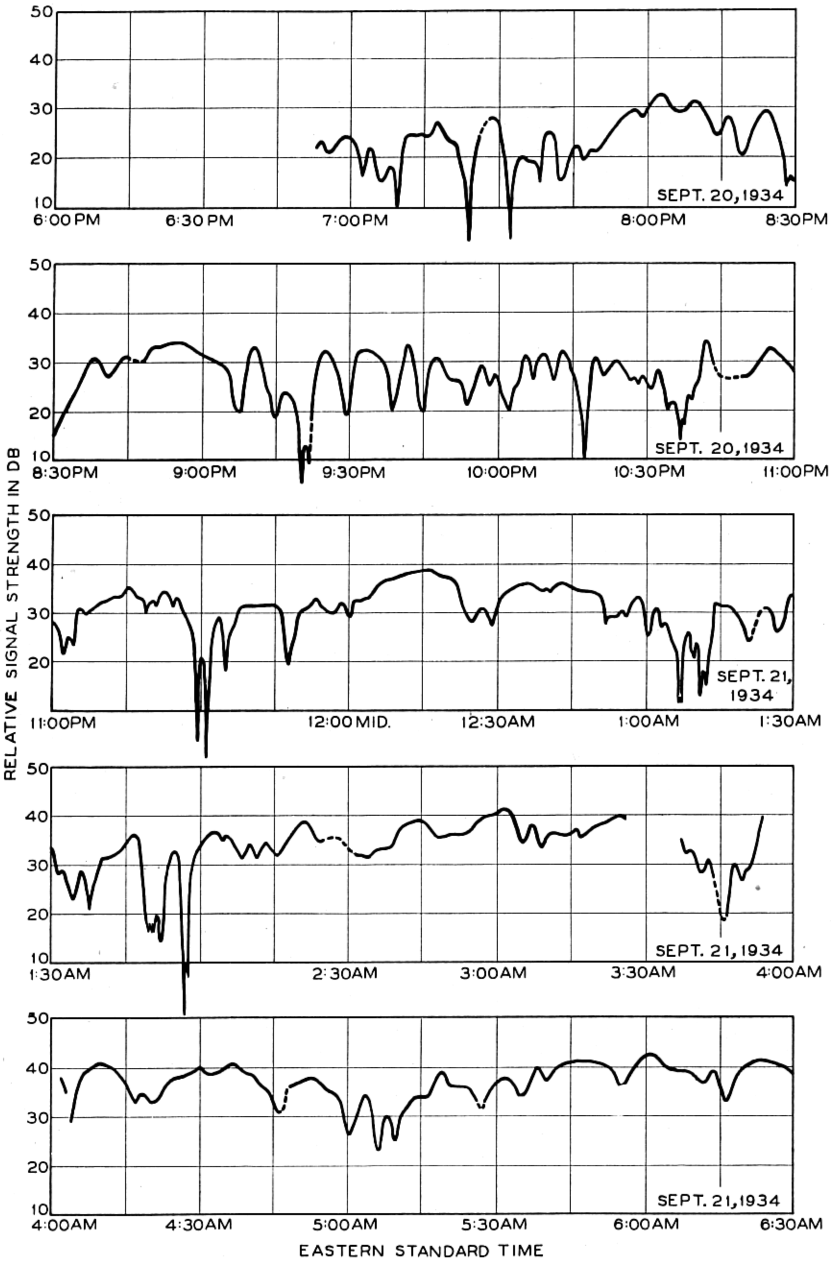
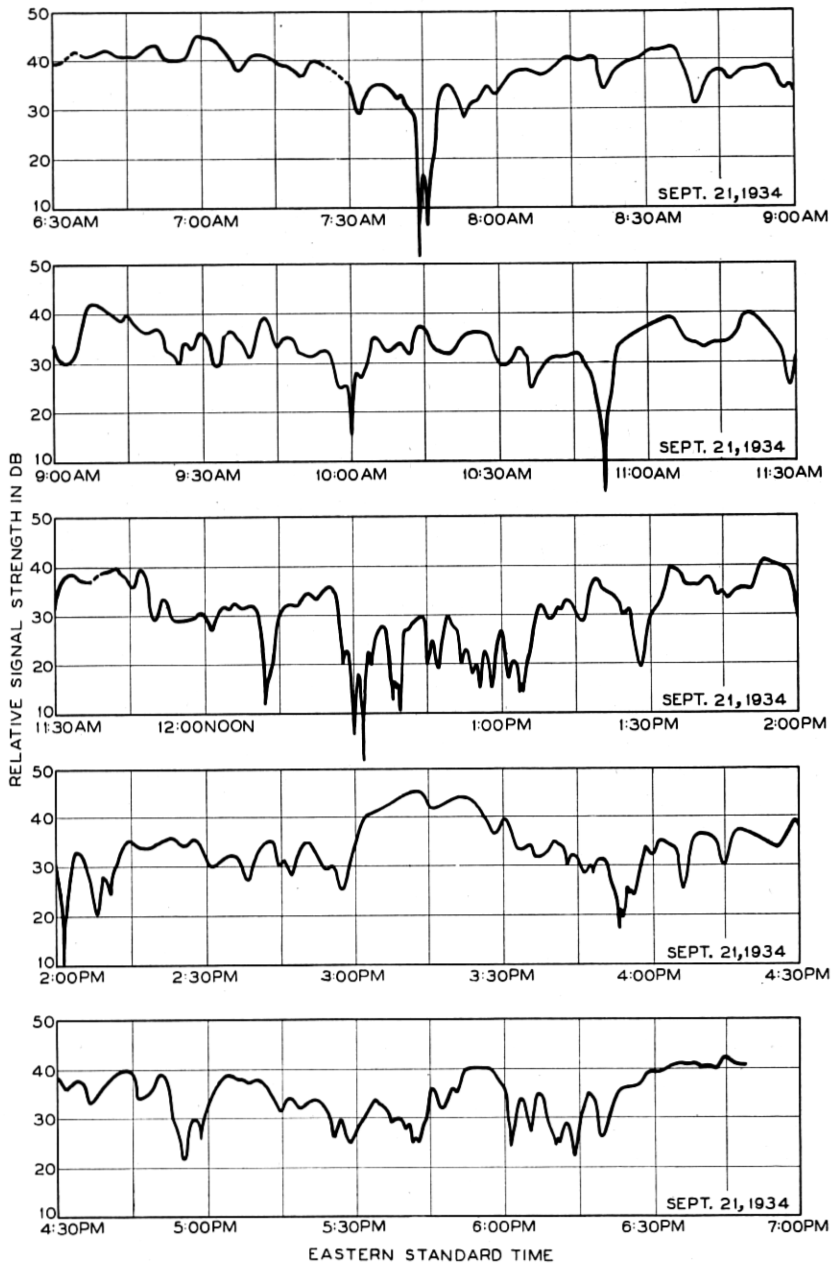


Fig. 5—Twenty-four hour run, vertically polarized



transmission, 4.74 meters wave-length.

Such a curve can also serve to check on the theoretical explanation of the cause of fading in certain cases. Thus if the fading is due to the combination of two radiation components in assigned random amplitude relation and arbitrary or random phase relation, a curve can be calculated from probability considerations and compared with the experimental curve.[2] Such a simple mechanism was inadequate for our fading most of the time. Moreover, the fading changed enormously from day to day. It is hoped that the samples given in the figures will give an adequate idea of this phenomenon.

