Very-High-Frequency and Ultra-High-Frequency Signal Ranges as Limited by Noise and Co-channel Interference*

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Summary—Theoretical ground-wave ranges for smooth-earth and standard-atmosphere conditions are shown for frequency-modulation and television broadcast services and for mobile services for frequencies between 30 and 3000 megacycles, and practical limits of antenna size and antenna gain are discussed. The effects of external noise, terrain, and penetration of buildings are considered and their probable trends with frequency are indicated, together with the need for comprehensive data for their evaluation.

A comparison is made between theoretical ground-wave and tropospheric ranges computed for 50 megacycles and the results of continuous field-intensity measurements made at various distances, from which it is concluded that theoretical ground-wave curves can be used as reliable measures of service ranges. Theoretical ground-wave curves are found not to be direct measures of probable ranges of tropospheric interference and it is suggested that a factor of 2 be applied to the station-separation distances obtained from such curves at 50 megacycles, with the probability of larger factors for higher frequencies.

Two families of curves, one for sporadic-*E*-layer and one for *F*-layer transmission, showing skip distances as a function of frequency for the frequency band under consideration, are derived from the National Bureau of Standards measurements of layer characteristics at Washington, D. C., for the purpose of estimating the occurrence of interference from one other co-channel station. The effect of increasing the number of stations is investigated, and estimates of five times the single-station interference for sporadic-*E*-layer and three times for *F*-layer interference are made.

Combining the above factors, an estimate is made of comparative service areas at 46 and 105 megacycles for frequency-modulation broadcast stations of 1 kilowatt and 340 kilowatts effective power, and the reduction in area due to the effects of external noise, hills, and station interference by bursts and sporadic-*E*- and *F*-layer propagation.

THE ABOVE subject is extremely broad, and no exhaustive treatment can be given in this paper. However, an attempt will be made to summarize the various major factors affecting radio wave propagation in the frequency range from 30 to 3000 megacycles to the extent they are known or can be predicted at the present time, and to estimate the probable service and interference ranges for broadcast and land mobile services within this part of the frequency spectrum. The theoretical ground-wave service ranges with simple antennas are first considered and the possibilities of increasing the ranges by the use of transmitting- and receiving-antenna gain are discussed. Factors which may modify the theoretical ranges are then considered in the following order: external noise levels, terrain, tropospheric-propagation effects, long-distance *F* layer, sporadic-*E* layer, and burst interference.

GROUND-WAVE RANGES

Theoretical ground-wave ranges for a smooth spherical earth of average conductivity have been computed[1] for frequency-modulation and television broadcast stations, land-station-to-mobile ranges, and mobile-to-mobile ranges throughout the frequency band under

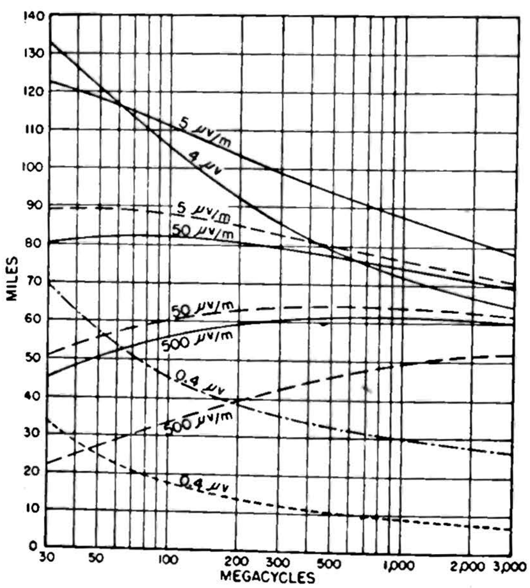

Fig. 1—The variation with frequency of ground-wave service and interference ranges.

consideration, and are plotted in Fig. 1. The solid curves show the distances in miles versus frequency to the 500-, 50-, and 5-microvolt-per-meter field-intensity contours, and to the 4-microvolt rural-receiver-input contour for broadcast stations having an effective radiated power of 50 kilowatts. The dashed curves show the distances to the 500-, 50-, and 5-microvolt-per-meter field-intensity contours of a 1-kilowatt broadcast station. For the broadcast stations the transmitting

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The paper was originally intended as a joint paper by K. A. Norton, Office of the Chief Signal Officer, War Department, and E. W. Allen, Jr., Federal Communications Commission. A large part of the material was prepared jointly, and some of the data and conclusions were entered into the record of the Federal Communications Commission hearing on frequency allocations, Docket 6651, by Mr. Norton. He has been unable, however, to devote an appreciable amount of time to the final preparation of the paper and has insisted that the presently indicated sole authorship is proper. This has been agreed to, with some reluctance, but grateful acknowledgment is made of the valuable participation of Mr. Norton in the preparation and interpretation of data and of his many helpful suggestions as to its form of presentation.

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[1] K. A. Norton, "The calculation of ground-wave field intensity over a finitely conducting spherical earth," PROC. I.R.E., vol. 29, pp. 623–639; December, 1941.

antennas are horizontal half-wave dipoles located at 1000 feet above the surrounding area. The receiving antennas are at a height of 30 feet, and for the 4-microvolt receiver-input curve a half-wave dipole antenna and a receiver input impedance of 70 ohms are assumed. The distance ranges for 250-watt land-to-mobile operation and 50-watt mobile-to-mobile operation are shown by the dash-dot and the dotted curves, respectively. For the land station, a vertical half-wave dipole 100 feet above ground is taken as a typical antenna. Mobile units are assumed to use a quarter-wave vertical antenna mounted in the center of the top of the vehicle at 6 feet above ground, with a 70-ohm receiver input.

The theoretical 4-microvolt rural-broadcast-receiver contour assumes that reception is limited by 1 microvolt of set noise, over which 2 microvolts of actual signal on the set terminals will provide a useful signal. This allows for a 6-decibel attenuation from the theoretical due to terrain and losses in the receiving antenna lead-in. It is evident that the indicated ranges can be obtained only in very quiet rural areas where the external noise and undesired-signal field strengths are less than one half as strong as the desired signal. Also, a good receiver with a low noise level and a 2-to-1 noise and co-channel rejection is required. While the assumption of a higher required receiver-input voltage will reduce the absolute values of the service ranges accordingly, the relative ranges with respect to frequency are not affected appreciably. The 0.4-microvolt mobile-receiver contours likewise provide for an additional attenuation of 6 decibels below the theoretical, and assume that 0.2 microvolts of signal at the set terminals is sufficient to override set noise of 0.1 microvolt.

The theoretical curves show that distances to the 500-microvolt-per-meter service contour of the 1-kilowatt broadcast station increase with frequency throughout the band, while for 50 kilowatts the distances increase up to about 1000 megacycles, after which a slight decrease occurs. For the 50-microvolt-per-meter service contour the change is less marked with frequency, a slight increase in distance being noted for the 1-kilowatt station up to 500 megacycles, while the maximum distance for the 50-kilowatt station occurs at about 70 to 80 megacycles. The maximum range of the 5-microvolt-per-meter interference contour occurs at 50 megacycles and decreases thereafter for the 1-kilowatt station but decreases with frequency throughout the band for a 50-kilowatt station. In general, it may be said that the protected service ranges increase and the interference range decreases with frequency. In contrast, the rural frequency-modulation broadcast range and the mobile service ranges decrease rather rapidly with frequency.

Effects of Antenna Gain

If a road clearance of 10 feet is assumed for the mobile units, it will not be possible to use a top-mounted quarter-wave antenna at frequencies below 60 megacycles. Aside from directional effects, however, a bumper-mounted antenna will be just about as effective at these frequencies as a top-mounted antenna, and will not disturb the theoretical ranges materially. Top-mounted half-wave antennas should be practical beginning at about 150 megacycles and multiple-bay antennas from 300 megacycles upward. Use of the higher frequencies will also make other types of high-gain antennas practicable. Since the signal-to-external noise ratio will vary directly with the transmitting-antenna field gain and the signal-to-set-noise ratio will vary as the product of the transmitting- and receiving-antenna field gains, it is probable that high-gain mobile antennas will be adopted above 300 megacycles in order to increase the limited range of mobile-to-mobile contact.

It will be noted that the 4-microvolt rural contour crosses the 50-microvolt-per-meter contour of a 50-kilowatt broadcast station at 600 megacycles. Consequently, at higher frequencies it appears to be expedient to protect a higher contour, or set noise rather than co-channel station interference will be the limiting factor. An alternative to increasing the contour is to assume the use of a high-gain antenna at the receiving location. Antennas with a field gain of 2.5 or more appear to be of a practical size for home use at 100 megacycles and above.[2]

The broadcast ranges and land-station-to-mobile range can be increased by increase of power, antenna gain, or antenna height. Theoretically, the preferred method is by increasing antenna height, as this results in an increased service range without a material increase in the sky-wave and tropospheric interference. Next in order of preference is antenna gain, as this tends to discriminate against high-angle radiation which may cause interference. However, available transmitter sites and economic factors generally result in a balance which is not optimum from the standpoint of minimizing interference. There are also certain limitations on the amount of antenna gain which can be used. First, there are practical limitations which, at frequencies below 50 megacycles, appear to limit the power gain to about a factor of 10 for a turnstile antenna. Second, the gain in the horizontal plane cannot be so great that the antenna does not provide a sufficient field in the area below the antenna.

Fig. 2 shows the results of a theoretical investigation to determine the probable limits on gain from the latter cause. In Fig. 2, the ordinates represent relative field strengths and the abscissas are the angles of radiation ϕ, 0 degrees being in the horizontal direction and 90 degrees straight downward or upward. The antennas are assumed to be elevated above an urban area which requires a signal level of 1000 microvolts per meter to overcome the ambient noise. The strength of the radiation in a particular direction which is required to produce a field of 1000 microvolts per meter at the receiving antenna is dependent upon the distance between the transmitting and receiving antennas and upon the

[2] "A.R.R.L. Antenna Handbook" ("Parasitic arrays"); American Radio Relay League, West Hartford, Connecticut, 1939, p. 65.

relative phases of the direct and ground-reflected waves. If we let R_ϕ be the ground-reflection coefficient at any angle ϕ and H be the antenna height, the maximum and minimum limits of the required radiation E_ϕ at the angle ϕ from the transmitting antenna to furnish a field strength E at the receiving antenna are given by the equations $E=E_\phi(1+R_\phi)$ $(\sin\phi)/H$, for receiving sites in which the direct and ground-reflected waves reinforce each other, and $E=E_\phi(1-R_\phi)(\sin\phi)/H$, in which they

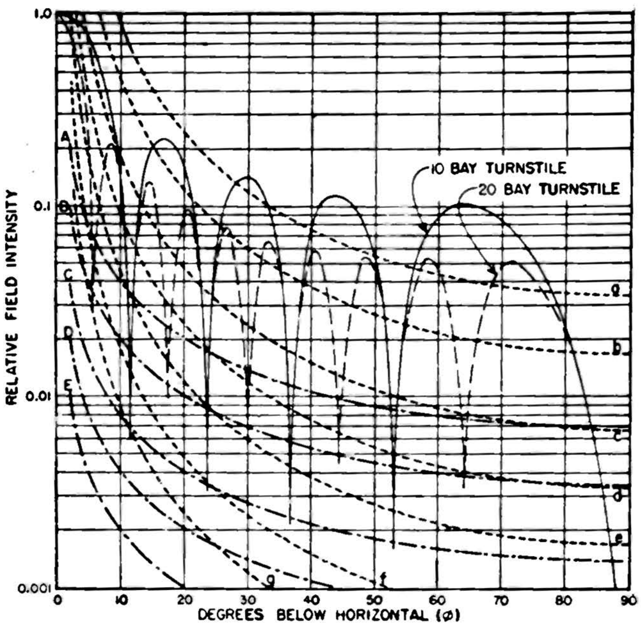

Fig. 2—Effect of vertical directivity of elevated very-high-frequency broadcast antennas on proximate service fields.

tend to cancel each other. The first formula yields the family of dot-dash curves (A, B, C, D, E) and the second formula yields the dashed curves (a, b, c, d, e, f, g) for an effective radiated power of 1 kilowatt (137.6-microvolt-per-meter free-space field at one mile) and antenna heights of 10,000, 5000, 2000, 1000, 500, 200, and 100 feet. The curves are also applicable to other powers and antenna heights in accordance with Table I. Typical conditions of effective radiated power and antenna height are confined to curves E and below.

Superposed on the limiting directivity curves are vertical-directivity patterns for a 10-bay turnstile (solid) and for a 20-bay turnstile (dashed) antenna. It is believed that we may neglect the deep nulls shown by the calculated patterns at large angles from the horizontal, as but a slight current unbalance in the separate bays is required to fill them materially. The zones around the antenna corresponding to these nulls will also tend to fill in, owing to reflections and reradiation from buildings and other objects. The nulls at small angles of 10 degrees or less require a much larger current unbalance to fill in, but for high antennas the radiation in this part of the pattern may be directed beyond the area of high noise level. At the lower end of the frequency band under consideration the direct and ground-reflected waves do not cancel for small angles, so that the solid lines more nearly represent the limiting conditions. The limits are well below the 20-bay pattern, and it may well be that the limitations on directivity will be practical

TABLE I

ANTENNA HEIGHTS VERSUS EFFECTIVE RADIATED POWER FOR 1-MICROVOLT-PER-METER FIELD

Curve	1 Kilowatt	25 Kilowatts	100 Kilowatts	400 Kilowatts
A	10,000	50,000	100,000	200,000
B	5,000	25,000	50,000	100,000
C	2,000	10,000	20,000	40,000
D	1,000	5,000	10,000	20,000
E	500	2,500	5,000	10,000
F	200	1,000	2,000	4,000
G	100	500	1,000	2,000

rather than theoretical throughout the band under consideration. However, as the frequency increases there will be an opportunity for employing types of transmitting antennas other than the turnstile to which present practical difficulties may not apply.

EXTERNAL NOISE LEVELS

Having compared theoretical ground-wave service and interference ranges for the band under consideration, the major factors which are expected to modify the theoretical predictions will be considered in the following order: external noise levels, terrain, tropospheric-propagation effects, long-distance F-layer and sporadic-E-layer interference, and bursts.

The 50-microvolt-per-meter contour for frequency modulation and the 500-microvolt-per-meter contour for television were chosen so as to give the required protection from average values of external noise encountered in rural areas. These contours may therefore be modified upward or downward in accordance with the experience as to noise levels to be encountered on the various frequencies.[3]

The 4-microvolt contour is based upon the assumption that the external noise level is so low that the internal receiving-set noise is the limiting factor. The presence of external noise of sufficient value to become the limiting factor rather than set noise will change the slope of the curve to conform more nearly to the slopes of the 5-microvolt-per-meter and 50-microvolt-per-meter curves, the absolute distances being dependent upon the external noise levels encountered at various frequencies. External noise will likewise reduce the mobile service ranges to a greater extent at lower frequencies. However, present information indicates that the residual service ranges will continue to be considerably greater at the lower end of the band.

TERRAIN

Irregularities in terrain, such as hills and buildings, are expected to cast deeper shadows at the higher frequencies, but much work remains to be done to

[3] R. W. George, "Field strength of motorcar ignition between 40 and 450 megacycles," PROC. I.R.E., vol. 28, pp. 409–412; September, 1940.

evaluate these effects. This is believed to be especially important for mobile services where mobile transmitting antennas, and frequently the land-station antennas, are not elevated above immediately surrounding buildings. For elevated broadcast antennas the shadows will tend to fill in behind buildings by reason of reflections from buildings beyond the shadow. Shadows behind hills in rural areas probably will not fill in as well as behind city buildings, and it is expected that somewhat more difficulty may be found in serving hilly areas at the higher frequencies.