Only rarely was fading practically absent for periods of an hour or two. Such a period is illustrated in Curve *a*, Fig. 2. Two days later the extreme fading of Curve *b* was recorded. It is significant, as will later appear, that the non-fading situation was the one of higher signal. The amplitude range of curve *b* is nearly normal; the fading rate is much greater than normal, for vertical polarization. In Fig. 3 the fading rate is normal but the amplitude range is excessive. In Fig. 4 a characteristic type of fading, which we have termed "scintillation," is recorded. In this case the fading, initially erratic and of a fairly wide amplitude range, subsides in a characteristic manner to a steady, fast rate oscillation, or scintillation, of moderate amplitude.

In Fig. 5 a 24-hour run is recorded. The rambling erratic character of the fading is well shown here. Characteristic deep short-period minima occur at intervals, occasionally they are twinned, some of them have a fine structure at the bottom. There are several "dropouts" where the signal practically disappeared.

No sunrise-sunset variations in fading were noticed, though looked for. Diurnal variations could not be established since automatic recording was not available. A seasonal falling off in average signal was noticed in the winter; the 1.6 meter wave, because of its normally low level, dropped below the noise level in the winter of '34–'35. No effect of ocean waves, clouds, or other visible weather phenomena could be established. It is true, however, that to be certain of the non-effect of such phenomena as clouds, a cloud observer at the midway point should have been present. In so far as cloud layers make air mass boundaries visible they may well affect the transmission. Cloud bottoms which represent merely the adiabatic dew point level should apparently not cause much signal reflection at these wavelengths.

Effect of Polarization on Fading

After some preliminary experimenting it was found that comparisons of two transmissions were worthless unless made on simultaneous recordings. The recorders were therefore fitted with telechron motors operating on a circuit of the Patchogue division of the Long Island 60-cycle power network. The resulting timing was faultless and by transmitting the same radiation on crossed antennas, and receiving the vertical and horizontal components separately, a comparison was obtained.

In general the horizontal component showed the worse fading, more fades per minute and greater amplitude range. This was always true when the fading on vertical polarization was bad. There was then no noticeable coincidence between the two. When the fading had a smooth long period fade, or "roller," superposed on a short period oscillation, or "fine structure," there was at times coincidence between the roller components. Occasionally, with fine structure absent and

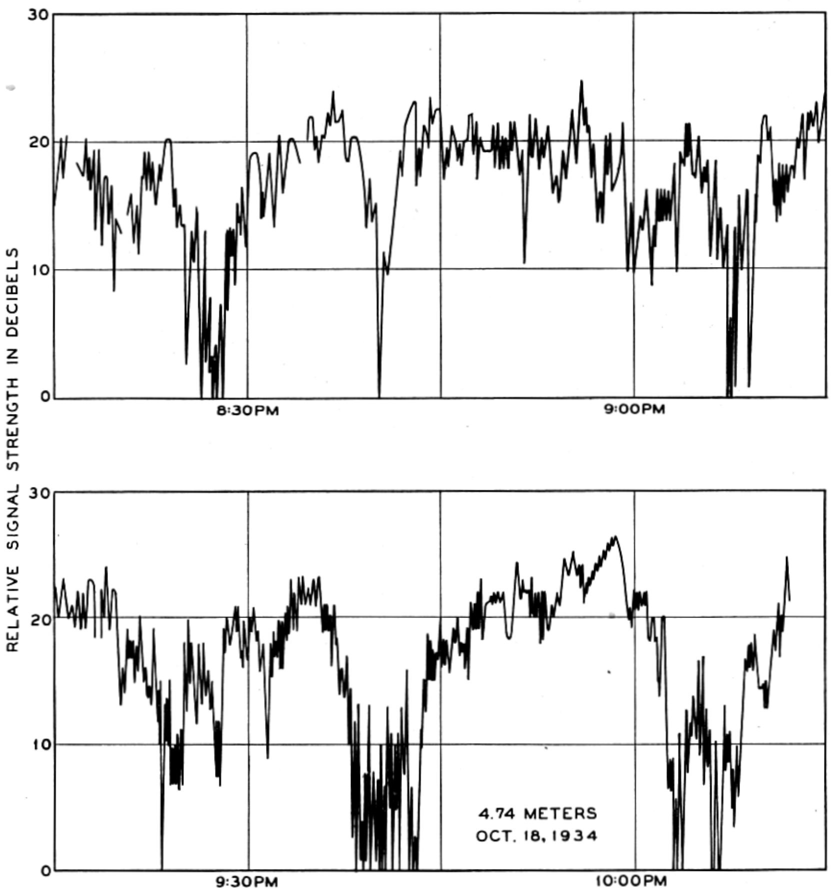


Fig. 6—Composite bad fading, horizontally polarized transmission.

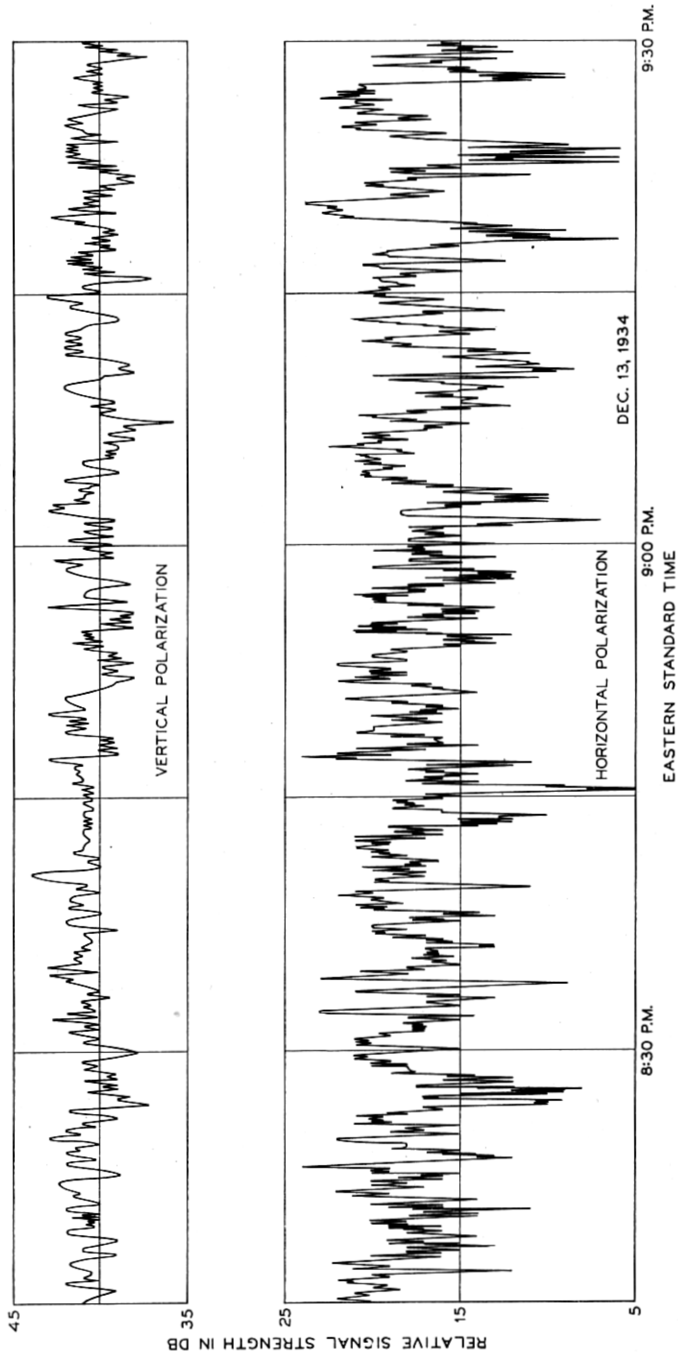


Fig. 7—Comparison of simultaneous bad fading on horizontally and vertically polarized transmissions, 4.74 meters wave-length.

moderate roller fading, a good coincidence between the two records resulted. This is discussed later.