There is evidence which indicates that frequencies around 100 megacycles do not penetrate buildings and other structures as well as do frequencies at the lower end of the band.[4] Whether this trend will continue with increasing frequency is not known, but it is quite possible that, when the wavelengths become short in comparison to openings which are surrounded by closed conducting circuits (steel building skeletons, metal window and door frames, etc.), the penetration may improve with increasing frequency. The poorer penetration at some frequencies will affect not only the field strengths of the desired signals but also the field strengths of undesired signals and of noise, if the noise source is removed some distance from the receiving point. It does not appear to be possible to predict what effect differences in penetration will have upon the ratios of desired to undesired signal and signal to external noise which are obtainable with an inside antenna at typical receiver locations. The only answer lies in making comprehensive surveys of signal and noise field strengths at receiver locations. If, as a result of such surveys, it is established that poorer penetration exists at some frequencies but that signal-to-external-noise ratios are not appreciably affected thereby, it is evident that at some locations with low signal intensity it will be necessary to use an outside antenna to overcome receiver noise for a frequency with poor penetration, whereas an inside antenna would be usable for a frequency with good penetration. Only quantitative measurements can establish whether this condition will occur within the protected contours at any given frequency.

Tropospheric Effects

Present knowledge of tropospheric effects does not extend over much of the band under consideration. Continuous recordings of frequency-modulation and television stations have been made by the Federal Communications Commission over a period of about two years. A year's recordings of frequency-modulation stations made at four distances were analyzed to determine the fields exceeded for 0, 10, 50, and 90 per cent of the time, the 100-per cent value being below noise level in each case. These fields were reduced to equivalent values for 1 kilowatt radiated from a half-wave antenna at 500 feet and plotted at the proper distances in relation to K. A. Norton's theoretical ground-wave and tropospheric-wave curves in Fig. 3. The theoretical ground-wave curves agree with the measured

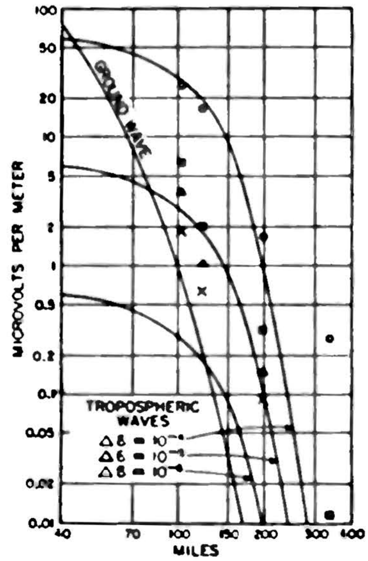

Fig. 3—Tropospheric-wave and ground-wave field intensity versus distance.

Frequency: 50 megacycles
Antenna heights: 500 feet: 300 feet
Polarization: horizontal
Power: 1 kilowatt
Ground constants $\begin{cases} \sigma = 5 \times 10^{-14} \text{ electromagnetic units} \\ \mathcal{E} = 15 \end{cases}$
Tropospheric layer height: 1.5 kilometers
Measured 50 per cent hourly values, 1943–1944:
⊙ Maximum value
⊡ Value exceeded 10 per cent of time
⚠ Value exceeded 50 per cent of time
× Value exceeded 90 per cent of time

values exceeded for more than 90 per cent of the time, and appear to be a relatively reliable measure of service ranges. The maximum measured values greatly exceed the theoretical, so that, in order to protect adjacent stations, the distance to the 5-microvolt-per-meter interference contour may need to be doubled. Measured values at 72 megacycles were also found to verify the theoretical service ranges. The fields were somewhat more variable than at 46 megacycles, so that the interference range should be increased by something more than a factor of 2.[5]

Quantitative data similar to the above are not available on higher frequencies. The experiences of amateurs on 112, 224, and 400 megacycles represent probably the best published data. The 112-megacycle reports are in agreement with the trend indicated at 44 and 72 megacycles; namely, the greater variability of the tropospheric effects with increasing frequency and the necessity for greater station separation to prevent interference due to tropospheric signals. Under favorable tropospheric conditions and with high transmitter and/or receiver locations, amateur stations have been

[4] L. F. Jones, "A study of the propagation of wavelengths between three and eight meters," Proc. I.R.E., vol. 21, pp. 349–386; March, 1933.
R. S. Holmes and A. H. Turner, "An urban field strength survey at thirty and one hundred megacycles," Proc. I.R.E., vol. 24, pp. 755–770; May, 1936.

[5] "Report on VHF field strength measurements 1943–1944," Federal Communications Commission Mimeo 77785; Federal Communications Commission Docket 6651, Exhibit No. 4.

heard over distances between 350 and 400 miles at 112 megacycles.[6] The long-distance-contact records are less at 224 and 400 megacycles, but this may be due to the lesser activity and to equipment development rather than to a change in the trend of tropospheric effects.

F-Layer Interference

The best data on this subject are the regular ionosphere measurements which have been made for many years at the National Bureau of Standards' laboratories near Washington, D. C., and more recently at a very

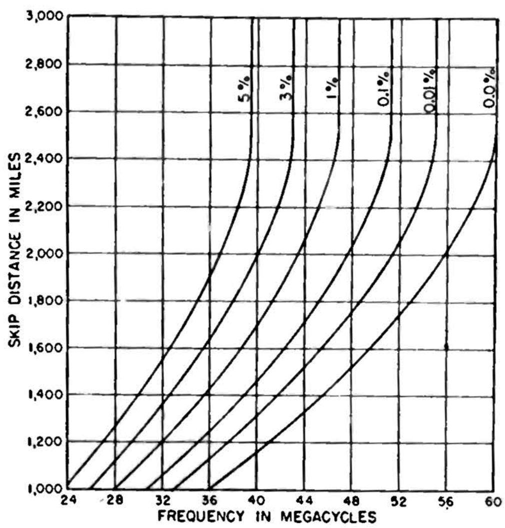

Fig. 4—*F*-layer interference: skip distance versus frequency for various percentages of the listening hours, six A.M. to midnight.

large number of other points throughout the world. These recent measurements have been made by the Interservice Radio Propagation Laboratory under the joint control of the Army and Navy. The Washington measurements have been made throughout a period including the maximum of one phase of the sunspot cycle. The published data[7] for Washington of monthly average values during the months October through March of the three winters centered about the previous sunspot maximum (1936–37, 1937–38, and 1938–39) were corrected for daily variations and analyzed so as to express critical frequencies as a percentage of the listening hours, 6 A.M. to midnight, solar time. Using methods formulated by the Bureau of Standards, the critical frequencies (maximum frequency reflected at vertical incidence) were converted to values of maximum usable frequency versus distance. These data are plotted in Fig. 4.

Assume a frequency-modulation station operating on 44 megacycles during the maximum of the last sunspot cycle. Then, according to Fig. 4, *F*-layer reflections would not have been expected at distances less than 1320 miles. However, *F*-layer transmissions would have been expected at all distances greater than 2060 miles for 1 per cent or more of the listening hours or for a total of 723 hours during the last sunspot cycle. On a frequency higher than 60 megacycles, however, *F*-layer transmissions would not have been expected at any distance provided the transmission path had its midpoint near Washington, D. C. It has been found that the ionosphere directly over many of the other ionospheric recording stations would be expected to support much higher-frequency transmissions than the ionosphere over Washington. It is estimated that the frequencies shown in Fig. 4 should be increased by 15 per cent when considering conditions applicable to interference throughout the United States. In other words, the present 40-megacycle marking on the horizontal scale should be renumbered 46 megacycles, the 60-megacycle marking should be 69 megacycles, etc. The foregoing analysis of conditions during the last sunspot cycle will not apply strictly to future conditions, since the numbers and intensities of the sunspots vary from cycle to cycle. There is also a reversal in sunspot polarity on alternate cycles, which may have some effect.

Fig. 4 applies to the estimated interference via the *F*-layer from a single co-channel station. To what extent will an increase in the number of stations on a single channel increase the expected time of interference? Assume a 46-megacycle station in New York City with six co-channel stations of about the same power located at Athens, London, Georgetown, Bogota, San Francisco, and Honolulu. Fig. 5 is a section of a world map showing the paths under consideration. The Georgetown, Bogota, and San Francisco paths are 2500 miles in length, and transmission is assumed via one reflection point at the *F* layer. The Athens, London, and Honolulu paths involve two reflections at the layer. For simplicity's sake, the assumption will be made that the *F*-layer conditions do not vary between the latitudes represented by the northernmost reflection or control[8] point (2) and the southernmost control point (4). This is not in accordance with the facts but will provide an approximation which is believed to be on the conservative side, if average conditions for the United States are used. The vertical lines on the map are meridians of longitude at 15-degree intervals, so that they are separated by one hour's difference in time. Each meridian is marked at the bottom with the New York time corresponding to noon at the meridian. Assume a winter day near the sunspot maximum on which four hours of interference would be experienced from one station at 2500 miles, beginning at noon at the control point and continuing until 4 P.M. at the control point. For the Athens-New York circuit, the interference at New York would begin at noon at

[6] E. P. Tilton, "On the ultrahighs," *QST*, vol. 25, pp. 54–55; October, 1941.

[7] Published in PROC. I.R.E. for the periods in question.

[8] This is not the "control-point" method of predicting propagation via *F* layer, in which points 1250 miles distant from the transmitter and receiver determine the maximum usable frequency for paths greater than 2500 miles in length. The control-point method and the effects of latitude on maximum usable frequencies were classified material at the time of presentation of the paper and could not be discussed in detail.

[This footnote was added by the author subsequent to completion of the discussion accompanying this paper.—*Editor*] the westernmost of the two control points (1) and end at 4 P.M. local time at the easternmost point. These times correspond to about 10:20 and 10:50 New York time, yielding 30 minutes of interference as shown by the duration chart at the bottom of Fig. 5. The duration of interference can be similarly estimated for the other paths, which when totaled gives about $7\frac{1}{2}$ hours of interference as against 4 hours for one station. Similar analyses for other periods of expected interference from a single station will show that the ratio of multistation to single-station interference increases somewhat with decreasing times of single-station interference. This is expected to increase the ratio slightly when estimating the over-all percentage of time throughout the sunspot cycle, so that the multistation interference may finally be about three times the estimated single-station interference.

Sporadic-*E*-Layer Interference

Again the best data available for determining the practical importance of these transmissions at various frequencies are the systematic observations of the ionosphere made by the Interservice Radio Propaga-

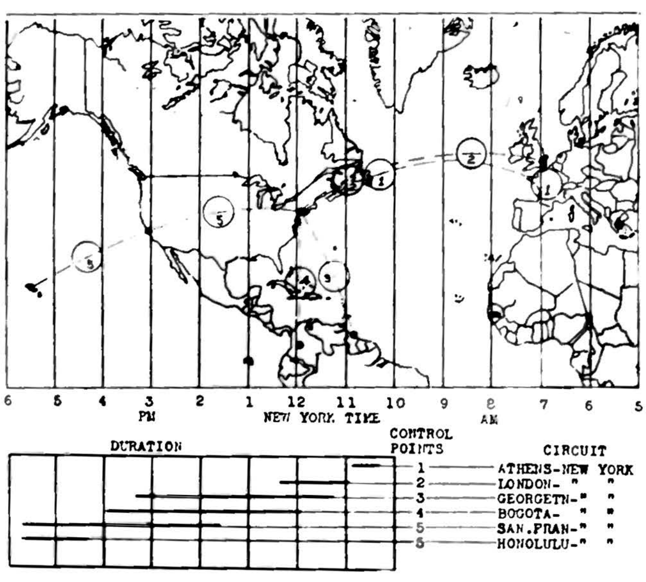

Fig. 5—Estimated increase in *F*-layer interference due to a plurality of co-channel stations.

tion Laboratory. Fig. 6 shows sporadic-*E*-layer skip distance as a function of frequency for various percentages of the listening hours during the year September, 1943, through August, 1944, estimated from vertical-incidence measurements of sporadic-*E*-layer critical frequencies made near Washington, D. C., on frequencies of 3, 5, and 7 megacycles. The curves were arrived at by extrapolating for vertical incidence frequencies above 7 megacycles, in accordance with the logarithmic decrease in occurrence with frequency as determined by the measurements at 3, 5, and 7 megacycles, and applying the standard method of computing skip distances for normal *E*-layer transmission. This particular year was chosen for analysis since it was for this year that the sporadic-*E*-layer field intensities of station WGTR were measured at several Federal Communications Commission monitoring stations. An analysis of similar data obtained at two other ionosphere stations at widely separated points in the United States and for the same period of time yielded very nearly

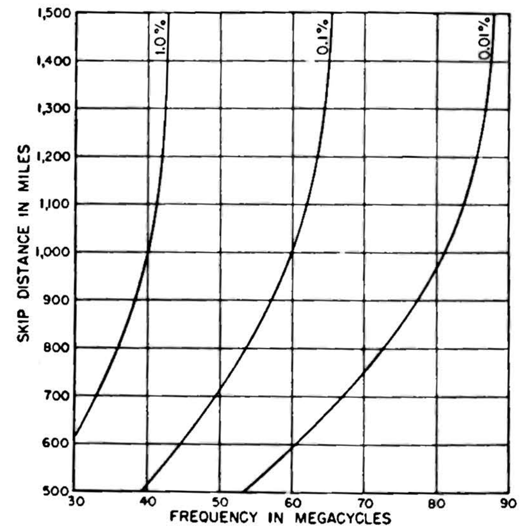

Fig. 6—Sporadic-*E*-layer interference: skip distance versus frequency for various percentages of the listening hours, six A.M. to midnight.

identical results. The Washington data, which are available throughout one phase of the sunspot cycle, did not indicate any systematic variations throughout this last cycle, but did indicate that the conditions for the period analyzed were about average. Consequently, Fig. 6 is believed to represent a reasonably good estimate of the percentage of time that a single frequency-modulation or television station would be expected to interfere with another similar station on the same frequency at the distances shown. At 43 megacycles interference is expected between 0.1 and 1.0 per cent of the time for distances between 600 and 1400 miles. The field intensities at which interference occurs at these percentages of time are treated in a succeeding section.

In an effort to obtain an estimate of the effect of increasing the numbers of stations on the occurrence of sporadic-*E* interference, Fig. 7 was prepared. This is a map of the central and eastern parts of the United States on which has been located the *E*-layer reflection points (1), (2), (3), (4), for the paths over which station WGTR was measured at the Federal Communications Commission monitoring stations at Atlanta, Laurel, Allegan, and Grand Island. Reflection points (*A*) and (*I*) are also shown for paths by which interference might be caused to a Kansas City station by stations located in nine cities 800 miles from Kansas City and 300 miles or more from the adjacent cities. A reliable estimate of the interference to be expected at Kansas City under the assumed conditions will require an extended analysis of available data which has not been possible to date, together with further knowledge of the mechanism of sporadic-E reflections. However, a simplified analysis may permit an educated guess as to what may be expected.

Over the period September, 1943, through August, 1944, sporadic-E fields of 25 microvolts per meter were recorded for 1.71 per cent of the time for path (1), 0.05 per cent for path (2), 0.39 per cent for path (3), and 0.55 per cent for path (4). There was some overlap in

Fig. 7—Estimated increase in sporadic-E-layer interference due to a plurality of co-channel stations.

the times during which transmission occurred, the combined time being 2.23 per cent for all paths, against 2.70 per cent for the arithmetic sum. Thus three additional paths with a total of 0.99 per cent added 0.52 per cent to the occurrence over path (1). This appears to indicate that three additional paths with control points of comparable distance from point (1) and each having 1.71 per cent would have raised the multipath interference to 4.40 per cent. Applying the ratio to the Kansas City case of nine paths, each over a distance likely to give 1.71 per cent occurrence of sporadic E, we obtain a total of 8.89 per cent. Considered solely from the standpoint of probability, the ratio 52/99 which applies to the case of three additional stations with small percentages of interference is too high for eight additional stations each causing a larger percentage of interference, assuming comparable spacings between control points. Increased control-point spacing in any direction will tend to increase the ratio because of the apparently random nature of the sporadic-E-layer at times.[6] Increased spacing east and west should increase the ratio owing to systematic diurnal effects. For the present it will be assumed that latitude effects are canceled, since control point (1), which has been used to estimate quantitatively the interference over each path, is at an average latitude. Interference from ten to fifteen additional stations spaced at other distances from Kansas City will, of course, add materially to the over-all time of expected interference. Considering all the factors, it appears probable that a midwestern station with twenty co-channel stations may experience interference amounting to five or more times the estimated interference for a single path.

Sporadic-E- and F-Layer Field Strengths

Fig. 8 shows curves of the variation of tropospheric, sporadic-E-layer, and F-layer field strengths with time and distance for station WGTR, Paxton, Massachusetts, at 44.3 megacycles. The tropospheric curves shown in Fig. 8 were prepared from the data used in Fig. 3, and their effect on theoretical service and interference ranges has already been discussed in connection with that figure. The F-layer curve is a theoretical curve of the variation of F-layer median field intensities, and the intensity at any distance approximates the free-space field at one mile, 2540 millivolts per meter,

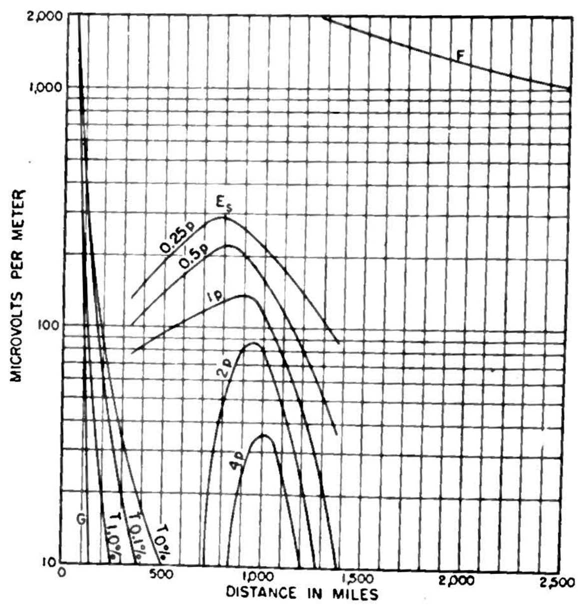

Fig. 8—Ground-wave, tropospheric wave, sporadic-E-layer sky-wave, and F-layer sky-wave field intensities for frequency-modulation station WGTR at Paxton, Massachusetts.

Free-space field at one mile = 2540 microvolts per meter
Antenna height = 1600 feet.
G = Ground wave
$T_{0\%}$, $T_{0.1\%}$, $T_{1\%}$ = Tropospheric-wave field intensities exceeded for the percentages of time indicated
$E_s(np)$ = Sporadic-E-layer sky-wave field intensities exceeded for n times the percentages of the time shown in Fig. 6
F = F-layer sky-wave intensity

divided by the distance in miles. For sporadic-E fields, the data recorded at each of the four recording points previously mentioned were analyzed to determine the percentages of time during which the fields exceeded various intensity levels. From these data and the skip-distance curves of Fig. 6, a family of curves E_s were computed. Each curve is labeled with a factor by which the percentages of time shown by Fig. 6 must be multiplied in order to obtain the percentages of time for which the indicated intensities occur. Thus the curve $1p$ shows expected field strengths versus distance for the percentages of time predicted by the curves of Fig. 6, the maximum occurring at about 900 miles. For lesser percentages of time ($0.25\ p$ and $0.5\ p$) higher field strengths will occur and for greater percentages of the time ($2p$ and $4p$) weaker fields will occur at a given distance.

Interference from Bursts

The measurements made at the same four Federal Communications Commission monitoring stations from several high-powered frequency-modulation stations over a two-year period indicate that negligible interference will be caused to the 50-microvolt-per-meter protected contour from this source.[5] Although not entirely free of this interference, reasonably good service may be possible to about the 5- or 10-microvolt-per-meter contour. If the bursts are caused by meteoric ionization, which is the present assumption, the numbers, amplitudes, and average durations should decrease with frequency. This is in agreement with such observations as we have made on the aural channels of television stations and with observations of other persons at frequencies down to about 10 megacycles.[9,10]

Comparison of Service Areas at 46 and 105 Megacycles

Having considered individually certain factors which affect the service ranges to be expected in the band under consideration, the combined effect of these factors on frequency-modulation broadcast service areas will now be considered. Fig. 9 presents a comparison of the service areas to be expected at 46 and 105 megacycles for transmitting stations having a 500-foot antenna. The receiving antennas are at 30 feet in each case, and a 6-decibel reduction in the received field is allowed for irregularities in terrain, line loss, etc.

The figures in the top row show the theoretical coverage over smooth earth for a large station with an effective radiated power of 340 kilowatts. The inner circle of each figure represents the primary service area to the 50-microvolt-per-meter contour, within which it is desired to protect the signal from interference by other stations. The primary area at 46 megacycles is slightly larger than at 105 megacycles. The outer circle at 46 megacycles and the middle circle at 105 megacycles represent the service limits obtainable in very quiet rural areas with external noise sufficiently low so that set noise is the limiting factor, with good receivers capable of delivering a usable signal with a 2-microvolt input, and with negligible interference from other stations. The extra 46-megacycle area under these conditions is almost twice as large as the area at 105 megacycles. By the use of multiple-element Yagi receiving antennas at 105 megacycles, an extra rural area approximating three fourths of the 46-megacycle rural area may be obtained. The middle row of figures gives a similar comparison for a station with an effective radiated power of 1 kilowatt.

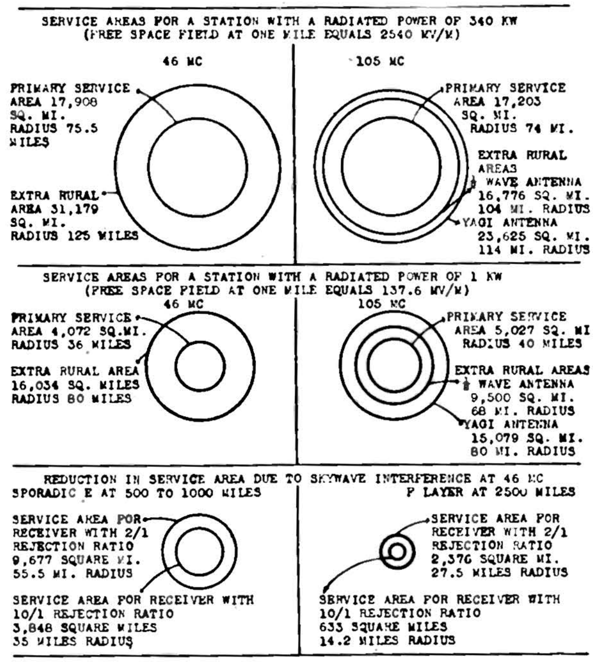

Fig. 9—Comparison of frequency-modulation service areas available on 46 and 105 megacycles.

In this case, the 105-megacycle primary area is the larger, with the total area at 46 megacycles equal in size to the 105-megacycle area for Yagi receiving antennas.

Owing to shadow effects, coverage within the primary and rural areas is likely to be somewhat more spotty at 105 megacycles than at 46 megacycles. External noise levels will also eliminate large portions of the rural areas, and external noise of a given intensity will become effective against the areas obtainable with the Yagi antenna before it affects the areas obtainable with a half-wave receiving antenna. The tendency to reduce the 105-megacycle area to a greater extent should be offset somewhat, but not completely, by the decrease in external noise level with frequency. The assignment of other stations to the same channel will limit the useful area to the 50-microvolt-per-meter contour, if they are close. If the co-channel stations are distant, the extra rural areas will be affected by burst interference at 46 megacycles and probably, to a lesser extent, at 105 megacycles. At 46 megacycles sporadic-*E*-layer and *F*-layer interference from distant stations is expected to affect both primary and rural areas seriously at certain times.

[9] J. A. Pierce, "Abnormal ionization in the E Region of the ionosphere," Proc. I.R.E., vol. 26, pp. 892–908; July, 1938.
[10] T. L. Eckersley, "Analysis of the effect of scattering in radio transmission," *Jour. I. E. E.* (London), Wireless Section, vol. 15, pp. 74–93; June, 1940.

Referring to the left figure of the bottom row on Fig. 9, residual areas for a broadcast station are shown for conditions of sporadic-E interference which are expected for 0.1 per cent of the time from a single co-channel station of equal power or for 0.5 per cent or more of the time for a fully utilized channel.[11] The larger station sustains a reduction in its primary area of 46 per cent for good receivers with a 2-to-1 rejection ratio and 78 per cent for an average receiver with a 10-to-1 rejection ratio. The 1-kilowatt station sustains a reduction in primary area of 5 per cent for an average receiver. A good receiver will still give service beyond the 50-microvolt-per-meter contour for these conditions of interference and will permit reduction in service area for an estimated 0.05 per cent of the time for a fully utilized channel.

[11] The estimated interference of 0.5 per cent of the time for full channel occupancy was subsequently realized to be too conservative for the following reasons. The interfering field intensity required to limit the service to the indicated contours is 100 microvolts per meter when the desired and undesired station each have 340 kilowatts effective radiated power. This corresponds to the level exceeded by the $1p$ curve of Fig. 8 between distances of 600 to 1000 miles. The percentages of time during which this will occur for individual stations located at different distances is determined by reference to Fig. 6. At 46 megacycles the percentages of time range from 0.1 per cent at 625 miles to 0.5 per cent at 1000 miles for a single interfering station, as determined by logarithmic interpolation between the curves. Increasing the number of stations per channel to about twenty has been estimated to increase the total interference to a station in the Midwest to about five times the interference from a single station at a distance of 800 to 900 miles, which gives a total of about 2 per cent of the time during which the service will be limited to the designated area.

The effect of F-layer sky-wave interference is shown in the right figure of the bottom row on Fig. 9. At 46 megacycles this is expected to occur about 5 per cent of the time for a single co-channel station, with an increase to 10 or 15 per cent for a fully utilized channel. The occurrence of this condition at 105 megacycles is expected to be negligible. The large station suffers reductions in area of 86 and 96 per cent for good and average receivers, respectively. The corresponding reductions for the small station are 41 and 84 per cent, respectively. In order to reduce the sky waves from stations separated by 2500 miles to the point where mutual protection will be given to the best receiver at the 50-microvolt-per-meter contour, the effective radiated power of each must be limited to 200 watts.

In addition to contrasting the expected conditions of interference on 46 and 105 megacycles, Fig. 9 shows the importance of using a receiver which is capable of rejecting a strong interfering signal. Tests on several commercial models of frequency-modulation receivers have indicated that single-limited models may require a desired signal more than ten times as strong as the undesired in order to obtain an acceptable output, while the best double-limited receiver tested required about three to one. The service areas obtainable with the good receiver having a 2-to-1 rejection ratio are therefore larger than are obtainable with any of the receivers tested.

Discussion

C. M. Jansky:[1] The paper, "Very-High-Frequency and Ultra-High-Frequency Signal Ranges as Limited by Noise and Co-channel Interference," published under the name of E. W. Allen, Jr., is one of the most important ever presented to The Institute of Radio Engineers. This is because it constitutes a presentation to the scientific world of a large portion of the technical evidence upon which rested the decision of the Federal Communications Commission to uproot frequency-modulation broadcasting from the allocation it previously had in a band of frequencies in the vicinity of 50 megacycles and to assign this service instead to a band in the vicinity of 100 megacycles.

The writer served as chairman of Panel 5 on frequency-modulation broadcasting of the Radio Technical Planning Board (RTPB) which was charged with the responsibility of preparing and presenting to the Federal Communications Commission the radio industry's proposal with respect to the technical requirements for an adequate frequency-modulation broadcasting allocation structure. The recommendation of the industry, supported almost unanimously in RTPB, was to the effect that the frequency-modulation broadcast band should be expanded upward from its original position in the vicinity of 50 megacycles. The decision of the Commission was to move the band to frequencies in the vicinity of 100 megacycles. Space does not permit a complete review of the history of this issue, but nevertheless an understanding of the paper and technical comment will be greatly enhanced if the reader has some general knowledge of the attendant circumstances.

[1] National Press Building, Washington 4, D. C.

As originally prepared for presentation at the Winter Technical Meeting of The Institute of Radio Engineers held at New York City, January 24–27, 1945, the paper, according to an appended note, was intended as a joint presentation by K. A. Norton, formerly an employee of the Federal Communications Commission, and E. W. Allen, Jr. Admittedly, the material was prepared jointly and contains data and conclusions entered into the record of the Federal Communications Commission Hearing on Frequency Allocations, Docket 6651, by Mr. Norton. Therefore, very properly, comment upon the paper can and should recognize not only the joint responsibility for the material but also its relevancy to the proceedings before the Commission.

It is well recognized that the science of radio propagation is one of great complexity. As the writer has stated, "It is unfortunate that, throughout the entire range of frequencies extending from 40 to 110 megacycles, data with respect to *all* of the phenomena of importance are not only meager but the interpretations which must be made to express the results in terms of interference and service areas are extremely complicated, frequently requiring assumptions of unproven validity and not easily understood by those who have not devoted years of study to the subject." (Page 6, Brief on behalf of Panel 5, FM Broadcasting, of the RTPB.)

In reply to an inquiry addressed by Panel 5 to Dr. J. H. Dellinger, Chief of the Radio Section of the United States Bureau of Standards, and Chief of the Interservice Radio Propagation Laboratory of the United States Government, Dr. Dellinger recommended that frequency-modulation broadcasting be kept in the vicinity of 50 megacycles and said, "It may also be stated that no frequencies are free from transmission vagaries." This leads to the logical conclusion that, in determining which of two bands is best for a particular service, it is necessary to weigh the relative importance of all the various detrimental effects which are present *to a greater or less degree* in both bands. In the case at hand we need to concern ourselves only with the propagation effects upon potential service of three transmission vagaries, namely: (1) F_2-layer phenomena, (2) sporadic-E-layer phenomena, and (3) tropospheric phenomena. Of course, of prime importance are the comparative characteristics of the propagation medium to transmit radio waves over given distances even assuming the complete absence in the two bands of the vagaries listed above.