Figure 6 is a sample of fading on horizontal polarization, at its worst. This particular specimen shows the superposition of roller and fine structure fading very well. No vertical-polarization record was taken along with this. Figure 7 shows a typical example of fading simultaneously observed on vertical and horizontal polarization during bad fading conditions. There is no coincidence. Figure 8, on the other hand, records an unusual condition when a mild roller type of fading shows a good coincidence on two polarizations.

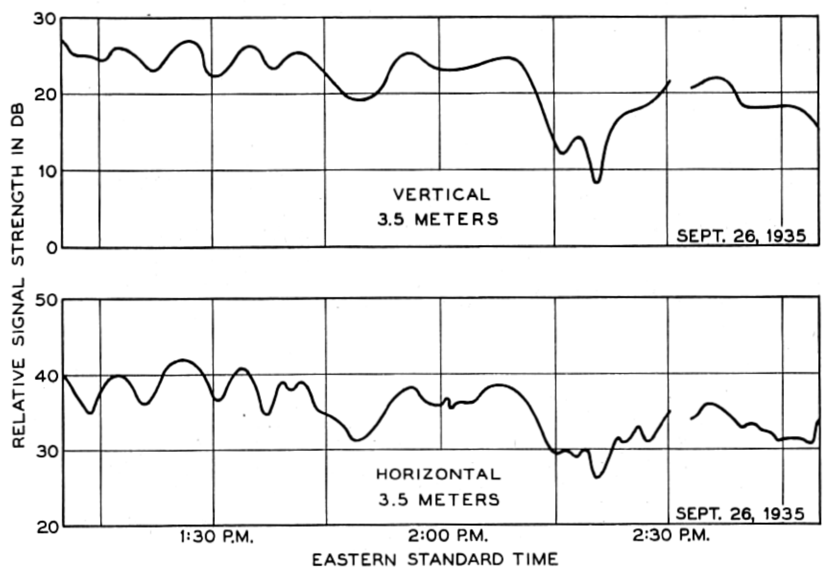


Fig. 8—Comparison of simultaneous mild roller fading on horizontally and vertically polarized transmissions.

Effect of Wave-length on Fading

The double wave-length records are not as contrasty as the double polarization ones. In general the shorter wave has the worse fading, either as higher fading rate, greater amplitude oscillation or both, and the greater the wave spacing the more certain this is to be true. Exceptions have occurred, however, where the fading was much the same, and one record was obtained where the fading rate on 4.7 meters was noticeably greater than on 4.5 meters.

Our first simultaneous records were taken at a wave-length ratio of 3 to 1 (4.7 to 1.58 meters) where the fading on the shorter wave was always worse. The remaining observations were confined to wave-length ratios of 1.5 to 1 and less. A comprehensive set of records was obtained for moderate to small wave-length spacings, down to 1 per cent difference. These records are all for vertical polarization. The few records taken on horizontal polarization happened to be obtained when the horizontal fading was much worse than the vertical fading and the records are too rough for good comparisons.

For these small wave-length-difference records the types of fading are more likely than not to be similar on the two wave-lengths. That is, the fading rate and amplitude excursion will average up much the same. More rarely, there will be a similarity between the two fading tracks which is evident to the eye, sometimes as a "retarded" similarity.

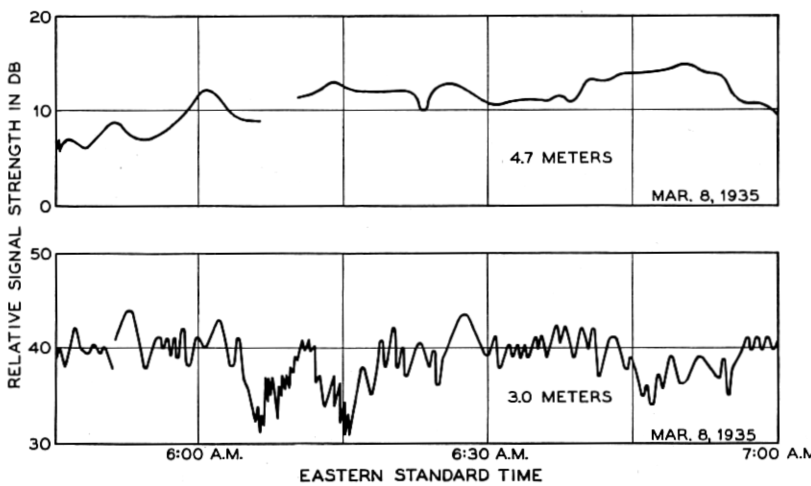


Fig. 9—Comparison of simultaneous fading on two well spaced wave-lengths, vertically polarized transmission.

Occasionally, and usually on the roller type of fading, there will be a marked coincidence between the two records; this coincidence will be better the milder the fading and the smaller the wave-length spacing. Genuine identity was never recorded on different wave-lengths even down to 1 per cent difference. With scintillation, coincidence was difficult to demonstrate; a similarity on the major swings was all that was shown.

Figure 9 shows a very marked difference between 4.7 and 3.0 meter fading. This is one of our most contrasty records. Figure 10 shows very slow fading, on two occasions, with wave-length differences of approximately 1 and 4 per cent respectively. There is good coincidence. Figure 11 shows active fading on short rollers for 4.7 and 4.65 meters, a wave-length difference of approximately 1.1 per cent. There is agreement in major features. Figure 12 shows a case of scintillation

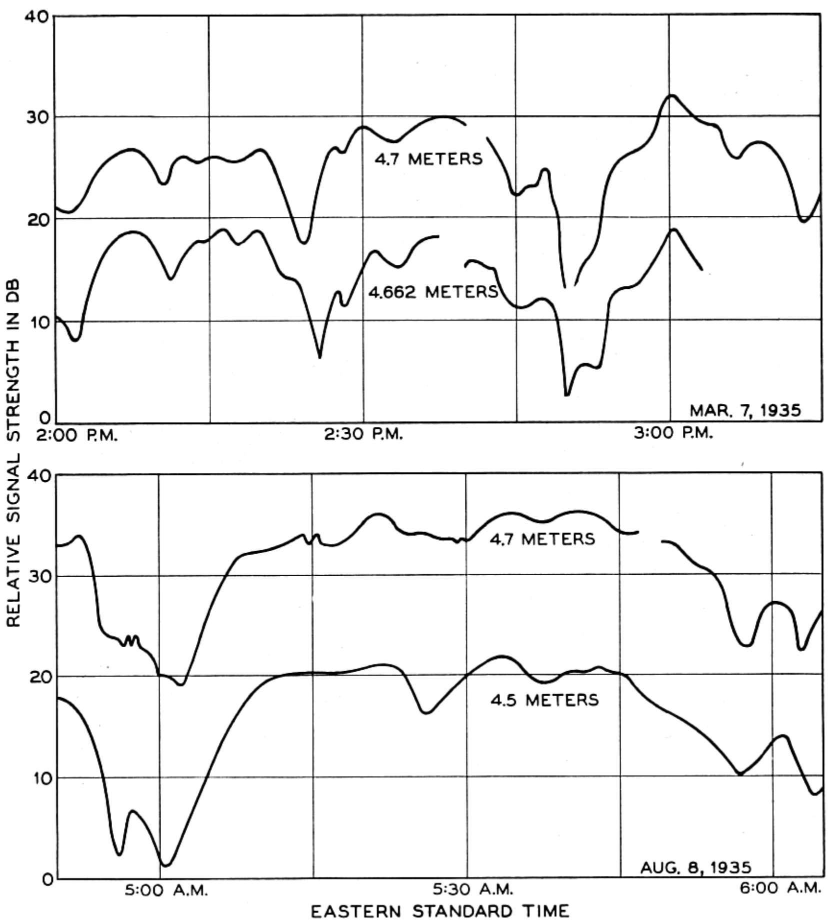


Fig. 10—Comparison of simultaneous slow fading on two slightly different wavelengths, vertically polarized transmission.