Briefly, when this paper is stripped of the data and argument purporting to justify the conclusions drawn by the author or authors, it will be found that their contention is (1) in general, the field intensities produced over given distances in the absence of transmission vagaries are at least as satisfactory near 100 megacycles as near 50 megacycles, (2) that tropospheric phenomena, while admittedly more detrimental at the higher band, are not of sufficient importance to materially affect the result, but (3) the severe interference effects of sporadic-E- and F_2-layer phenomena are of such importance that the possibilities of securing adequate rural coverage near 50 megacycles are not nearly so great as near 100 megacycles. Therefore, they imply and conclude that the frequency-modulation broadcast band should be near 100 megacycles.

In contrast, it was the opinion of the group of well-recognized propagation scientists called upon by Panel 5 for assistance in formulating its proposals (1) that the detrimental effects of sporadic-E- and F_2-layer phenomena were being grossly exaggerated by Messrs. Norton and Allen; (2) that, in addition, a fundamental error had been made in determining the importance of F_2-layer phenomena which vitiated the conclusion drawn regarding their effect; and (3) there was at least a strong probability that the detrimental effects of tropospheric phenomena near 100 megacycles were being much underestimated. This feeling with respect to tropospheric phenomena has been amply justified by field studies which have been made since the proceedings were started, and the contention that the basic propagation characteristics of 100 megacycles were substantially as satisfactory for large-area rural coverage as at 50 megacycles has been disproved.

Now that the veil of military secrecy has been lifted from the classified record taken at the hearing held March 12 and 13, 1945, the attention of the scientific world should be directed to the testimony of Dr. J. H. Dellinger, eminent authority in this field, who stated: "Nobody is interested in a lot of data but in what the data show. In this case, with what interference the data indicate and how the interference compares with that existing in other frequencies—that brings us to the question of why Mr. Norton's conclusions are different from mine. The reason is because, implicitly if not explicitly, of a *very considerable exaggeration of the effect of ionospheric interference.* Ionospheric interference is very little at either 50 or 100 megacycles. . . . *It is very little at either.* So that the elaborate demonstrations that it is many times less at 100 megacycles than at 50 megacycles are *pointless*" (emphasis added). The record shows that a large majority of those qualified to express opinion on the subject are in agreement with Dr. Dellinger.

The Findings of Fact released by the Federal Communications Commission in this proceeding show that the decision made by the Commission to shift the band assigned to frequency-modulation broadcasting from 50 to 100 megacycles rests almost entirely upon technical evidence which scientific opinion of the highest qualification has characterized as "pointless."

The writer will leave to others the evaluation of the effects of moving the frequency-modulation broadcast band upon a nascent industry. However, there are lessons of great value to the radio engineer in this proceeding which should not remain buried in the voluminous compilations of detailed testimony and argument.

It is unfortunate that throughout the entire history of radio communication it has been necessary to make allocations to the various radio services in the absence of truly adequate scientific data concerning radio propagation. It is equally unfortunate that where allocation mistakes are made they are lasting in effect and never can be completely corrected. As the writer stated in the Brief in support of the position taken in Panel 5, already referred to, "This is because man, by his ingenuity and inventiveness as time progresses, can design and build new and improved devices for the transmission and reception of radio waves but he can do nothing to control the characteristics of the transmission medium which connects the transmitter and the receiver." (Page 6.)

Since, in this country, the responsibility for final decision in matters of this sort rests upon courts and regulatory bodies the members of which are usually men without scientific training, it is of the highest importance that those who presume to speak with authority on scientific subjects do so with complete objectivity. To illustrate, the absence of knowledge on specific points should never become an excuse for ignoring those points and conclusions drawn should be strictly limited to what is justified by the data available. Again quoting the Panel 5 Brief, "Therefore, the responsibility resting upon those who presume to speak with authority and finality is very great. The adequacy of their data, thoroughness and objectivity of analysis, and the validity and completeness of their conclusion become matters of far greater importance than would be the case if the subject were simple." (Page 6.)

Unless radio engineers meet the full requirements of objectivity in presenting their findings and conclusions, in the final analysis they cannot expect to have much influence in shaping public policy affecting the art which they developed.

Edwin H. Armstrong:[2] What the first part of the paper which has appeared under Mr. Allen's name undertakes to do is to present as physical fact the calculated ranges of ultra-high-frequency transmissions based upon certain assumptions, without either apprising the reader what these assumptions really are or furnishing him with any supporting experimental data. It is in point to examine the bases on which the results are arrived at.

It appears that one of the conditions underlying the calculation of what is referred to as the theoretical "ground-wave" service range is the assumption of the existence of a standard atmosphere over the entire path of transmission. It further appears that the effect of this standard atmosphere to refract or bend the waves downward beyond the horizon is taken into account with other factors to predict the field strength at a given point. It also appears that, while fields of an intensity greater than that corresponding to the calculations for a "standard atmosphere" are contemplated, the possibility of substandard conditions is not considered.

No doubt, as an analytical exploration of what might happen in some world where weather changes are unknown and where the atmosphere of that world maintained a constant, unchanging relation to the assumptions made, the predicted values might be of some interest. But in the realities of the present world in which, unfortunately, we have to do our engineering, it is necessary to contend with a more complicated set of facts than were taken into account in these calculations.

It is unimportant in discussing the point of the paper that we understand exactly how the factors involved operate. The thing that is important is recognition of the fact that what is referred to as a "ground wave," and which is represented as being something that is always there with a field strength that may be increased in intensity but not decreased by the effect of the "troposphere," is not, in fact, a ground wave at all as that term is generally understood. It is, instead, a wave dependent on meteorological conditions whose effects on transmission are complex and whose exact relationship to the received field strength beyond the horizon cannot quantitatively be set down.

Anyone who has had a transmitter of sufficient power on the air in the very-high-frequency or ultra-high-frequency ranges to produce receivable signals well beyond the horizon over the terrain of this world knows the extraordinary extent of the variation of intensity below, as well as above, the predicted "ground-wave" value. Anyone who has compared the fading at 40 and 100 megacycles knows that the effect of meteorological changes produce larger variations in the higher frequencies. And anyone who has had experience with a broadcast service knows that it is the bottom of the fade, or the "drop out," and not the average or some long-time statistical value which determines the minimum boundaries of a broadcast service. Calculations based upon the assumption of a standard atmosphere are utterly useless in determining the answer to this very practical question, as the writers of the paper would very soon have learned had they taken the trouble to put a high-power station in operation and observe the field strength well beyond the horizon. But, quite oblivious to the realities of the situation, the writers proceed, on the basis of this statistical treatment resting on a series of unsound assumptions, to the vital comparison made in the second part of the paper.

What the second part of the paper undertakes to do is to make a comparison of interference ratios on the two specific frequencies of 46 and 105 megacycles. This comparison is made on the premise of the theoretically calculated "ground wave" for 105 megacycles giving perfect coverage 100 per cent of the time over its area (because it is assumed to be so) against a similarly calculated service area for 46 megacycles as indented by sporadic-E- and F_2-layer ionospheric interference. The interference values predicted for F_2 transmission are unsupported in any way by experimental evidence of actual received signal levels and are based on vertical-incidence measurements made by the Bureau of Standards and the Interservice Radio Propagation Laboratory, plus certain assumptions made by the writers. The sporadic-E interference is said to be based on the experimental evidence of recorded signal strengths and upon theoretically predicted values extracted from vertical-incidence measurements made by the organizations referred to above. The experimental and predicted results for this kind of interference have been stated to be in close agreement.

A considerable amount of experimental evidence is available concerning F_2-layer transmission that is not

[2] Columbia University, New York 27, New York.

in accord with the conclusions of the paper, but it is not necessary to consider it here insofar as the end result of the subject of the paper is concerned. It is now conceded that, at least as far as the United States is concerned, such transmission is not an important factor above 50 megacycles and the former predictions of the possibility of F_2-layer transmission up to 120 megacycles have been withdrawn.

The real question, therefore, from the practical broadcast standpoint, resolves itself into an evaluation of the relative effects of sporadic-E interference in the outer ranges of a 50-megacycle transmission, versus the absence of signal in those ranges during the greater fading periods of a 100-megacycle signal. In this evaluation there enters, of course, the effect of terrain, the importance of which seems to have been overlooked.

It is not possible to determine quantitatively the loss of service due to the absence of signal because of the lack of data of any sort in the paper concerning either fading or the ratio of the fading on the low and high band at points beyond the horizon. This matter has, however, been covered in a presentation before the Institute by C. W. Carnahan, and much experimental data bearing on this part of the problem will be available with the publication of that paper.[3]

It is possible, however, on the basis of the data furnished in the present paper, to examine the conclusions which are reached about the other part of the problem, that is, the extent of sporadic-E interference. These conclusions are summarized by Allen's Fig. 9. Examining this figure for the worst case of sporadic-E interference, that is, interference between high-power stations on the lower frequency (the interference over the service areas of low-power stations may be considered practically non-existent), we find the following results given for interference between two Paxton-type stations. These stations are assumed to have a radiated power of 340 kilowatts at a 500-foot antenna height. We find that on the basis of reported measured sporadic-E interference levels the predicted primary service radius of $75\frac{1}{2}$ miles for this type of station is reduced to $55\frac{1}{2}$ miles for 1/10th of 1 per cent of the time for the critical distance of 500 to 1000 miles for interference from a single frequency-modulation station.

The above time of interference is predicated on operation on 46 megacycles. Examining further the occurrence of sporadic-E interference, we find it stated that it decreases logarithmetically with respect to frequency, and the curves of Allen's Fig. 6 are plotted on this basis. It follows from this figure that the removal of the Paxton-type transmitter from an allocation in the vicinity of 46 megacycles to a frequency about 10 megacycles higher would result in a decrease of the interference time to above one-fifth of the above value, so that the service range would be indented from 75 to 55 miles by this form of interference for 1/50th of 1 per cent of the time.

It is stated that, if twenty stations of the Paxton type were operating on the same wavelength within the United States, the interference time for a single station would be increased five-fold. So it follows that, when twenty Paxton-type stations were all operating on the same channel in the vicinity of 55 megacycles, interference may be expected in the outer 20 miles of the normal 75-mile service range 1/10th of 1 per cent of the time. As a possible 50 channels out of an assigned 100 should normally be available for the use of high-power stations, it is interesting to speculate on the question of how many years removed we are from the realization of 1000 Paxton-type stations as a practical actuality!

Pointless as it is to pretend that the vagaries of ultra-high-frequency transmission could be predicted with the accuracy we are here discussing, it is in order to point out that there is a real effect not taken into account in the paper that serves to decrease still further the interference time.

During the summer months transmission efficiency rises sharply, so that the so-called 50-microvolt line is then at a substantially greater distance from the station than during the colder months of the year. Sporadic-E transmission is concentrated almost entirely during the months when this expanded tropospheric range is realized. As a consequence, there follows an automatic reduction within the normal service range of the amount of sporadic-E interference to figures below those given above.

Although there are a number of other factors that have an important bearing on the problem, attention has been called to a sufficient number of absurdities in the method of approach to an engineering problem to make it unnecessary to go further. The variables involved are so many that the abandonment of the time-honored approach of at least "listening to the signals" and its replacement by the approach of the "armchair geographer" is an incredible thing. It is more incredible that anyone should have paid any attention to it, and with this statement we could ordinarily let the matter rest.

There is, however, an extraordinary piece of legerdemain in the paper to which attention must be called because its purpose is obviously to preserve the fallacy that propagation questions of the sort we are dealing with are now a sort of exact science where coming events can be predicted and calculated with the precision we attribute to some of the older arts.

This engineering skulduggery appears in connection with the sporadic-E predictions, and attention must be called to it because Mr. Allen does not appear to be aware of its existence in the paper bearing his name. His Fig. 6 shows the sporadic-E-layer skip distance as a function of frequency for various percentages of time during the year September, 1943, through August, 1944, estimated from measurements of sporadic-E-layer

[3] C. W. Carnahan, N. W. Aram, and E. F. Classen, "Field intensities beyond line of sight at 45.5 and 91 megacycles," Proc. I.R.E., pp. 152–159, this issue.

critical frequencies made in Washington, D.C. It is stated that this figure is believed to represent a reasonably good estimate of the percentage of time that a single frequency-modulation station would be expected to interfere with another similar station on the same frequency at the distances shown. From this figure we find that the transmission over the Paxton–Atlanta path, which has its midpoint near Washington, would be supported about four-tenths of 1 per cent of the time. We also find that this theoretical prediction is not at all in accord with the experimental results reported for the reception of the Paxton signals at Atlanta, where levels in excess of 25 microvolts were recorded for 1.71 per cent of the time during which observations were made.

Here are grounds for questioning either the accuracy of the experimental results or the application of the predicted methods of Fig. 6. The paper does not do this, nor does it call attention to the disagreement between the two. Instead, the discrepancy is concealed by the ingenious device of the so-called "*p*" curves of Fig. 9, in which the 400 per cent difference between the observed time of transmission and the theoretically expected time is brought into agreement by introducing multiplication factors for the various field intensities. Mr. Allen appears to have been unaware of this juggling of the two into agreement, for during the discussion of the paper he said:

"I want to say that in reference to the curves which were shown for sporadic *E*, and which were predicted curves from data measured at vertical incidence by the National Bureau of Standards, using the accepted methods of extending critical frequencies at vertical incidence to maximum usable frequency versus distance, and correlating the data which was measured at Atlanta over a distance of 900 miles from Paxton, when we measured the percentage of time during which the signal exceeded 25 microvolts per meter and correlated it with the data which were extracted from the records of the National Bureau of Standards, we obtained a phenomenal, I might say, correlation over the years which we recorded."

Of course correlation was obtained. The experimental and the "extracted" results were made to correlate![4]

C. W. Carnahan and J. E. Brown:[5] That fading exists on frequencies above 30 megacycles for receiving points beyond the horizon has been known for at least fifteen years, as has also the fact that the prevalence and severity of this form of interference increases with frequency. While the author takes some cognizance of this in his discussion of tropospheric effects, the impression is given that a tropospheric component causes only an *increase* in field intensity over the ground-wave value, and never a decrease.

As a matter of record, the Federal Communication Commission's own measurements on frequencies of 84 and 107 megacycles[6] have shown that, at a distance of 70 miles from the transmitters, the amount of time during which the signal is lost due to fading is so great that an adequate broadcast service is impossible. In fact at 107 megacycles the signal was entirely absent for 20 per cent of the time, disappearing for hours at a time on successive days. Assuming 50 kilowatts radiated power on these frequencies, the fields predicted from Norton's curves were many times greater than the 4 microvolts per meter postulated by the author as adequate for rural broadcast service.

We understand that the author was requested to publish this paper in its original form. This is unfortunate, since a study of the above measurements indicates how meaningless are estimates of broadcast service beyond the horizon based on Norton's curves for the minimum field intensities without taking account of fading. The presentation of this one-sided picture at this time is doubly unfortunate since frequency-modulation broadcast services are about to be inaugurated in all parts of the world, and this paper will be used as a basis for the selection of frequencies.

As a result of the Zenith and Federal Communications Commission's measurements in 1945, we know now that at distances of 70–75 miles, and with radiated powers of 50 kilowatts, the fading on the old frequency-modulation band is not sufficient to impair rural service greatly, while the fading in the new band is so bad that no adequate service can be expected.

The service range in the new frequency-modulation band will be determined entirely by the fading characteristics at these frequencies, and not by the ground-wave field intensities as obtained from Norton's curves. Unfortunately, measurements so far made have not established the distance at which fading in the new band will be reduced to a satisfactory level, but an estimate of 60 per cent reduction in service area over that of the old band is reasonable.

The author, in his discussion of the effect of sporadic-*E*- and *F*-layer interference unfortunately leaves the impression that the new frequency-modulation band will be entirely free of interference. Actually, as we now know, in going to the new frequency-modulation band we have merely exchanged long-distance interference, which exists for only several months out of the year, for the much worse interference due to fading which exists practically every day.

Paul A. de Mars:[7] The paper, "Very-High-Frequency and Ultra-High-Frequency Signal Ranges as Limited by Noise and Co-channel Interference," published under the name of E. W. Allen, Jr., purports to summarize the various major factors affecting radio wave propagation in the frequency range from 30 to 3000 megacycles to the extent to which they are known or can be predicted and to establish the probable service and interference ranges for broadcast and land mobile services within this part of the frequency spectrum.

[4] For the sake of the record it is here noted that Mr. K. A. Norton, then listed as the co-author of the paper, took part in the discussion and the presentation of this paper and made no correction of Mr. Allen's statement.

[5] Zenith Radio Corporation, Chicago, Illinois.

[6] Federal Communications Commission Docket 6651, January 18–19, 1946.

[7] 1469 Church Street, N.W., Washington 5, D. C.

This paper was originally prepared for presentation at the Winter Meeting of The Institute of Radio Engineers at New York City, January 24–27, 1945, as a joint presentation by K. A. Norton, formerly employed by the Federal Communications Commission, and E. W. Allen, Jr. This paper contains data and conclusions entered into the record of the F.C.C. hearings on frequency allocations, Docket No. 6651, by Mr. Norton.

The author treats the extremely broad subject by first presenting ground-wave service ranges based upon theoretical considerations and later touches lightly upon tropospheric propagation effects and terrain as factors which modify the theoretical ranges. There then follows a more detailed treatment of long-distance *F*-layer and sporadic-*E*-layer and burst interference.

The scope of these comments will be limited to Mr. Allen's treatment of the effect of the troposphere and terrain on the service range of broadcast stations.

Although the conditions underlying the calculations of the so-called ground-wave ranges are not clearly set forth, it appears that these are based upon a smooth spherical earth with uniform ground constants and a standard atmosphere in which the dielectric constant of the air varies uniformly as the height above the earth increases. The average bending of the radio waves due to refraction in the standard atmosphere is included by assuming that the effective radius of the earth is increased to four-thirds of its actual value. It has long been known that atmospheric refraction can and does cause very large and persistent fluctuations in signal strengths and operating ranges in the frequencies under discussion. The meteorological origins of these effects are complex and varied and occur in some form all over the earth's surface. The concept of an equivalent earth's radius to account for reflection is totally inadequate to explain tropospheric variations in signal intensities. Furthermore, variations in signal intensities result from reflection and refraction from air-mass boundaries and other meteorological irregularities. The dependence of radio propagation on the weather increases as the frequency increases and the variation in signal intensity increases as the distance from the transmitter increases. Beyond the horizon the major factor affecting signal intensities is the effect of the troposphere.

The effect of the troposphere on signal intensities in the broadcast band is shown in Figs. 1, 2 and 3, which were prepared by the writer. Fig. 1 shows the signal intensities in microvolts per meter of Yankee Network's broadcast station WGTR, Paxton, Massachusetts, recorded at Seabrook Beach, New Hampshire, for a fourteen-month period from December, 1940, through February, 1942. WGTR at that time operated on a frequency of 44.3 megacycles with an effective radiated power estimated at 300 kilowatts. The airline distance from the transmitter to Seabrook Beach is 67 miles. The signal intensities plotted are average values obtained by plotting the running average for twenty-seven days. It will be noted that with twenty-seven day smoothing the seasonal effect of atmospheric refraction is very clearly indicated. The predicted signal intensity using the ground-wave signal-range curves adopted by the Federal Communications Commission would be about 400 microvolts per meter. The actual measured signal intensities are found to be distributed above and below this value, indicating that the tropospheric effects produce both superstandard and substandard propagation conditions. The Seabrook recordings further show that, even when twenty-seven day averages are used to obtain mean values, substandard

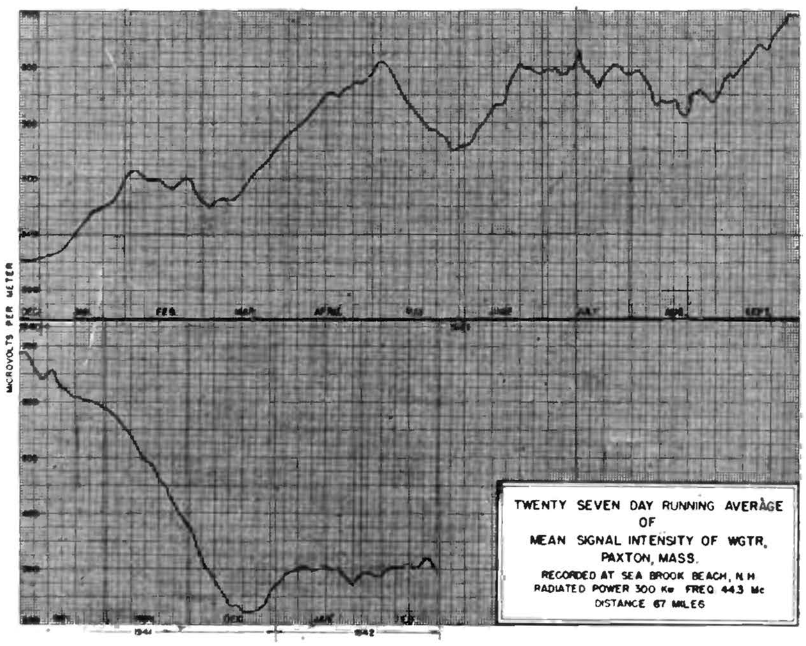

Fig. 1

propagation conditions exist for long periods of time, in this case about 40 per cent. Because of the observed physical fact that the variation in signal intensity increases with frequency, a similar curve based upon recordings over the Paxton-Seabrook path on a frequency of 100 megacycles would show a greater departure from values predicted on theoretical considerations.

The inner boundary of a broadcast service is determined by the minimum value of fading signals, and the interference to other stations is determined by the maximum intensity of fading signals. Fig. 2 presents a graphic representation of (1) the signal intensity versus distance exceeded 1 per cent of the time, (2) the signal intensity exceeded 99 per cent of the time, and (3) the signal intensity calculated on the assumption of a smooth spherical earth, uniform ground constants, and a standard atmosphere. In order to avoid confusion the effect of terrain is not included, and the signal intensities shown on Fig. 2 represent those that would result over a smooth earth. A scale is provided which permits signal intensities to be evaluated from radiated powers from 0.1 kilowatt to 1000 kilowatts in terms of decibels above 1 microvolt per meter, and also in microvolts per meter for antenna heights from 100 feet to 5000 feet. The theoretical signal intensities were taken from the Federal Communications Commission's ground-wave signal-range curves for frequency-modulation broadcast stations in the 88- to 108-megacycle band. The curves representing signal intensities exceeded 1 and 99 per cent of the time have been derived from a large number of signal-intensity measurements and recordings, many of which were made by the Federal Communications Commission at its own measuring stations. Portions of the curves of Fig. 2 extend beyond ranges at which signal intensities measurements have been made. The extrapolation has been made in accordance with empirical methods which are believed to yield substantially correct values for the distances shown. Included in the data upon which these curves are based are the values of signal intensities obtained in the tests made by the Zenith Radio Corporation, which covered a comparison of the fading on the 42- to 50-megacycle band and the 88- to 108-megacycle band at points beyond the horizon. These tests have been covered in a presentation before the Institute by C. W. Carnahan and an evaluation of the results will be available with the publication of that paper.[3]

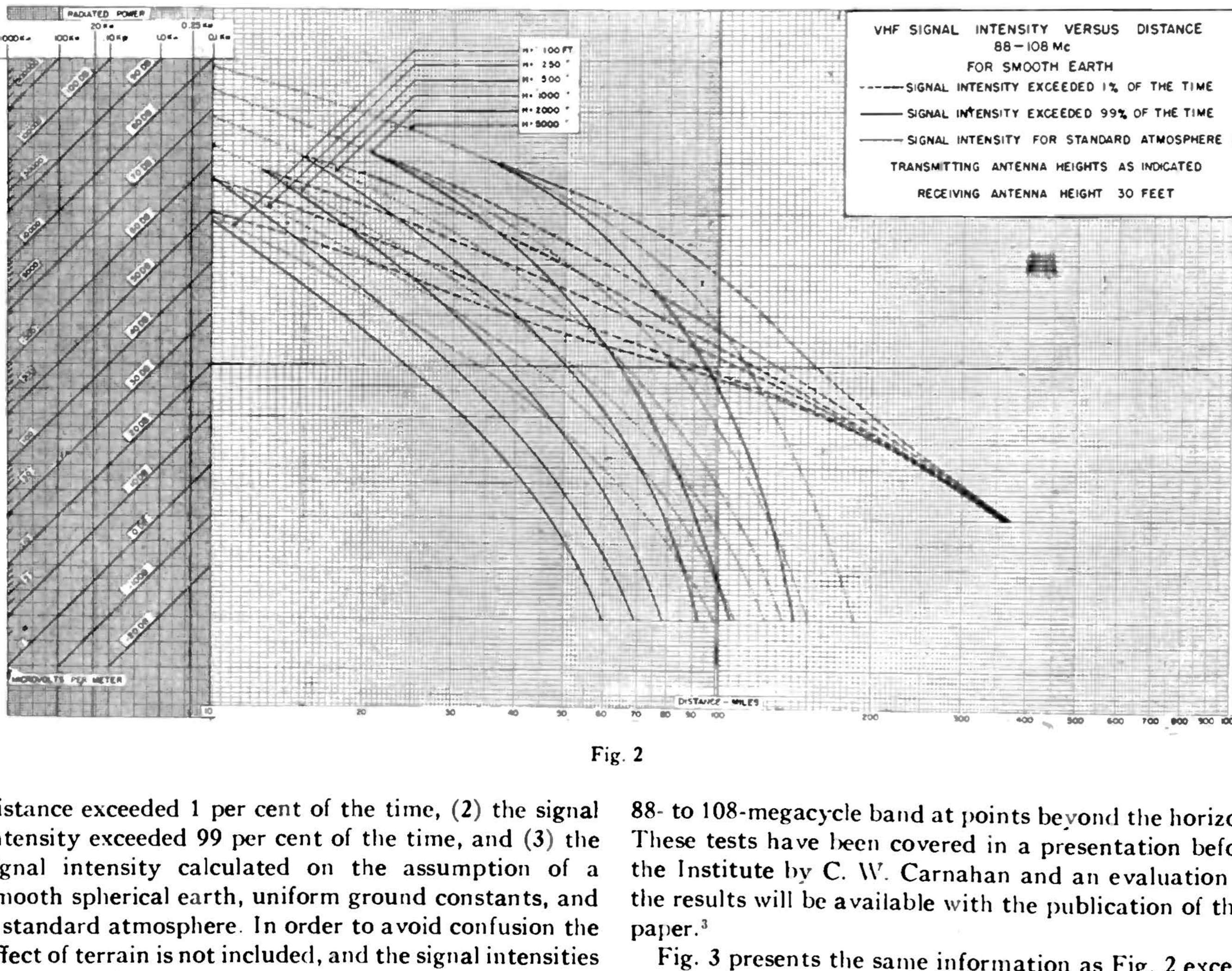

Fig. 2

Fig. 3 presents the same information as Fig. 2 except that the boundary curves of the fading ranges are for the signal intensities exceeded for 10 and 90 per cent of the time.

While it is conceded that sufficient data are not available at this time to present these curves as a precise representation of the variation of signal intensity versus distance in this frequency band, they do, however, clearly reflect and show the effect of the troposphere on broadcast signal intensities. The reader is invited to compare the curves of Figs. 2 and 3 with Fig. 3 of Mr. Allen's paper. His presentation creates the impression that the effect of the troposphere is to cause only signal intensities greater than would be predicted by standard atmosphere. This conclusion is misleading and is not in accord with observations and measurements in any portion of the frequency band under consideration.

The quasi-optical characteristics of the frequencies above 30 megacycles were recognized by the early experimenters and have been well known for the last fifteen years. The shadow loss behind hills is considerable at the lowest frequency and this loss increases with the frequency. In practice the shadow effect of hills results in signal intensities being less by varying amounts, depending upon the degree of irregularity of the terrain, than those predicted by theoretical calculations which assume a smooth earth.

Mr. Allen disposes of the effects of irregularities of terrain such as hills and mountains by stating that they are expected to cast deeper shadows at higher frequencies but that much work has to be done to evaluate these effects. He then speculates at considerable length on the relative penetrating effect with respect to frequency of buildings without arriving at any definite conclusions.

At the time Mr. Allen wrote his paper there was ample information available to permit accurate evaluation of the effect of terrain. Had he taken advantage of available information the effect of terrain would never have been given the treatment that it was accorded in the paper under discussion, which merely disposes of this major effect on the service range of frequency-modulation broadcast stations by allowing a factor of 6 decibels for the combined effect of terrain and antenna transmission-line losses.

In a large portion of the densely populated areas of this country, such as the Eastern and Northeastern portions and the West Coast, the effect of terrain on a substantial portion of the population within the proposed service area of broadcasting stations is to decrease the signal intensities to only a small fraction of that predicted by theoretical curves.