superposed on mild rollers, again for 4.7 and 4.65 meters. The time scale is here magnified three times. An in and out similarity can be seen, especially for the rollers. In the section on theory these similarities are further discussed.

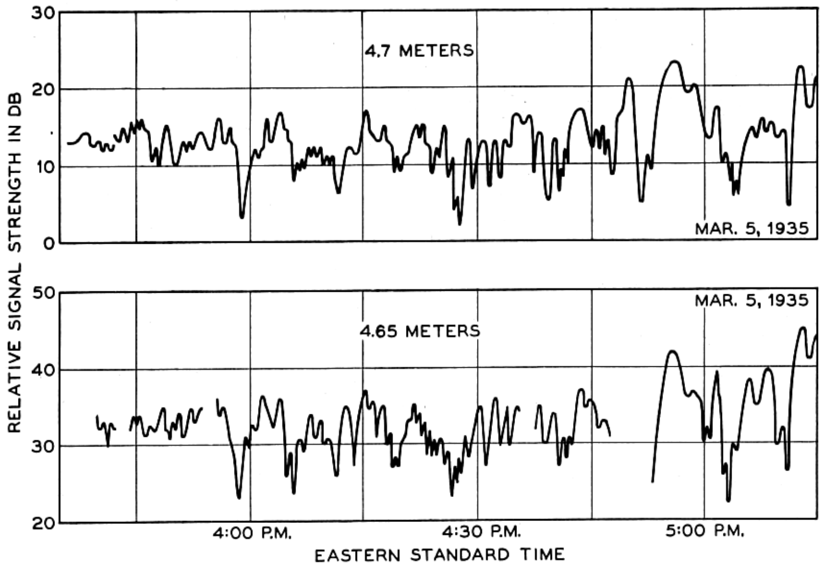


Fig. 11—Comparison of simultaneous active fading on two slightly different wave-lengths, vertically polarized transmission.

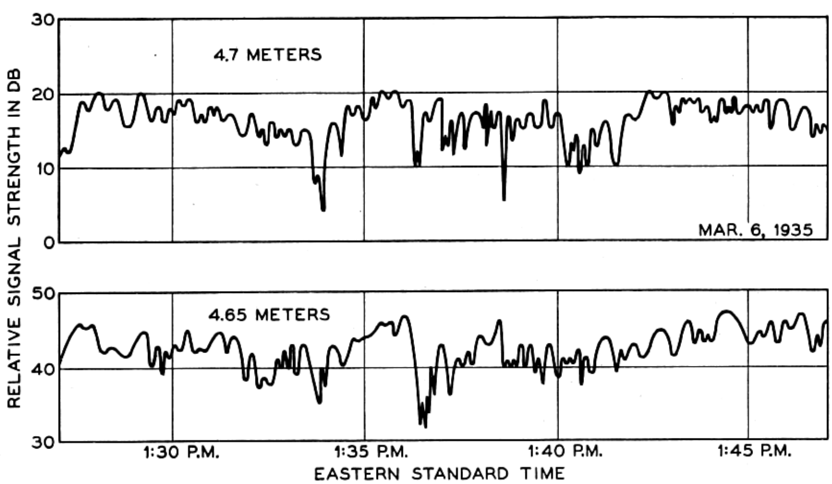


Fig. 12—Comparison of simultaneous "scintillation" fading on two slightly different wave-lengths, vertically polarized transmission. The time scale has been expanded.

Effect of Distance and Antenna Height on Fading

In planning this work a survey for a receiving site was made by means of a portable receiver in a car. Later, simultaneous reception was had at East Moriches and West Sayville, on three days. The survey data were not sufficient to establish any proposition beyond the statement that the signal strength fell rapidly with distance, with the intensity of fading coming up as the signal fell. The simultaneous two-distance recording showed random fading between the two records with less fading amplitude at the shorter distance. The fading rate was about the same. Unfortunately the recording took place under scintillation conditions, thus giving very poor records for comparison purposes.

By mounting two linear doublets on the 60-foot lattice mast simultaneous recording at two heights was carried out. For the two doublets (horizontal, at 14 and 52 feet respectively), a signal level difference of 12 db was observed, in favor of the higher antenna. The fading on the two records was identical. It may be added that, on calibrating the car receiver at East Moriches before moving to West Sayville, identical fading records were obtained with the two antenna systems 150 feet (45.7 meters) apart and substantially broadside to the radiation.

Frequency Sweep Patterns of Fading

The frequency sweep patterns were of many types, from slow to fast fading and from shallow to deep fading. Apparent path differences from 600 meters down to a few meters occurred. The patterns were usually complicated, indicating that more than two components were present. There is no reason to believe, however, that they were not all due to wave interference.[13]

On three days the predominant pattern was simple enough to be referable to two waves with a path difference consistently greater than 75 meters. These will be referred to later. In Figure 13 are given three sample runs illustrating a two-component pattern, a three-component pattern with two of the components forming a small path difference pair, and a multiple component pattern. The receiver characteristic is dotted in on one curve of each set.

Logs During Weather Bureau Airplane Flights

On forty-five mornings recording was carried out during the period of flight of the Mitchel Field Weather Bureau plane. This plane takes off about dawn every morning, when flying is possible, and by means of a meteorograph obtains records of air pressure, temperature and humidity, up to an altitude of about five kilometers. A record of the fading, on 4.7 meters and vertical polarization, was obtained for each of these mornings. In addition, on twenty-six mornings frequency sweep patterns were photographed at or shortly after the time of flight. These sweep patterns were all on horizontal polarization.

From the meteorograph data, kindly furnished us by the United States Weather Bureau, the dielectric constant of the air has been calculated [1] and plotted as a function of the altitude. On twenty-four days there were, above an altitude of 400 meters, changes in the dielectric constant curves equivalent to discontinuities of $\Delta\epsilon \geqq 10^{-5}$. Heights up to 3200 meters were recorded for these. Typical curves

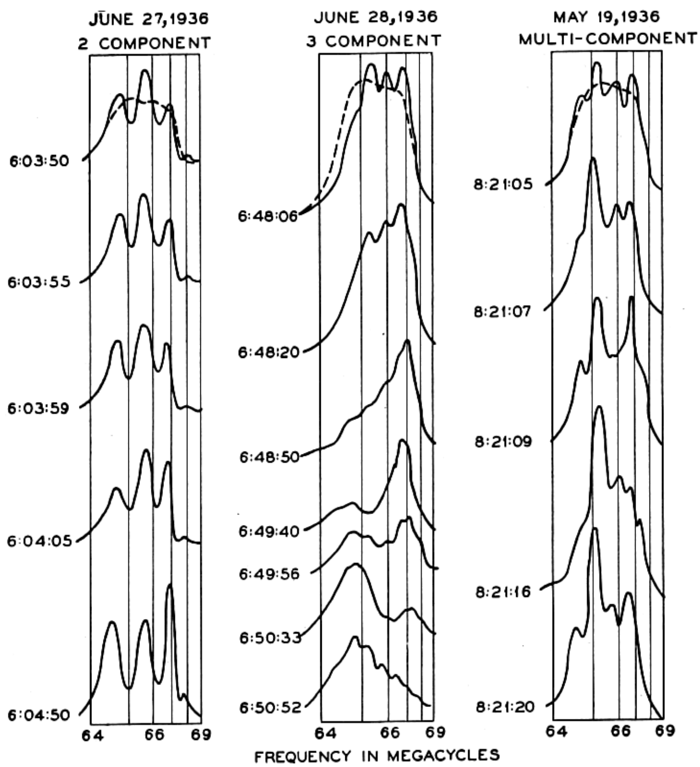


Fig. 13—Three sequences of frequency sweep patterns. Horizontally polarized transmission, 4.55 meters mean wave-length.

are given in Fig. 18 on the left-hand side. On four days there were small boundaries with $\Delta\epsilon < 10^{-5}$; on two days there were possible but not definite boundaries, the experimental points being too widely separated in altitude for precision; on five days there were possible boundaries below 400 meters altitude and on ten days the refractive index-height relation was an approximate exponential one without any evident boundaries. These data will be referred to later.

Theory

The fading phenomenon was explicable in several ways. In our previously cited work [1] we found that variable atmospheric refraction was present, the airplane carried receiver being up where the refracted-diffracted field strength was high and dominant. In general variable refraction would be expected to be a slow phenomenon, operating in hours, or even days, rather than in minutes, and much too slow to explain five-cycle-per-minute oscillations, for example.

Another explanation was air-mass boundary reflection (or refraction),[3] such a boundary readily explaining the rate of signal variation. No Kennelley-Heaviside layer reflection was in question; this had been quickly ruled out by the experimental data. When, therefore, we elected to transmit the frequency modulated signal, already described, and the oscillograph revealed a cyclic maximum-minimum frequency characteristic of the other path itself, it was evident that there was no possibility other than wave interference left—interference presumably between a direct-diffracted and one or more boundary-reflected components.

These boundaries have apparently not been positively identified at longer wave-lengths and for that reason we have tried to get some further experimental contact with them. Attempts, since the closing down of the Atlantic Highlands-East Moriches circuit, to demonstrate an air-mass boundary, any boundary whatever, by high-angle transmission, have failed. No reflected components have appeared. Of course an illy defined, or diffuse, boundary will operate in this manner since only for near grazing incidence can such a boundary give the appearance of a discontinuity for the incident radiation.

If we assume such a boundary a few kilometers up, and assign to it a relatively small discontinuity in index of refraction, compared with that of an earth or sea water boundary, then the four components of Fig. 14 will be the only important boundary reflected ones for a radio circuit such as ours. We now, fortunately, have theoretical formulæ [4, 5] for computing the diffraction of an ultra-short-wave radiation around the earth and the amplitude of the direct-diffracted component can be calculated at once.

That is, it can be calculated at once if the air mass has no refractive bending effect upon the radiation trajectory. Since such a bending effect is certainly present at times, and is equally certainly variable, even if only slowly, it must be taken into account.

If the refractive index of the air varies as a power of the distance to the earth's center, it has been shown [6] that the actual state of affairs can be duplicated by a homogeneous atmosphere over an earth, the radius of curvature of which is greater than that of the actual earth and is calculable from the exponent of the height variation function. With this "effective" earth radius, the formulæ already mentioned become usable. If the air refractive index does not vary as a power of the distance to the center of the earth we must take that exponent which gives the best first order fit over the height covering the refracted wave front, the alternative being a prohibitive complication of the theory.

A plausible physical picture of the fading mechanism can now be set up. If we lump the four boundary reflected components in one, and plot as a function of the distance, we have curves "*A*" of Fig. 15.

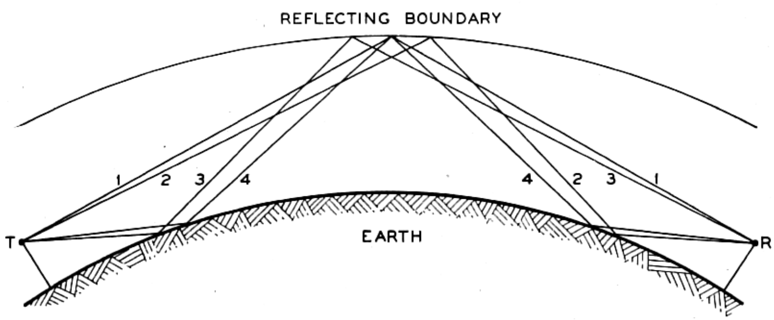


Fig. 14—Drawing illustrating the four components of a single reflection at an air boundary.

Curves "*B*" are the Wwedensky [4] * and Gray [5] theories. These are for our Highlands-East Moriches circuit with the average effective earth radius of 8500 kilometers and a 1500-meter boundary height. If we now imagine a receiver moving away from the transmitter we shall first traverse the zone of high "*B*" amplitude with no fading present. The signal amplitude will, for any given near-by point, and for any given antenna ampere-meters, depend on the height of the antenna above the ground and the ground constants. As the distance to the transmitter increases, the falling "*B*" curve approaches the rising "*A*" curve in ordinate and we enter a disturbed region where, for any instability of the boundary, more or less complete interference can result and fading will occur. (One such instability occurs when

* There is an error in the formula, as given by Wwedensky. It is corrected here. See appendix II.

a boundary with an irregular surface is carried past the reflection zone by the normal motion of the atmosphere.) A further increase in transmitter distance and the "*B*" or residual curve drops out of the picture leaving only the "*A*" curve and, presumably, fairly steady signal amplitude conditions. The location of these zones of undisturbed and disturbed signal will vary from day to day as: (1) the reflection coefficient and height of the layer change, (2) the effective radius of the earth changes. The effect of the height of the layer is shown in Fig. 16.