Fig. 4 is a nomographic chart for estimating the probable magnitude of the shadow loss due to irregularities in terrain. This chart was contained in the publication entitled "Propagation Curves," October, 1944, by Division 15 of the National Defense Research Committee. Although at that time a restricted publication, it was available to Mr. Allen. This publication has since been declassified. The information contained therein was prepared for the National Defense Research Committee by the Bell Telephone Laboratories, Inc. The method of obtaining the probable magnitude of the shadow loss behind a hill is readily understood from an examination of Fig. 4. It will be noted that, at distances of one-quarter to one-half mile behind hills of from 50 to 150 feet above the surrounding terrain, shadow losses of 6 decibels or more are obtained, and that for distances of a mile or two behind elevations up to 1,000 feet, losses of the order of 20 to 30 decibels are encountered. Measurements generally confirm the predictions of the shadow losses shown in Fig. 4. In practice,

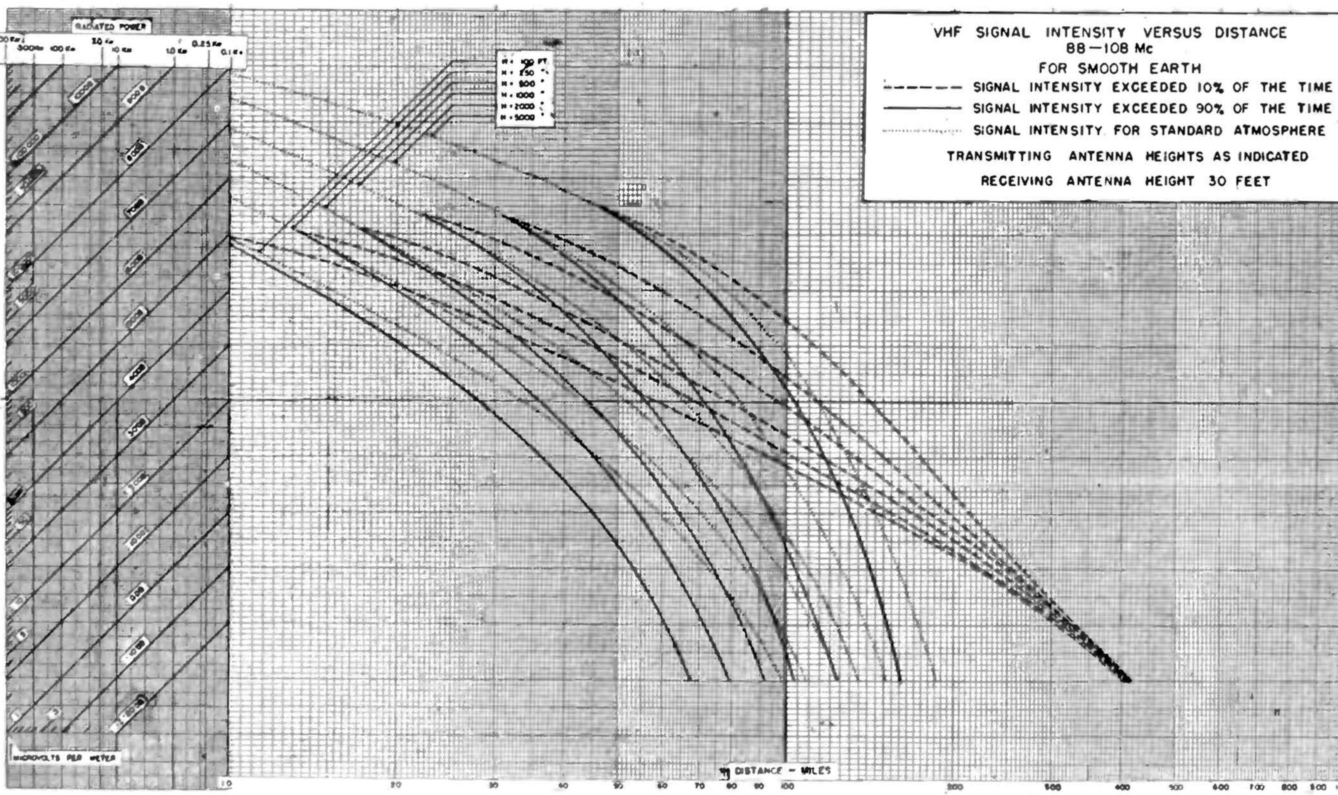

Fig. 3

where multiple irregularities exist the losses tend to exceed those predicted, especially at the higher frequencies.

The assumptions that Mr. Allen makes in his paper are so far from the true facts that the conclusions he draws therefrom must be in error. Since there is contained in this paper the substance of the technical evidence upon which rested the decision of the Federal Communications Commission to re-allocate frequency-modulation broadcasting from its previous allocation in a band of frequencies in the vicinity of 45 megacycles and to assign this service to a band in the vicinity of 100 megacycles, it is evident that this paper is one of the most important ever presented to this Institute. It merits the most careful consideration and critical analysis of the scientific world.

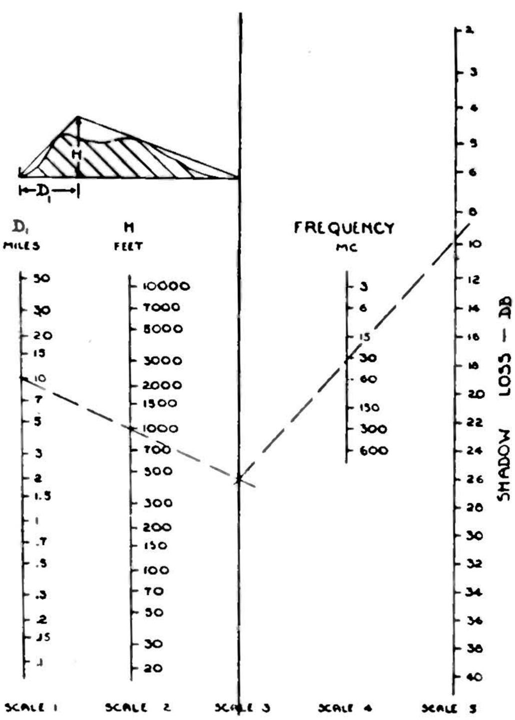

Fig. 4—Shadow loss.

Dale Pollack:[8] My first comment on the Allen paper is on the use of field intensity at the antenna, rather than voltage at the receiver (or antenna) terminals for the establishment of service ranges. This is, I believe, deceptive. I do not agree with Allen and Norton that the criterion of a good service is better expressed in terms of microvolts per meter than in terms of microvolts. When receiver noise is the limitation on range, I think Allen will agree that microvolts at the receiver terminals is the only proper criterion for comparison of one frequency against another. When other factors (such as ambient noise, or undesired signals) are limitations, then either signal strength or voltage are equally good criteria. The ratio of desired to undesired signals, mathematically, if not experimentally, will be identical measured in either way. Therefore, since in the only instance in which a preference exists, that preference is for voltage measurements, the emphasis should be placed on voltage data and not on microvolts per meter, as in the Allen paper.

The Allen paper sets up standards for coverage based on certain field intensities (500, 50, and 5 microvolts per meter, depending upon the class of service), irrespective of frequency. Since the voltage pick-up from the type of antenna which is likely to be used reduces as the frequency increases, the performance of the higher frequencies will suffer. I myself may install a directional antenna (if Allen compels me to by moving my favorite stations to the high band), but the typical listener certainly will not fuss with a rotating beam. The comparison, to be impartial, must be based on equal voltages at the antenna terminals at the different frequencies, not on field intensities. Allen, in effect, admits this when he states' " . . . at higher frequencies it appears to be expedient to protect a higher contour, or set noise rather than co-channel station interference will be the limiting factor." He then proceeds to ignore this rule.

My second comment has to do with the accuracy of the computations themselves. In Allen's Fig. 1, the distance to the 50 microvolts per meter line (for the 1000-foot, 50-kilowatt transmitter) is almost independent of frequency. This distance is about 80 miles, twice optical. If this is true, a directional antenna having the same physical dimensions at 10 centimeters as one at 10 meters should develop approximately the same voltage at the receiver terminals. It seems unreasonable to me. Has anyone dared to space microwave relay stations much farther apart than optical?

I have replotted the high-power data of Allen's Fig. 1 in Fig. 5, giving field intensity against range for three frequencies. The curves intersect at between 1.5 and 2 times line-of-sight. This is contrary to my own experience with such computations, which always have shown intersections at less than line-of-sight distances. At between 1.2 and 1.5 times line-of-sight the 10-centimeter field intensity is heading straight up. It is difficult to believe that the 10-centimeter field is going to be so much stronger than the 7-meter field at 1.3 times line-of-sight, as the curve indicates will be the case. Is it appropriate to ask if the Allen-Norton curves have been checked by an independent authority?

The third point I wish to make is one which was first made by Norton in his testimony before the Federal Communications Commission at the January, 1946, hearing. In his statement Norton attempted to reconcile the Zenith propagation tests with his calculations. He calculated the effect of hills and valleys between the transmitting and receiving antennas and stated " . . . the 550-foot rise in terrain between transmitter and receiver . . . has the effect of decreasing the calculated ground-wave field in the ratio of 10 to 1 on 98 megacycles. The corresponding decrease on 46 megacycles is only in the ratio of 5 to 1. Thus we see that

[8] 352 Pequot Avenue, New London, Connecticut.

comparatively small systematic deviations in the terrain cause relatively larger variations in the expected ground-wave field intensity at points well beyond the line of sight." Thus a hill between transmitter and receiver has reduced the 98-megacycle field by twice as much as it has reduced the 46-megacycle field.

Norton implies further that a valley between the two points would have the reverse effect (as might be expected qualitatively). He then states that for general allocation studies the curves for smooth terrain should be used, since it is equally likely that the transmitter and receiver will be at higher or lower levels than the intervening terrain. It is here that Allen and Norton err. Average conditions are not the criteria in propagation work.

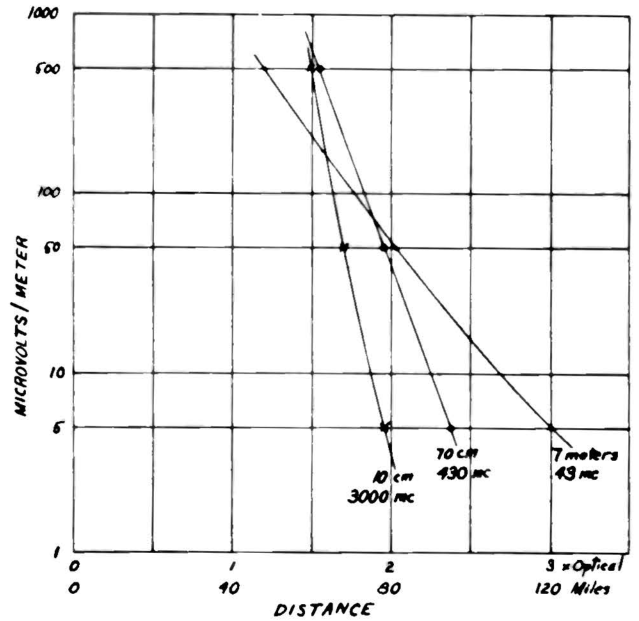

Fig. 5—Replot of part of Allen's Fig. 1. Antenna heights, 1000 and 30 feet. Power, 50 kilowatts. Horizontal half-wave antenna.

I will try to make this point clearer. Consider two receiver locations, at the same distance from the transmitter, near the extreme service range but off in different directions. In one direction a valley intervenes, in the other, a hill. For the receiver beyond the valley, while a 98-megacycle signal will have been increased more than a 46-megacycle signal, both signals will be strong and reception will be good on either band. For the receiver behind the hill, however, at 98 megacycles the signal will have been reduced more than at 46 megacycles and, since we are dealing with marginal signals, we will have reception at the low frequency and not at the high. It is unnecessary to worry about receivers beyond the valleys. They will have good signals irrespective of frequency. The case to be concerned about is that of the receiver beyond the hill, for which, by Norton's own testimony, the high frequencies will be attenuated more than the low.

There are many other points which are open to question in the Allen paper. These have been raised by others and presumably will be presented by them.

As Jansky remarked at the discussion held at the Winter Technical Meeting on January 27, 1945, it is important to "draw a sharp line between facts and interpretation of facts." In very-high-frequency propagation, too few facts are known. Allen and Norton are better able to discuss these few facts than perhaps anyone else. Their interpretation of the facts, however, I believe to be contrary to experience. It is regrettable that their interpretations have been used as the basis for allocations which will hamper the development of frequency modulation for some time to come.

Edward W. Allen, Jr.:[9] Concerning Major Armstrong's allegation of skulduggery in the predictions of the field intensities to be expected for sporadic-E-layer interference, Mr. Norton and I went over the method of analysis with him for both E- and F-layer predictions in October, 1944, prior to the presentation of the paper. The curves included in the present paper (Fig. 8) were presented at the meeting, yet the Major elects to interpret the general statement made in the discussion at the meeting and quoted by him as belying the accuracy of the curves. As I recall it, the statement was made in response to a query as to the reliability of the method of extrapolating the Bureau of Standards vertical incidence measurements, not as to the reliability of the measurements made by the Federal Communications Commission. The statement was based upon a study which I had made of the month-to-month correlation of our measured values with the extrapolation of the Bureau of Standards values, in which I had found a remarkable agreement in the upward and downward trends. The actual number of minutes of occurrence for any month given by the two methods need not be in exact agreement in order to obtain correlation, for, as with any fading signal, these are a function of the reference level at which the analysis is made. In order to expect numerical agreement, analysis of the Federal Communications Commission recordings should be made at a level consistent with the sensitivity of the Bureau of Standards pulse-measuring apparatus; that is, at 140 microvolts per meter for 340 kilowatts, or about 7 microvolts per meter for a 1-kilowatt pulse transmitter, which seems to be a reasonable figure. You will recalled that I made a change in the description of Fig. 8 in order to clarify the method of arriving at the sporadic-E intensity curves.

It remains to be seen whether experience will bear out the statements made by Messrs. Carnahan and Brown as to the relative service areas in the old and new frequency-modulated bands, based on a few short-time measurements made during that part of the year when tropospheric effects are at or near a maximum. It should be pointed out that the estimate is not as to an actual reduction in service area, but a reduction in the area in which service is possible in locations where

[9] Federal Communications Commission, Washington 25, D. C.

ambient noise and station interference are not a problem and where the set owner uses a simple doublet rather than an antenna of comparable size for the two bands. Fig. 9 of my paper recognizes an approximate reduction of 50 per cent in the extended rural area and of 30 per cent in the over-all area when simple doublet receiving antennas are employed, assuming undisturbed fields of values predicted by Norton's curves.

Their estimate of 60 per cent reduction in service is apparently not based on measurements but on Major Armstrong's unsupported estimate that a 100-mile radius can be obtained at 46 megacycles with a 1000-foot transmitting antenna irrespective of tropospheric fading. According to data furnished by RCA, which was placed in the record of the allocations hearing, fading on 43 megacycles during October and November, when propagation is above average, appeared to be too severe at Riverhead on a receiving antenna 60 feet above ground to give good service from Mount Asnebumsket, 1600 feet above sea level and 103 miles distant. Some 20 miles of this path are over sea water, and the fading was undoubtedly much less than would have occurred over a land path of similar length and with lower antennas. On the basis of Mr. Carnahan's own analysis of the Zenith and the Federal Communications Commission's data, service at 70 to 75 miles for a 35-kilowatt station on 45 megacycles is marginal rather than satisfactory. If it is assumed, for the sake of argument, that a 70-mile radius is average for 45 megacycles, a 60 per cent reduction in area would result in an effective radius of 45 miles at 100 megacycles. The measurements made for the Federal Communications Commission by the RCA Laboratories at Princeton, at a distance of 45 miles from transmitters in New York City, show that there is little difference in the fading of 43, 84, and 107 megacycles at this distance, so that an estimate of 60 per cent reduction in area on this basis appears to be entirely unreasonable.

Relative to the question of international allocations of frequencies, it was apparent to those familiar with world-wide ionospheric conditions that the 42- to 50-megacycle band was even less suitable for frequency modulation in certain other areas of the world than in the United States, so that the upward move of frequency modulation has improved rather than deteriorated its outlook in this respect. In this regard I should like to call attention to the 4000-kilometer F_2-layer maximum-usable-frequency predictions for November, 1946,[10] in which frequencies of 42 to 44 megacycles are shown for 50 degrees North latitude in the United States, and frequencies up to 62 megacycles for other parts of the world. These are monthly average figures and a frequency distribution of plus or minus 10 per cent may occur around the average frequency.

[10] Ref. CPRL-D24, Basic radio propagation predictions for November, 1946, Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.

Mr. de Mars' curves of very-high-frequency signal-intensity versus distance are very interesting and are a significant contribution to present knowledge of the effects of the troposphere on very-high-frequency propagation. While I am in agreement qualitatively with the results of his study, I feel that the tropospheric curves are somewhat low as compared to the standard atmosphere curves. It has been our experience and the experience of others in the field that the standard-atmosphere or undisturbed value will be exceeded by instantaneous values of tropospheric field for about 60 to 90 per cent of the time, depending upon frequency, antenna height, distance, terrain, time of year, and other factors, whereas the undisturbed value seems to approximate the median or 50 per cent value for some of his curves. This error may be due to a comparison of actual measured tropospheric data with smooth-earth theoretical undisturbed values such as appeared in some of the data furnished to Mr. de Mars. While Mr. de Mars' statement, that the inner boundary of a service area is determined by the minimum value of fading signals, is undoubtedly correct, it should not be inferred that a comparison between the undisturbed and the minimum curves of his Figs. 2 and 3 represents a comparison of the relative signal ranges at 50 and 100 megacycles. Fading below the undisturbed values occurs also at 50 megacycles, and only adequate data at both frequency ranges, similarly analyzed, will provide such a comparison.