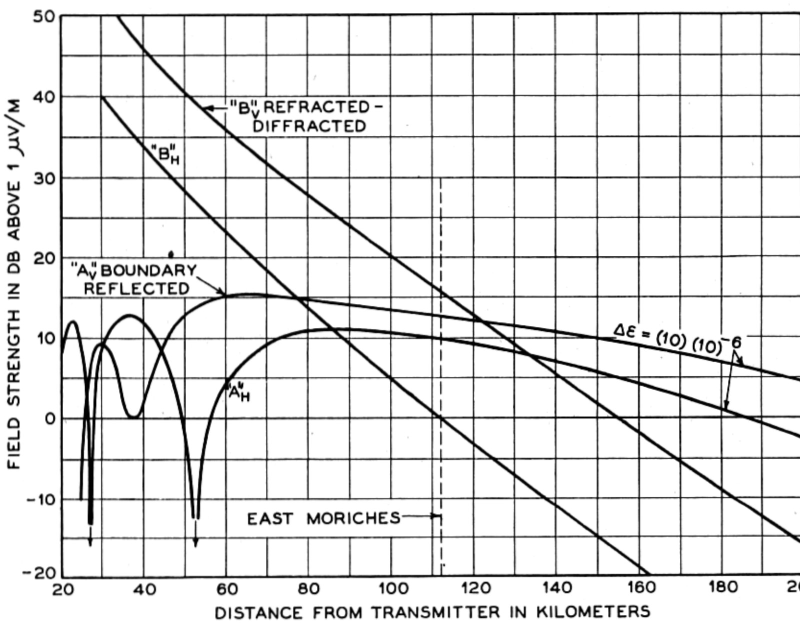


Fig. 15—Calculated curves for air boundary reflected and earth refracted-diffracted radiation components, in both vertical and horizontal polarization. Short doublet antennas, 1 kw. power radiated, wave-length 4.7 meters, $\sigma = 5 \times 10^{-11}$ (E.M.U.) and $\epsilon = 80$ for sea water. Height of transmitter antenna 42 meters, of receiver antenna 5 meters, air boundary height 1500 meters, effective radius of earth 8500 kilometers.

Since the major lobe of the polar characteristic of any simple antenna, such as ours, is directed forward and away from the earth, the signal intensity at the reflecting boundary surface will be comparatively high and will, in some measure, make up for a small reflection coefficient. For longer waves, such as broadcast waves, the high level of the "*B*" curve will move the disturbed zone so far out that the low residual signal level and the Kennelley-Heaviside layer reflections will conceal or mask the atmospheric boundary reflections. Several observations which can be ascribed to such boundaries have nevertheless been published.[7, 8] Obviously, only boundaries lying considerably higher than those discussed here will give the path differences to produce the same type fading at these longer waves. At the same time the apparent diffuseness of a boundary will fall off with increase in wave-length, thus removing the restriction of reflection to near grazing incidence angles only.

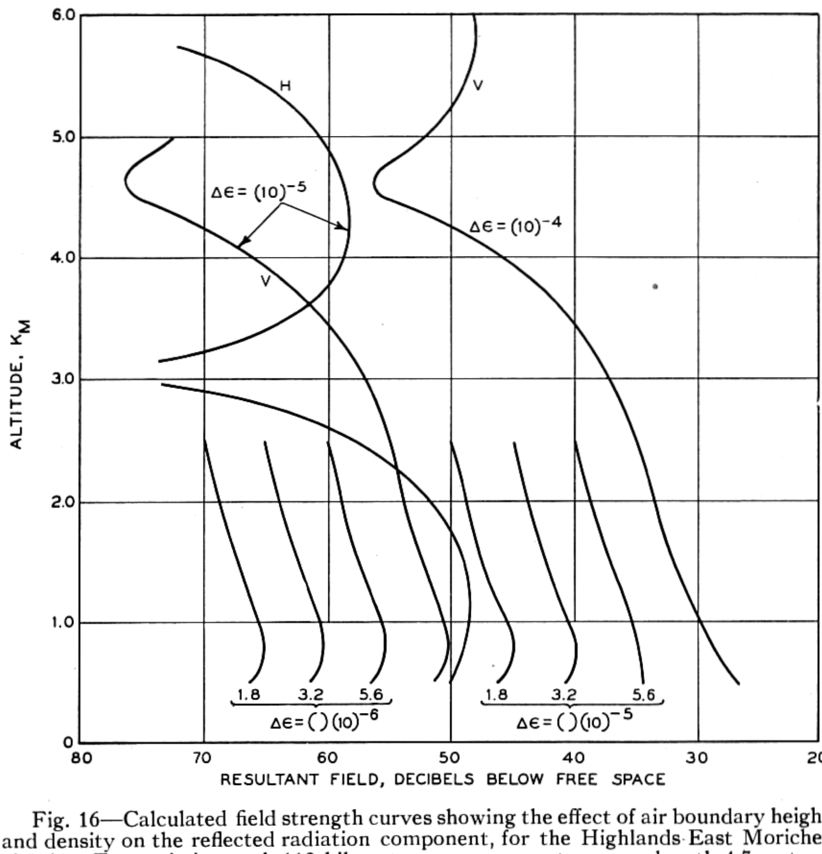


Fig. 16—Calculated field strength curves showing the effect of air boundary height and density on the reflected radiation component, for the Highlands-East Moriches circuit. Transmission path 112 kilometers, over sea water, wave-length 4.7 meters, polarization both vertical and horizontal. Vertical antennas 42 and 5 meters high, horizontal antennas 45 and 9.5 meters high, respectively.

This tentative mechanism also explains several other observed features. Thus, for a given type of boundary instability, the fading rate will increase as the wave-length decreases. Furthermore, since the slope of the "*B*" curve increases as the wave-length decreases, the disturbance zone is effectively moved nearer the transmitter and the probability of increase in fading amplitude is enhanced. The usual increase of fading with decrease in wave-length is thus explained. When the wave-length difference is small, on the other hand, the fading type should be much the same on both wave-lengths, as was generally found. The lack of coincidence would arise from the fact that the path difference being a considerable number of wave-lengths, a small wave-length change can introduce a marked randomness in fading without appreciably affecting the type.

As has been mentioned earlier, a multiple of reflecting boundaries is the normal condition, rather than that of a single boundary. This circumstance, without invalidating the explanations already given, makes a further elaboration of the theory possible. The "roller" type or component of fading, in particular, requires explanation. In addition to the smooth signal modulation, from which the name has been derived, this type of fading is characterized by showing more or less frequent deep minima or drop-outs and these are often distinctively twinned. Further, the roller component is that component of fading which shows coincidence, in spite of wave-length or polarization differences. Such coincidence indicates small path difference and this is what we have when a double boundary or stratum exists. Such a stratum would give two "*A*" components and, if of variable thickness, would, as it was carried along by the prevailing air currents, give the steep, deep, minima at phase opposition thickness. Further, if the stratum contour were that of a hump, thick enough to carry the second "*A*" component past phase opposition to the first one, the twinned minima would result as the hump entered and left the reflection zone. Occasionally the two "*A*" components would add properly, with the residual "*B*" component, to give complete extinction, a result less likely from the phase addition of a single "*A*" and the "*B*" component.

This explanation of "roller" fading assumes, tacitly, that the "*B*" component is, at the time, relatively subdued, that is, the disturbance zone has moved inwards due to an increase in the reflection coefficient of the layers or to a decreased "effective" earth radius. The fine structure often appearing at the bottom of a prolonged roller minimum corroborates this, the mutual cancellation of the two "*A*" components having uncovered, so to speak, the weaker "*B*" component with its much shorter traversed path.

With the "roller" condition characteristic of high "*A*" component signal amplitude, the "scintillation" condition would be characteristic of low "*A*" component signal amplitude, the relatively steady "*B*" component having superposed on it a small amplitude, variable phase, "A" component. A relatively low mean amplitude value and the coincidence of scintillation conditions with conditions of convective instability of the atmosphere would thus be explained. All the scintillation records came on days of relatively high wind and convective instability. A turbulent atmospheric condition would dissipate or attenuate any boundaries, especially the lower ones. The rapid flutter about the mean amplitude value is the normal expectation from a high, turbulent, low reflection coefficient boundary.

Our two polarization results are qualitatively explicable on the mechanism proposed. As can be seen in Fig. 15, the change from vertical to horizontal polarization results in a relative lowering of the "B" curve without much change in the "A" curve, which should result in increased fading. For our circuit and a boundary at 1500 meters the relative "B" vs. "A" drop is 13 db.

As Fig. 16 shows, the variations of the "A" components with height are markedly different for the two polarizations. The "A_V" component falls steadily with height up to 4700 meters; the "A_H" component has a deep and sharp minimum at 3000 meters after which it rises again. Since most of our observations concerned boundaries at 2000 meters or less, this high altitude disparity between "A_H" and "A_V" does not affect our explanation. The disparity between vertical and horizontal fading should be much more marked for high boundaries than for low boundaries.

Further Experimental Curves and Checks

The curves given have illustrated the variability in the fading, a variability which no short period of recording can encompass. The tentative explanations proposed have been shown to be in accord with several of the features characteristic of this fading. Certain other experimental results will now be adduced which offer further verification along somewhat different lines.

For the forty-five mornings on which simultaneous recording was carried out during the United States Weather Bureau plane flight, we have calculated, from the airplane data, the values of the "A" and "B" components. As stated earlier, there were twenty-four days when boundaries above 400 meters altitude, and of sufficient distinctness to be fairly accurately estimated ($\Delta\epsilon \geqq 10^{-5}$) were shown by the meteorograph records. For these the "A" components have been computed. By taking the dielectric constant gradient for the first half kilometer, the effective earth's radius was determined and inserted in the Wwedensky formula to give the "B" component. These calculated values

("*A*" component as triangles, "*B*" component as circles) are plotted on Fig. 17 together with the maximum and median * observed values. These latter are joined by lines. For the 10 mornings on which no boundaries were evident the calculated "*B*" component appears to be some 8 db higher than the observed values. With this correction the agreement between observed and total calculated fields is fairly good. A partial explanation of this 8 db discrepancy may lie in the fact that the ocean water trajectory assumed in the calculation differs from the actual one by the land terminals and the three tongues of land intervening.

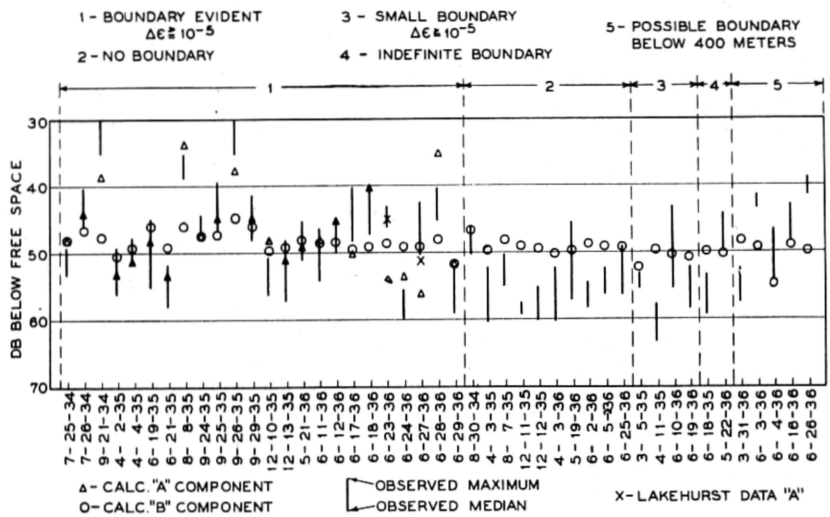


Fig. 17—Comparison of "*A*" and "*B*" radiation components, calculated from the U. S. Weather Bureau free air data, with measured maximum and median signal strengths. Vertically polarized transmission.

On the twenty-six morning frequency sweep runs there were only three on which the predominant sweep pattern was simple enough to be interpreted as due to two components with path difference greater than 75 meters. For those days a series of measurements of the film patterns was made by determining the frequency spacing between a maximum and a minimum and calculating the resulting path difference and boundary height. The dielectric constant-height function was also calculated from the Weather Bureau data. These curves are

* The signal is half of the time greater and half of the time less than its median value. For random phase with "*B*" component equal to "*A*" component the resultant median value signal is $\sqrt{2} \times A$ or 3 db up; it falls from this value to "*A*" as "*B*" decreases to zero.

plotted in Fig. 18 with the calculated boundary heights set down at the right hand, spread out in time of observation. The boundary height coincidence is pretty definitely located in this manner. Many of the more complicated frequency sweep patterns carried a fine struc-

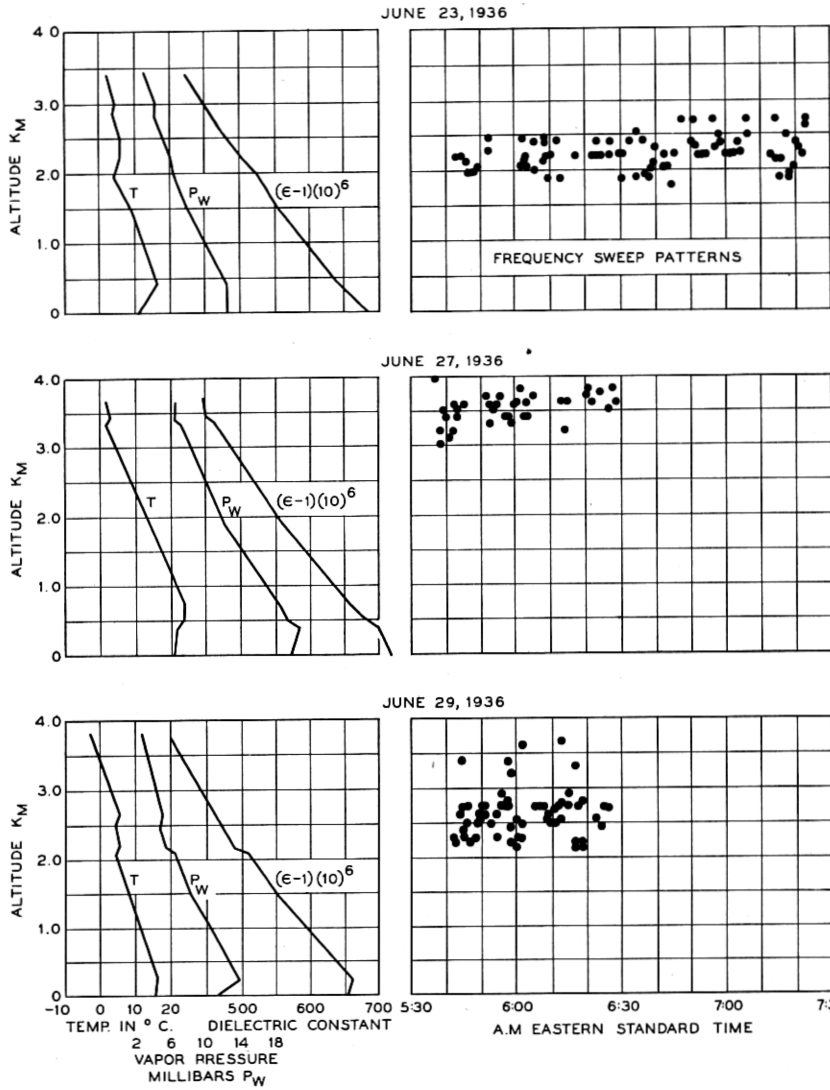


Fig. 18—Comparison of boundary heights shown by the U. S. Weather Bureau free air data, with boundary heights measured from frequency sweep patterns. Horizontally polarized transmission.

ture which indicated weak boundaries at higher altitudes up to, roughly, 5.5 km.; most of the patterns, however, were characteristic of layers below two kilometers. The path difference corresponding to two kilometers is 85 meters. The theoretical limit of resolution of the amplifier band for a maximum to minimum frequency spacing is $\Delta l = 2(C/\Delta f)$ where Δl = path difference, C = velocity of light and Δf = frequency band. For $\Delta f = 2 \times 10^6$ cycles this gives 75 meters, and hence boundary heights at and below 1900 meters are unresolvable by our receiver. It is a remarkable result that the bulk of the disturbing boundaries should lie so low.