Relative to Mr. de Mars' comment on Fig. 3 of my paper, I should like to reiterate that the tropospheric field values shown are taken from actual measurements. The data were analyzed in terms of hourly median values rather than instantaneous values. Since the distances shown are all in the region where rapid fading occurs for a majority of the time, analysis on an instantaneous basis could readily lead to a different result. If the fading of instantaneous values over short periods of time follows a Rayleigh or similar distribution in which fading below the median value is more pronounced than above the median, the values derived from an analysis on an instantaneous basis will be lower than on an hourly median basis, as indicated by the data presented by Mr. de Mars.

Since the shadow-loss nomograph presented by Mr. de Mars was classified at the time of presentation of the paper, no reference could, of course, be made to it. It is based on diffraction theory, and, while it provides a good guide in cases where the diffracted field is the major component of received field, it oversimplifies the general problem in that it takes no account of other contributions such as scattering and reflections (see original text accompanying the nomograph), which in general will be greater at 100 megacycles and may more than offset the 2 decibels difference in the diffracted fields at 50 and 100 megacycles. In such surveys as we have made, directly comparing 50 and 100 megacycles coverage, no systematic difference in shadow effects has been observed between the two bands. In addition, the use of this nomograph presupposes a knowledge of the terrain in question and it is not a measure as to what shadow loss may be expected on the average, in the absence of data on average terrain conditions. In view of the insuperable task of working out a detailed allocation, examining the terrain in each case and obtaining an average terrain factor, it became necessary to make a reasonable assumption in this regard. Perhaps the assumption was too low, but the relative effect at the two frequencies is apparently not too different for given terrain conditions.

Referring to Mr. Pollack's comments on the use of field intensities rather than microvolts available at the receiver terminals as a basis of comparison of the relative ranges of two frequencies, it should be stressed that the determining factor is the available signal-to-noise ratio or desired-to-undesired-signal ratio in any case. For receiver noise, the receiver terminal voltage ratio at two frequencies is a proper measure only if the receiver noise figure is the same at the two frequencies; otherwise, a comparison of the two signal-to-noise ratios should be used. It has been conventional to express ambient noise and station interference in terms of field strengths (see reference 4), so that a simpler and more direct measure of the available signal-to-noise ratio is obtained by using the same units for the desired field. This makes it unnecessary to specify antenna characteristics, line losses, line impedance, etc. In microwave work it has become conventional to express signals and noise in terms of power, and at some future date this may also be applied to the lower ultra-high-frequency and perhaps very-high-frequency ranges.

As to the accuracy of the computations, the curves of Fig. 1 are in agreement with the field-intensity versus distance curves which have appeared in several of Mr. Norton's papers and which have been adopted as Federal Communications Commission standards. The basic curves were very thoroughly checked before publication, and such recent calculations as we have made have not revealed any systematic errors. Consequently, I believe that the calculations will be found to be correct.

Edwin H. Armstrong:[2] Mr. Allen's discussion contains some very important statements. It is now admitted that the theory of a minimum "ground-wave" level which is present at all times is not correct. It is likewise admitted that it is a mistake to analyze recordings on an hourly median basis and that they must be analyzed on a basis of instantaneous values if the analysis is to have any relation to what the listener actually hears.

We have come indeed a long way from the Federal Communications Commission hearing when I testified to the depth of fading observed by me years ago on a 70-mile 117-megacycle transmission and Mr. Allen questioned whether my receiver was operating properly.

However, there is still no frank facing of the situation as it actually exists, because in the final paragraph of Mr. Allen's discussion it is reiterated, in insisting on the accuracy of the Norton propagation curves, that his computations have been checked and that no *systematic* errors have been revealed. That is not the point. The calculations can be quite in order but error will still have been committed. That error consists in applying results obtained from calculations based on totally inadequate assumptions to the solution of a problem where the facts of life bear no relation to the assumptions made.

The measurements of field strength made simultaneously at Andalusia, Pa. (70 miles), and Princeton, N.J. (40 miles), on some transmissions from New York City by the Federal Communications Commission and the RCA Laboratories, respectively, illustrate the situation perfectly. Transmission was observed on 46, 83, and 107 megacycles during the period of August and September, 1945. The transmission paths are coincidental.

On 83 megacycles there were five identical hours when the hourly average at the 70-mile point was higher than that measured at the 40-mile point. There were eleven additional hours when the 70-mile point may have been higher, but due to the recorder running off scale at Andalusia the exact level remains indeterminate. There were still eleven more hours when the 70-mile signal level averaged 50 per cent or more of the 40-mile average, making a total of 27 abnormal hours in 51 days of operation.

The same phenomena was observed on 107 megacycles. It did not appear on 46 megacycles.

Such changes in hourly averages at Andalusia (83 megacycles) as from over 160 microvolts per meter (off scale) for 8–9 A.M. to 4.6 microvolts per meter for 1–2 P.M., from over 161 microvolts per meter (off scale) for 8–9 A.M. to 6.3 microvolts per meter for 1–2 P.M., and from 160 microvolts per meter at 9–10 A.M. to 1.8 microvolts per meter for 11–12 A.M.—to select only a few days at random—show how utterly meaningless it is to talk of the accuracy of computations when one has first to learn how to write a formula for the weather, an undertaking which I believe has not yet successfully been accomplished.

Predicted value for the above-mentioned transmission is approximately 8.9 microvolts per meter. The above hourly averages do not, of course, reflect the depths of the fades.

Turning now to the question of the hocus pocus in connection with the sporadic-*E* predictions, Mr. Allen's explanation does not explain. The caption of his Fig. 6 is as plain as the English language can make it. It is entitled: "Percentage of the time and the number of hours during the period September, 1943, through August, 1944, for which the sporadic-*E*-layer skip distance was less than the value shown for particular frequencies."

After describing the methods of deriving these curves from the vertical-incidence measurements of the critical frequencies and pointing out that they appear not to be affected by the sunspot cycle, the statement is made: "Consequently Fig. 6 is believed to represent a reasonably good estimate of the percentage of time that a single frequency-modulation or television station would be expected to interfere with another similar station on the same frequency at the distances shown." This is a plain statement that you either have transmission or you do not, depending on whether or not the layer supports it, for no one would lump two services dissimilarly vulnerable to interference, such as frequency modulation and television, in the same breath were an intensity factor involved.

Mr. Allen's explanation that the curves of Fig. 6 are to be taken as representative of the number of hours that a 140-microvolt signal would come through from Paxton forces the following conclusion. The title of Fig. 6 and the statement above referred to, and most particularly with respect to television, is meaningless, since under the standards of television service of a 500-microvolt limit and 100-to-1 signal-to-disturbance ratio, a 5-microvolt sporadic-E transmission would cause interference. For the transmission under consideration this would certainly occur on the basis of the Commission's measurements for a period of 5- to 10-fold the time of transmission indicated on Fig. 6.

If anyone cares to take the trouble to read the record of the proceedings before the Federal Communications Commission he will, I believe, find my previous explanation of the reason for the p curves to be the correct one. I did not raise the question when Mr. Allen presented this paper before the Institute for the reason that at that time the discrepancy between the predicted and actual times of transmission and the use of the p curves to conceal it had not then been discovered.

There is one further statement to which attention ought to be called. Mr. Allen refers to my "unsupported estimate that a 100-mile radius can be obtained at 46 megacycles with a 1000-foot transmitting antenna irrespective of tropospheric fading." My statement was based on observation of transmission from Alpine to a point in Haddonfield, New Jersey, 100 miles away, where the signals were observed for a period of three years. The estimate is likewise supported by a recently published report issued by the British Broadcasting Corporation, prepared by Mr. H. L. Kirke, Director of Research of the British Broadcasting Corporation Engineering Division. It is likewise supported by the experience of others.

Note is made herewith that my discussion of the duration and extent of sporadic-E interference was based on Mr. Allen's Fig. 9 as it was originally presented to the Institute and as it stands in the paper today.

For the sake of the record, attention is called to the fact that footnote 11 in Mr. Allen's paper on page 136 appeared as a part of the paper after all discussion had been concluded. It does not change the basis of my criticism nor its conclusions.

C. W. Carnahan and J. E. Brown:[6] Mr. Allen objects to our estimate of a 60 per cent reduction in service area for the new band. Assuming a 70-mile radius at 45 megacycles, a 60 per cent reduction in service *area* at 100 megacycles would decrease this radius to 55 miles, not 45 miles. As to the measurements quoted, while there was little fading on the high frequencies at Princeton, which is almost within line of sight of the high New York antennas, the fading at Andalusia, Pa., a distance of 72 miles, far exceeded any tolerable value, while the low-band signal was still acceptable. The high-band signals completely deteriorated in the 28 miles between Princeton and Andalusia, and our estimate of 55 miles as the outer limit of the service area is certainly not unreasonable.

Most engineers do not have the time or the facilities for reading the entire record of the Hearings before the Federal Communications Commission on the frequency-modulation allocations. If they did they would know that the data collected in the Milwaukee-Deerfield tests only substantiates what every propagation expert who testified before the Federal Communications Commision has found, namely, that you do not get the reliable coverage at 100 megacycles that you do at 50 megacycles.

Mr. Allen in his comment states "... it was apparent to those familiar with world-wide ionospheric conditions that the 42- to 50-megacycle band was even less suitable for frequency modulation in certain other areas of the world than in the United States...." It is strange indeed that the British have reopened their television service in the 40- to 50-megacycle range. The Federal Communications Commission has authorized television in this same range, and undoubtedly other countries will do the same. It would appear that the matter of long-distance transmission is of no great concern, or television, which is much more susceptible to interference than frequency-modulation would not be expected to work satisfactorily in this part of the spectrum. It would appear from the record that no one in the whole world but Mr. Allen and Mr. Norton is worried about this long-distance transmission.

Paul A. de Mars:[7] In his discussion Mr. Allen states that he is in agreement qualitatively with the very-high-frequency signal-intensity versus distance curves presented with my discussion of his paper. He admits that the inner boundary of a service area is determined by the minimum value of a fading signal. He acknowledges that the analysis of signals on an hourly median basis does not yield correct results to evaluate the service to broadcast listeners.

It is felt that the importance of this subject merits examination in detail of Mr. Allen's discussion in order to clarify some of the statements contained therein.

Mr. Allen states in reference to the above-mentioned curves (Figs. 2 and 3 of my discussion) that he feels the tropospheric curves are somewhat low as compared to the standard atmosphere curves. In support of this opinion Mr. Allen states: "It has been our experience, and the experience of others in the field, that the standard atmosphere or undisturbed value will be exceeded by instantaneous values of tropospheric field for about 60 to 90 per cent of the time, depending upon frequency, antenna height, distance, terrain, time of year, and other factors, whereas the undisturbed value seems to approximate the median or 50 per cent value for some of these curves." One can hardly disagree with this statement because it covers too much territory and is protected by too many qualifications, except to point out that the seeming approximate correspondence of the undisturbed values (standard-atmosphere curves) with median or 50 per cent values is not necessarily a fact. Mr. Allen has no right to assume that it is a fact unless the distribution of the instantaneous field intensities is stated to be, or is known to be, about the same above and below the median value. Mr. Allen concedes that if actual measured tropospheric field intensities are analyzed in terms of instantaneous values rather than hourly median values, the results will differ from those shown in Fig. 3 of his paper, and will correspond more with the data presented in my discussion.

Examination of the family of curves in question discloses that every factor mentioned by Mr. Allen above is taken into consideration and is clearly designated in the legend. The curves mean just what their designation says they mean.

Mr. Allen then continues to state: "This error may be due to the comparison of actual measured tropospheric data with smooth-earth theoretical undisturbed values such as appeared in some of the data furnished to Mr. de Mars." "This error" refers to what, in Mr. Allen's mind, is the seeming approximation of the standard atmosphere curves to the median or 50 per cent value for some of my curves. Assumption that "error" exists is not supported by Mr. Allen's statements because, as shown in the foregoing, a fact has been assumed that is not true. Here, as in all other fields, mistaken conclusions inevitably result unless the facts are true.

The reader is warned by Mr. Allen quite unnecessarily that it should not be inferred that a comparison between the undisturbed and the minimum curves of my Figs. 2 and 3 represent a comparison of the relative signal ranges at 50 and 100 megacycles. Nothing in the text of my discussion or in the titles of the curves can possibly be construed as tending to lure the reader into such a misunderstanding.

At this point comparison is invited of Figs. 2 and 3 of my discussion, with which Mr. Allen is now in qualitative agreement, with his Fig. 3 in the light of the above. The reader should understand by now that the actual service range, which is determined by the minimum signal, can be markedly less than that predicted by theoretical ground-wave curves which represent only the assumed standard atmosphere condition and fail to take into consideration the fluctuations of signal intensity that accompany meteorological changes.

In that portion of my discussion of Mr. Allen's paper relative to the effects of terrain, I limited my comments to the shadow losses behind hills. Mr. Allen admits that the nomograph, presented as Fig. 4 of my discussion, is a good guide in estimating these losses in cases where the diffracted field is the major component of the received field. It is recognized that under certain very special conditions the field intensity behind a hill may be greater than would be obtained if the terrain between the antennas were level ground. It is found, however, that in general intervening hills cause a loss in field intensity. Also, scattering and reflections from nearby hills near the straight-line path may have an appreciable effect. In some cases a stronger signal may be obtained by devious routes than can be expected by diffraction over the straight-line path. Experience shows, however, that these exceptional cases occur too infrequently to be of importance in considering the coverage of a broadcast service. Such exceptions are, in fact, hard to find in practice and may be fairly considered to be curiosities.

Experience supports the opinion that in general the major component of the signal behind hills would be the diffracted field and that Fig. 4 is, therefore, a good practical guide in estimating the magnitude of shadow loss. This being the case, Mr. Allen's allowance of 6 decibels for the combined effect of terrain and antenna transmission-line loss is totally inadequate.

This conclusion is supported by my own observations and measurements in the hilly and mountainous terrain of New England and by measurements made by the Radio Corporation of America. It is also supported by a recently published report issued by the British Broadcasting Corporation, prepared by Mr. H. L. Kirke, Head of the Research Department of the BBC Engineering Division.

Mr. Allen's failure to present a practical estimate of broadcast service ranges in the very-high-frequency band is not readily understood. As stated earlier, the dependence of the signal intensities on weather and the effect of terrain were observed and accurately reported many years ago. This information was available to Mr. Allen. About this there can be no question because exhibits quantitatively presenting the effect of the troposphere and terrain in the 40- to 50-megacycle band were introduced into the record at the frequency-modulation hearing before the Federal Communications Commission in March, 1940.

Three of these exhibits merit presentation in order that there may be no question that the true facts were known at the time Mr. Allen prepared his paper. Figs. 6 and 7 were prepared by me and were introduced as exhibits with accompanying testimony in behalf of FM

Broadcasters, Inc., for whom I was at that time directing the preparation and presentation of that organization's technical testimony.