It was mentioned earlier that several observations referable to air-mass boundaries have been published. In addition there have been reports, for three consecutive years, of long distance ultra-short-wave reception by American amateurs [9] during the month of May. We have copies of the U. S. Weather Bureau atmosphere cross-sections for several of these days and have been curious enough to examine them. On May 9, 1936, during the long distance amateur reception, there was an extensive boundary at 4 km. between an upper Superior air mass and a lower Tropical Gulf air mass. On May 15, 1937, a similar boundary at 4–5 km. had a Superior air mass above a wedge of Transitional Polar to Tropical Atlantic air. Below this at 3–4 km. lay a Transitional Polar Continental air mass.

On June 11, 1936, when Colwell and Friend [7] report an extra strong 0–2 km. "*C*" reflection, a subsiding Transitional Polar Pacific air mass lay above a Transitional Polar Continental air mass with the boundary at about 1.5 km. On June 29, 1936, when they reported a very strong 3.5 km. "*C*" reflection, there existed four wedge-shaped air masses with a Superior air mass over a Transitional Polar air mass at 3–4 kilometers. The wave-lengths used were 186, 125 and 86 meters approximately.

These coincidences may or may not be significant but it is very questionable that any boundaries at such altitudes are due to either electron or gas ion distributions.

The characteristic properties of North American air masses have been published,[11] as average summer and winter values, and show some marked seasonal differences. The greater dielectric constants for summer conditions are due chiefly to greater water content.

For a single air-mass distribution, horizontal stratifications are at a minimum and the radio transmission is via the "*B*" component. This component can be calculated from the corresponding effective earth radius. The table below gives this radius for three important air mass types.

Air Mass Type	Effective Earth Radius	
	Summer	Winter
Tropical Gulf—T_g	$1.53 \times R$	$1.43 \times R$
Polar Continental—P_c.....	$1.31 \times R$	$1.25 \times R$
Superior—S..............	$1.25 \times R$	$1.25 \times R$

"R" = actual earth radius

The boundaries between different air-mass types furnish discontinuities adequate for radio reflections. The greater the stability of the boundary, the more abrupt it is likely to be. In general, when "S" air overlays either "T_g" or "P_c" air, the resulting boundary is stable. Possible discontinuities, for the three types discussed, may be summarized in the following table. Here the positive sign means that the radiation originates in the more refractive medium. For stability the lower medium is the denser though not necessarily the more refractive.

Altitude	$\Delta\epsilon \times 10^6$					
	Summer			Winter		
	S/T_g	S/P_c	T_g/P_c	S/T_g	S/P_c	T_g/P_c
1.0 Km..............	100	20	−80	55	25	−30
2.0 Km..............	50	10	−40	50	15	−35
3.0 Km..............	30	10	−20	35	10	−25

Concluding Remarks

The characteristics of this seventy-mile circuit indicate that for ultra-short-wave transmission it rates as a long distance one. If we assume that the air refraction is on the average such that the effective earth's radius is 4/3 the actual one, then the receiving station lay 1400 feet below the line of sight from the transmitter. This is equivalent to 0.57° below the horizon. The reception, using high effective-height antennas, was good; there was, however, very little lee-way left, above set noise, for reception with simple doublet antennas. Any longer circuit will require to be terminated on elevations such as to keep the intermediate horizon height down. The fading was too slow to be noticeable on amplitude modulated speech unless a deep minimum or drop-out occurred.

The circuit was probably unusable for television, most of the time. A system adhering to the R.M.A. standard [12] of 441 lines on an interlaced 60-cycle scanning will have a unit time element of 0.17 microseconds. This corresponds to a path difference of 51 meters and only a fraction of this is necessary to produce a ghost. A rough estimate of the boundary height range involved in our fading is one-half to five-and-one-half kilometers. The corresponding path difference range is 8 to 580 meters. As the fading records show, no matter whether the "*A*" or the "*B*" component predominated, the other component was usually present in amplitude only second to the other. It may be pointed out that where a standing wave system exists,[10] reflected components with much larger path differences than those recorded here are almost certain to be found.

Appendix I

In the Wwedensky [4] paper the author applies his theory to one of the experimental curves from a previous paper of ours. He uses the normal earth radius "*R*," however, without any correction for air refraction. If we assume, as a more probable effective earth radius, the value $4/3R$,[6] the agreement with our curve is markedly improved.

Appendix II

In the first Wwedensky paper, *Tech. Phys.* U. S. S. R. Vol. 2, p. 632, 1935 eq. (7, 1) the sign of the term $|\tau_m|^2 \sin 2\theta_m$ should be minus.

Appendix III

The fading produced by moving bodies such as airplanes has been referred to in one of our earlier papers.[10] It happened one day, during the present investigation, that fading of this type appeared when mechanical recorders were being used and, by speeding up the paper, a record in two polarizations was obtained. The airplane itself (or other cause) was not visible. The results are given in Fig. 19. Again the horizontal component was the worse one. At first the two fadings, both fine and coarse components, were in step; later they passed entirely out of step where the fading was so rapid as to smear the paper. These "airplane" fadings were observed, off and on, at other times but were not recorded.

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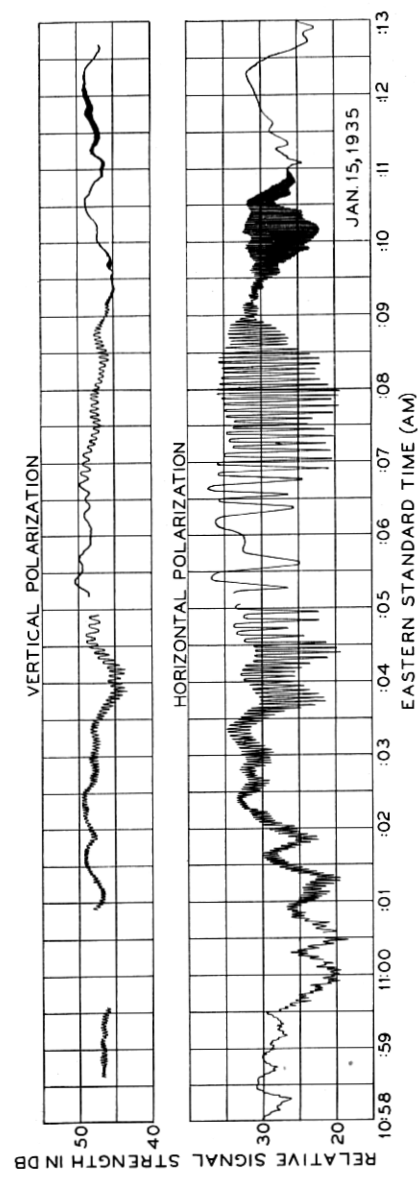

Fig. 19—Records, in two polarizations, of a transient high speed fading attributable to radio reflection from a moving airplane.

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* The case of vertical polarization is treated by references 4, that of horizontal polarization by reference 5.