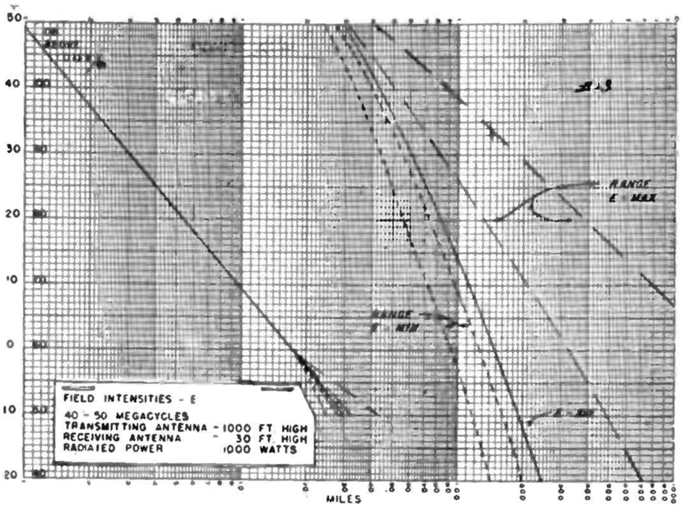

Fig. 6

Fig. 6 purports to show the effect of the troposphere on the signal-intensity versus distance, antenna height, and radiated power shown. The solid curve represents the signal-intensity versus distance derived from meas-

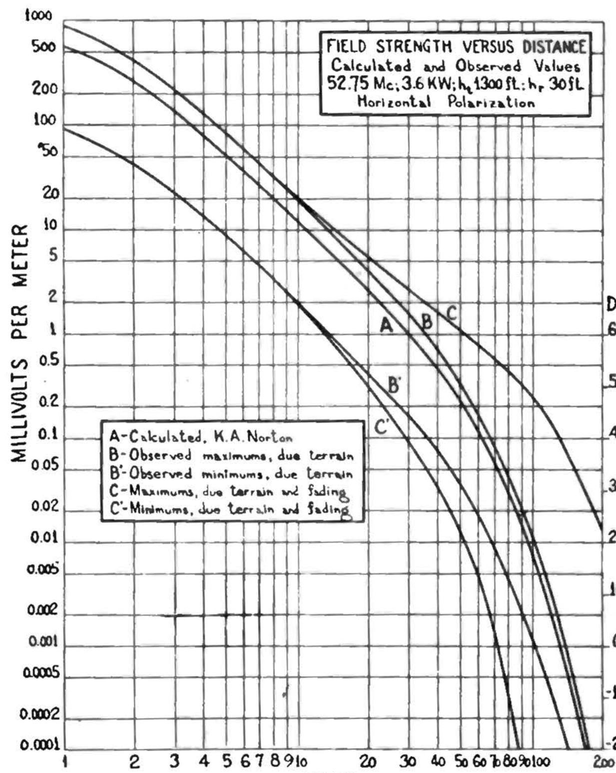

Fig. 7

urements made under what were believed to be average meteorological conditions. The dotted curves show the range of fluctuating signal intensities under substandard atmospheric conditions. The dashed curves show the range of fluctuations of signal intensities under superstandard atmospheric conditions.

Fig. 7 was originally prepared in June, 1937, in connection with the application of the Yankee Network, Inc., for a 50-kilowatt experimental frequency-modulation broadcast station on the summit of Mount Wachusett in Princeton, Massachusetts. The propagation curves shown thereon were derived from field-intensity measurements from a transmitter on the summit of Mount Wachusett. These measurements were made to determine accurately the effect of terrain because at that time the opinion of A. D. Ring, then Assistant Chief Engineer, Broadcast Division, of the Federal Communications Commission, was that the 40- to 50-mega-

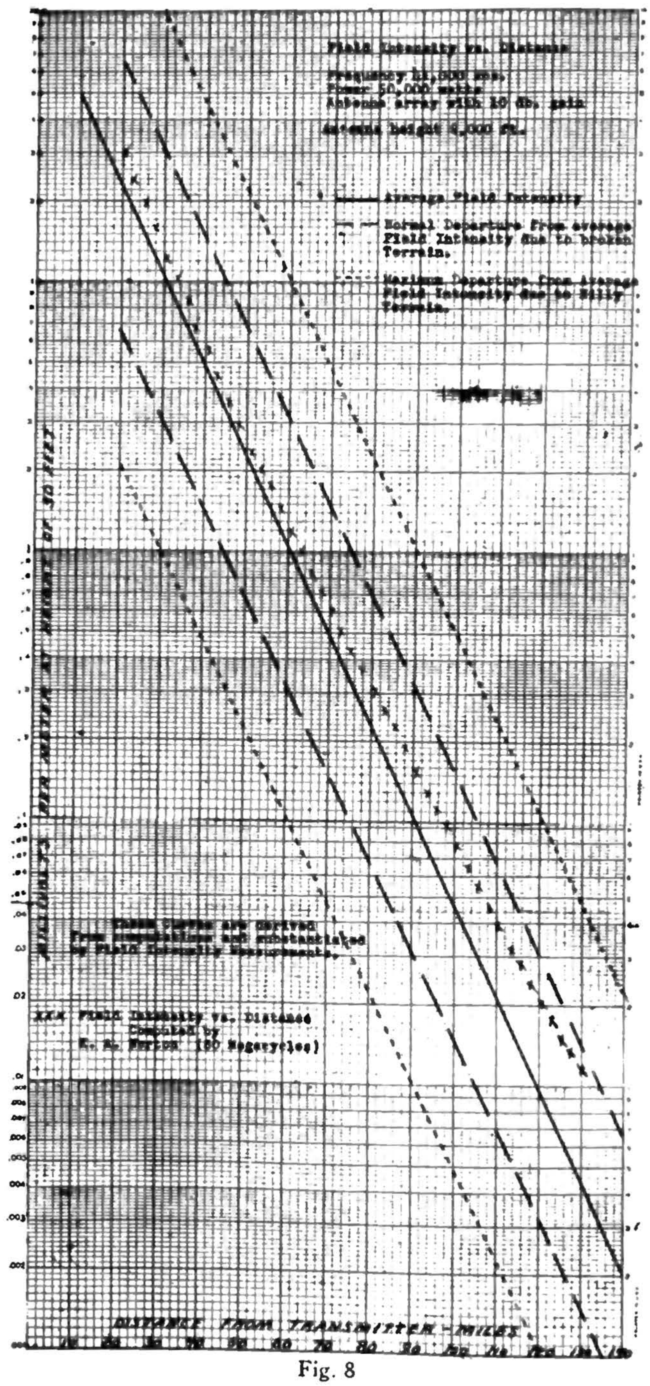

Fig. 8

cycle band could not provide service behind hills. These propagation curves were adopted by FM Broadcasters, Inc., and were presented by me to show the effect of terrain. K. A. Norton's theoretical ground-wave curve for 50 megacycles was added to permit ready comparison. The significance of these curves lies in the magnitude of the range of signal intensities observed due to the effect of terrain and to the fact that signals fall far below the theoretical calculated values.

Fig. 8 was introduced at the hearing by Dr. H. H. Beverage in behalf of the Radio Corporation of America. Presented in this figure are curves showing the observed effects of terrain and fading and K. A. Norton's theoretical calculated ground-wave curve.

The fundamental accuracy of Figs. 6, 7 and 8 have never been attacked on the record. Not even when Fig. 6 was again presented to the Federal Communications Commission in the closed hearing on March 13, 1945, Docket 6651, was its accuracy questioned.

It is believed that fundamental defects in Mr. Allen's treatment of this subject have been pointed out which establish that his conclusions concerning broadcast service ranges are inaccurate and misleading.

Dale Pollack:[8] Allen's reply to my comment on the use of field intensities rather than microvolts at the receiver terminals is very much to the point. The paper would have been less misunderstood if it had conformed.

Since Allen does not answer my other two points, I have no further comment.

E. W. Allen, Jr.:[9] I feel that Major Armstrong is making an unwarranted assumption in his statement, "It is now admitted that the theory of a minimum ground-wave level which is present at all times is not correct," and Mr. deMars also in subscribing to it. I do not recall having advocated such a theory. The problem is one of determining whether theoretical curves, which take into account a fixed value of atmospheric refraction obtained under "standard-atmosphere" conditions, can be used as a reliable prediction for expected service and interference ranges in the very-high-frequency portion of the spectrum. While furnishing a perfect service would require consideration of the minimum signal from the desired station and the maximum signal from an undesired station, assuming that the fading is not coordinated, practical standards usually involve some compromise, so that a determination must be made as to an acceptable percentage of time during which the signal must exceed a minimum service level and lie below a tolerable interference level. The problem thus becomes a statistical one which is susceptible of several methods of attack. The most direct one is to analyze all available data on an instantaneous-field-strength basis. This method becomes cumbersome when large amounts of data are to be handled, and in the past we have adopted the procedure of determining separate distributions for long-period and short-period variations and then combining the two in order to evaluate the over-all distribution. This method has worked well for ionospheric propagation in the standard broadcast band, and there is no apparent reason why it cannot be applied successfully in the very-high-frequency and ultra-high-frequency bands for tropospheric fields. Burrows, Decino and Hunt[11] found that the distribution of instantaneous fading follows a normal law, which is symmetrical with respect to the median value, rather than the Rayleigh or some other asymmetric law, and this has been substantiated by more recent data. Knowing the law of the distribution of instantaneous fields for short time periods, the over-all variation can be obtained by the proper treatment of the hourly median fields. Using this type of analysis, I reached the conclusion that the "standard-atmosphere" curves could be used for the prediction of service ranges, since they were exceeded for more than 90 per cent of the time. There was no finding that the minimum fields were equal to or above the predicted values, as these fields were at or below the recorder noise levels. While more recently available data indicate that the above analysis gave results which were somewhat high as compared to analysis on an instantaneous basis, and that short-period instantaneous distributions obtained at a particular frequency and distance will not hold true at another frequency or distance, it does not follow that the method of attack is in error. One further probable reason for the high field-intensity values obtained in the above analysis is that the majority of the data were for afternoon and evening hours.

Relative to the alleged discrepancy between the measurements made by the Federal Communications Commission and the sporadic-*E* skip-distance curves computed from the National Bureau of Standards data, my explanation of the reasons for the differences in the observed data are simple and straightforward and I believe they need no further expansion. The skip-distance terminology is conventional for use in both *E*- and *F*-layer propagation, and I think that most engineers with experience in the matter will agree that it is a good guide as to when transmission can be expected but that actual periods of communication or of interference will depend upon receiver sensitivity or interference level and upon transmitter power. That is our experience in connection with the measurement of sporadic *E*-layer propagation and is supported by the reports of reception of the London television signals via *F* layer. The interference level for both frequency modulation and television at the outermost protected contour is the same, 5 microvolts per meter, so I see no error in a joint reference to the two services, even though the interference ratios are different, as well as the signal contours at which interference occurs. The residual areas for television will be less than shown in my Fig. 9, just as the service area for television is less than for frequency moduation at a given radiated power.

I fail to find any substantiation of Major Armstrong's estimate of a 100-mile service radius, under conditions of tropospheric fading, in the report of British Broadcasting Corporation Field Trials on Frequency Modulation, by H. L. Kirke. The service-area tables take no

[11] C. R. Burrows, A. Decino, and L. E. Hunt, "Stability of two-meter waves," Proc. I.R.E., vol. 26, pp. 516–528; May, 1938.

account of tropospheric effects, but are apparently based on Norton's curves, with appropriate values of required field intensity selected so as to overcome ignition noise and effects of terrain. The listening tests at distances up to 120 miles were made in the evening, when tropospheric fields are usually higher than average, but in no case can be taken as proof that a useful signal level will be exceeded for an acceptable percentage of the time at that distance. Antenna heights of 1000 feet or more will be the exception rather than the rule, and the average height is likely to be near 500 feet. Under these conditions I am inclined to agree with Mr. de Mars' estimate of a range of 70 to 75 miles at 50 megacycles. Present data indicate that the range at 100 megacycles will be somewhat less, but I do not feel that they are sufficiently comprehensive and reliable to make a real prediction as to what reduction will occur. Messrs. Carnahan's and Brown's estimate of a 55-mile radius is believed to be somewhat pessimistic, but even if this proves to be the case the resulting reduction in service area will be 40 per cent rather than the 60 per cent reduction which they estimated originally. Such estimates in the reduction of service areas do not apply to the majority of cases because the close spacing of stations, arising from the demand for facilities, will result in limitation of area by co-channel and adjacent-channel interference, rather than by failure of the signal from fading. On the other hand, the duplication will greatly increase the amount of interference within the protected area from sky-wave signals in the 50-megacycle band.

With regard to the reopening of British television on 41 and 45 megacycles, rather than on a higher frequency, I believe that a study of the situation will reveal that the primary consideration was the utilization of presently available television transmitting and receiving equipment, rather than the propagation characteristics of various frequencies. While the reception of the London television signals at Riverhead, Long Island, has entered into the discussions by way of comparison between experience and Bureau of Standards predictions for the last sunspot maximum, the probability of interference between 40 and 50 megacycles across the North Atlantic has not appeared to be too serious, as the path lies near the auroral zone and maximum usable frequencies are likely to be much lower than for other paths over which interference may be encountered. It is the areas of high maximum usable frequencies which constitute the principal problem of F_2-layer interference to this and other countries adjacent to such areas.

In making my comment upon the curves in Mr. de Mars' Figs. 6 and 7, the only assumption required, and I feel it to be a reasonable one, was that the data which he used in preparing his curves followed the same laws as the data which I have available to me. There appears to be good agreement generally between the data and the curves as to the range of fading, but the absolute values still appear to be low as compared to the standard-atmosphere curves, when both are based on smooth-earth conditions.

In his discussion of shadow effects Mr. de Mars loses sight of the fact that the comparison of service areas in my Fig. 9 was not made for hilly or mountainous conditions but upon an assumption of average conditions. The loss of additional areas due to shadow effects behind hills was discussed in the text, with greater losses expected at the higher frequencies. The nomograph submitted by Mr. de Mars shows a consistent 2-decibel difference in field intensity between the shadow loss on 50 and 100 megacycles, so that, even if the effects of scattering are neglected, the larger losses behind hills will apply almost to the same degree for both frequencies. Our experience has been that scattering does have a large effect and that there is no systematic difference between frequencies which is readily identifiable with features of terrain.

Field Intensities Beyond Line of Sight at 45.5 and 91 Megacycles*

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Summary—This paper presents the results of a field-intensity monitoring project initiated by the Federal Communications Commission during the summer of 1945. Field intensities on 45.5 and 91 megacycles from transmitters at Richfield, Wisconsin, were continuously monitored for a period of two months at Deerfield, Illinois, over a transmission path of 76 miles. The data is analyzed in terms of the average median field intensities and their diurnal variation. The number of hours of unsatisfactory broadcast reception due to fading is estimated for both frequencies, assuming representative transmitter power and receiver sensitivity. Comparison is made with similar analyses of data obtained by the Federal Communications Commission in the measurement of field intensities on 46.7, 83.75, and 107 megacycles at Andalusia, Pennsylvania.

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Introduction

In May of 1945 the Federal Communications Commission elicited the aid of various interested parties in making a number of field-intensity recordings on the old frequency-modulation broadcast band, 42 to 50 megacycles, and the proposed new band, 88 to 108 megacycles. These tests were to furnish more